TAMPERE UNIVERSITY OF TECHNOLOGY

**JUHANI JANHUNEN**

# QUALITY INSPECTION OF A PRODUCTION LINE WITH A SMART CAMERA

Master of Science Thesis

Examiner: Professor José L. Martinez Lastra
Examiner and topic approved in the Automation, Mechanical and Materials Engineering Faculty Council meeting on 11 January 2012.

**ABSTRACT**

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The technologies for continuous monitoring, diagnostics, prognostics, and control of assets have been developing tremendously in recent years. The new technologies provide tools to achieve greater predictability of plant behaviour and visibility, reduced safety risks, enhanced security and cost efficiency. eSonia project is researching a possibility to create an asset-aware and self recovery plant. In this thesis is implemented quality inspection part of eSonia project. The implementation includes choosing the camera and the components, building the inspection and the user interfaces, and also creating robust communication between the camera and the plant by using mixture of old industrial standards (like Modbus) and new technologies (like web services). The roadmap for building a machine vision application was tailored to suit smart cameras, and all the steps for building the inspection has been presented in detail. The implementation was done by using National Instrument's NI1774C smart camera, and National Instruments Vision Builder AI software, and the web service was build on Inico's remote terminal unit S1000. The hardware and software composition proved to be suitable to perform all the tasks, and to be well suited to the asset-aware factory environment. In this thesis is also presented the state of arts of smart cameras, for off-the-shelf solutions as well as for research projects. The market for smart cameras is increasing rapidly, and the market situation is presented together with the direction for future technological development.

# TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
Konetekniikan koulutusohjelma
**JANHUNEN, JUHANI**: Teolliset älykamerat ja tuotantolinjan laaduntarkastussovelluksen rakentaminen
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Teknologiat jatkuvaan seurantaan, diagnostiikkaan, ennakointiin ja omaisuuden hallintaan ovat kasvaneet merkittävästi viimevuosina. Uudet teknologiat tarjoavat mahdollisuuksia tehtaiden tehokkaampaan käyttäytymisen ennakointiin, tiedon näkyvyyden lisääntymiseen, turvallisuusriskien vähentymiseen, sekä turvallisuuden ja kustannustehokkuuden parantumiseen. eSonia hankkeen tavoitteena on tehostaa omaisuuden hallintaa ja luoda itsestään toipuva tehdas. Tässä diplomityössä on toteutettu tuotantolinjan laadunvalvonta osana eSonia hanketta. Toteutukseen kuuluu konenäkökameran ja muiden komponenttien valinta, laaduntarkastusapplikaation ja käyttöliittymän rakentaminen, sekä järjestelmän kommunikaation rakentaminen. Kommunikaatiossa käytettiin niin vanhoja (kuten Modbus) kuin uusiakin (kuten web service) standardeja. Toteutuksen eri vaiheet ovat kuvattu yksityiskohtaisesti ja ne ovat räätälöity sopimaan erityisesti älykamerajärjestelmille. Toteutus tapahtui käyttäen National Instrumentin NI1774C älykameraa ja Vision Builder AI ohjelmistoa, ja web service toteutettiin käyttäen Inicon S1000 RTU:ta (Remote Terminal Unit). Järjestelmä osoittautui toimivaksi ja sopivan hyvin osaksi palvelusuuntautunutta tulevaisuuden tehdasta. Tässä diplomityössä on esitelty niin teollisten älykameroiden kuin tutkimusälykameroiden state-of-the-art ratkaisut. Älykameroiden markkinat kasvavat voimakkaasti ja diplomityössä on esitelty myös tämänhetkinen markkinatilanne, sekä älykameroiden tulevaisuuden suuntaukset.

# PREFACE

I started writing the thesis on September 2011. I had been always interested in photography and artistic points of views in different areas of life. I felt machine vision as a subject was perfect way to combine my personal artistic interests with my educational background in engineering. The process required acquisition of knowledge in many different fields, and joy of learning new things guided me to get deeper in the almost endlessly wide subject. The project offered me a change to go to conferences, build and purchase technologically advanced equipment, train my engineering skills, learn the science behind imaging and manufacturing technology, and meet lot of inspiring people as colleagues, suppliers and partners. Special thanks for everybody who were interviewed for the thesis.

I would like to express my gratitude to my supervisor Dr. Jani Jokinen for offering this change to take one step closer in fulfilling my dreams. Jani was offering me invaluable insights and the direction where to go throughout the whole project. I'm also in gratitude for Professor Jose Martinez Lastra, the head of FAST laboratory, who provided everything I needed to complete my tasks. The Tampere University of Technology's Production Engineering department offered me the support I needed, and especially Timo Prusi was supporting this thesis by lending cameras, equipment, related literature, and also by giving his valuable insights about the subject. As a working environment the FAST laboratory has been one of the bests I have ever been. The atmosphere was inspiring and supportive, and the equipment was up-to-date. We had lot of memorable moments with the staff in the working place, as well as in free time. I made lot of new and lifelong friends during the process, learned lot from different cultures, and improved my Italian and Spanish skills. Thank you for Luis Gonzalez Moctezuma, Stefano Storti, Prasad Karipireddy, Oscar Neira Millan, Anna Kuutti, Ahmed Sadik, Axel Vidales Ramos, Matti Aarnio, and all the others for the support. I will cherish the moments spent with you rest of my life.

In Tampere February 29, 2012
Juhani Janhunen

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## ABBREVIATIONS

| | |
|---|---|
| **AIA** | Automated Imaging Association |
| **ASIP** | Application-specific information processing |
| **CCD** | Charge-coupled device |
| **CMOS** | Complementary metal oxide semiconductor |
| **CPU** | Central processing unit |
| **CTMV** | Consulting Team Machine Vision |
| **DSP** | Digital signal processor |
| **EMVA** | European Machine Vision Association |
| **FOV** | Field of view |
| **FPGA** | Field-programmable gate array |
| **fps** | Frames per second |
| **GDP** | Gross Domestic Product |
| **NEP** | noise-equivalent power |
| **ROI** | Return of Investment |
| **SCARA** | Selective Compliant Assembly Robot Arm |
| **SDK** | Software Development Kit |
| **ToF** | Time-of-flight |
| **VSN** | Visual Sensor Network |
| **WSDL** | Web Service Definition Language |

# 1. INTRODUCTION

This thesis is about applying machine vision (MV) system to a production line of several Sony SRX-611 robots. The task of the MV system is to do quality inspection to the production line, and alarm if there are any quality errors. The extracted information can be used also to other tasks, such as giving feedback to the drawing robots to increase the quality of the system. This thesis is divided in to seven parts. After the introduction is the Theoretical background for building a machine vision inspection. That chapter works as the theoretical framework for the thesis. After that is offered the actual framework for building a MV system. The implementation of a machine vision inspection consists usually four basic steps: 1. Spesification of the task, 2. Design of the system, 3. Calculation of the costs, and 4. Development and installation of the system. Each individual step is important for the success of the project, and there has been dedicated a subchapter for each of the steps.

After defining the task and mapping out the possible camera system options the choice between a traditional camera system and a smart camera system had to be made. The analysis stated that the most optimal camera system to be installed to the production line would be a smart camera system. Due to that the thesis also focuses on smart cameras, and the Chapter 3 is dedicated to smart cameras.

Chapter 4 focuses on the designing of FAST laboratory quality inspection application. In that chapter are told the specification of the task, design of the system, and calculation of the costs. It follows the framework offered in the theoretical background chapter. Chapter 5 is about implementation of this specific application, and it follows the framework offered in the theoretical background chapter as well. Chapter 6 is dedicated for the conclusions.

## 1.1. Background for the thesis

Production engineering department of Tampere University of Technology (TUT) is participating to a project called eSonia. In eSonia the aim is to create an asset-aware and self-recovery factory trough holistic and continuous measurement and visualization of relevant information. One part of the holistic measurements is implementing quality inspection for the output of the factory. The quality inspection is implemented trough modular MV system. The implementation of the MV system is described in this thesis. The implementation of the system requires background information related to the technologies used. This thesis consists also description of the related technologies, and especially smart camera technologies.

## 1.2. Objectives of the thesis work

This thesis work has two objectives: 1: to present a real-life case of building a MV inspection application which implements web service based control and communication, and 2: to offer an insight to the field of smart cameras. The quality inspection should inspect the quality of the products in the production line, and publish the quality inspection results to be used in the system. The web service based control and communication opens new possibilities in future factories.

## 1.3. Limitations of the thesis work

The area of machine vision is vast and involves technologies from building semiconductors to understanding the complex vision system of a human being. In one thesis it is not possible to deal everything related to MV in detail and that’s why there has been made choices to give small introduction of all relevant subjects and concentrate in higher detail to the areas which involve implementing flexible and modular MV system. In this context flexible means a system which easily adapts to changing applications. The hardware is bought mainly for quality inspection task which is introduced in this thesis but the system needs to be modular, and the software flexible, so the relocation of the system is possible in the future.

## 1.4. Research methods and materials

The information related to the state of the art in smart cameras will be gained through interviews with the experts of the field, reading books, research articles, magazines, and web research. The laboratory itself has already huge knowledge base related to web services in factory environment, and it will be utilized in the web service based control and communication part. Also the implementation and tests of the actual system will offer lot of valuable information.

# 2. THEORETICAL BACKGROUND FOR BUILDING A MACHINE VISION INSPECTION

This chapter provides the theoretical background for building a MV inspection. The term machine vision is used for industrial applications, when a system with a single vision sensor or several vision sensors is doing automatic inspection, process control or robot guidance. The basic structure of a MV system is shown in Figure 2.1. The parts of a MV system are optics, illumination, illumination control, imaging, imaging synchronization, image transfer, image processing, inspection results processing, sending the control signals (I/O), and the results.

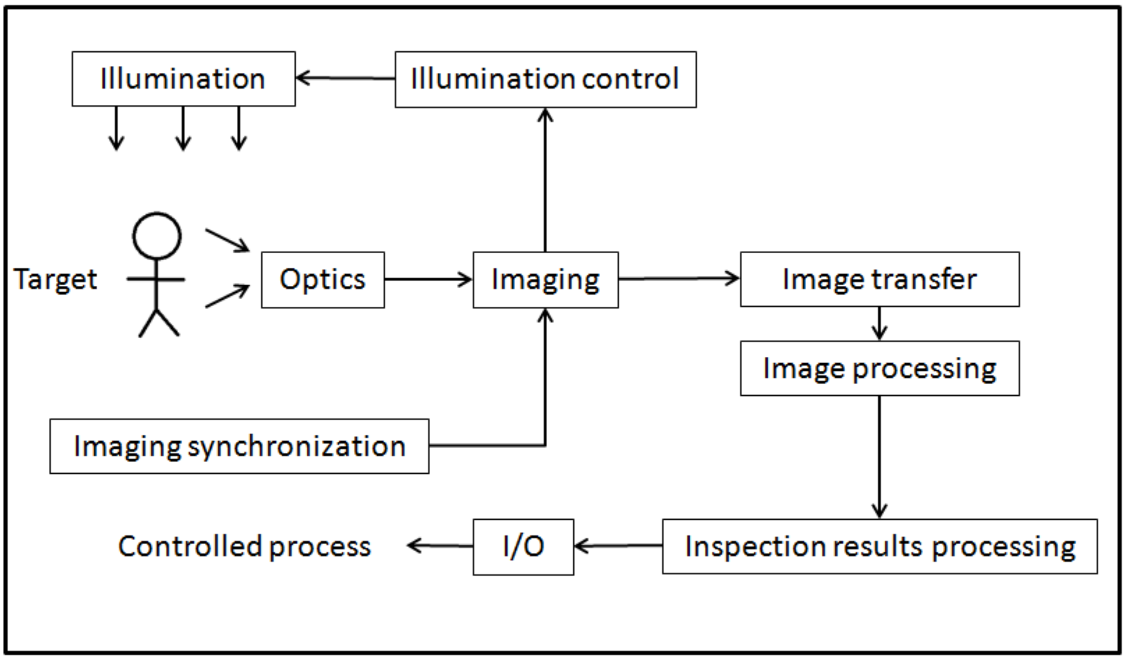


***Figure 2.1.*** *The basic structure of a MV system.*

In a smart camera MV system optics, imaging, illumination control, image transfer, image processing, and inspection results processing are combined inside to a single housing, and smart camera is sending control signals (e.g. I/O) to control the process. A simplified example of a smart camera MV inspection is shown in Figure 2.2, and the whole structure of the example smart camera MV system is shown in Figure 2.3.

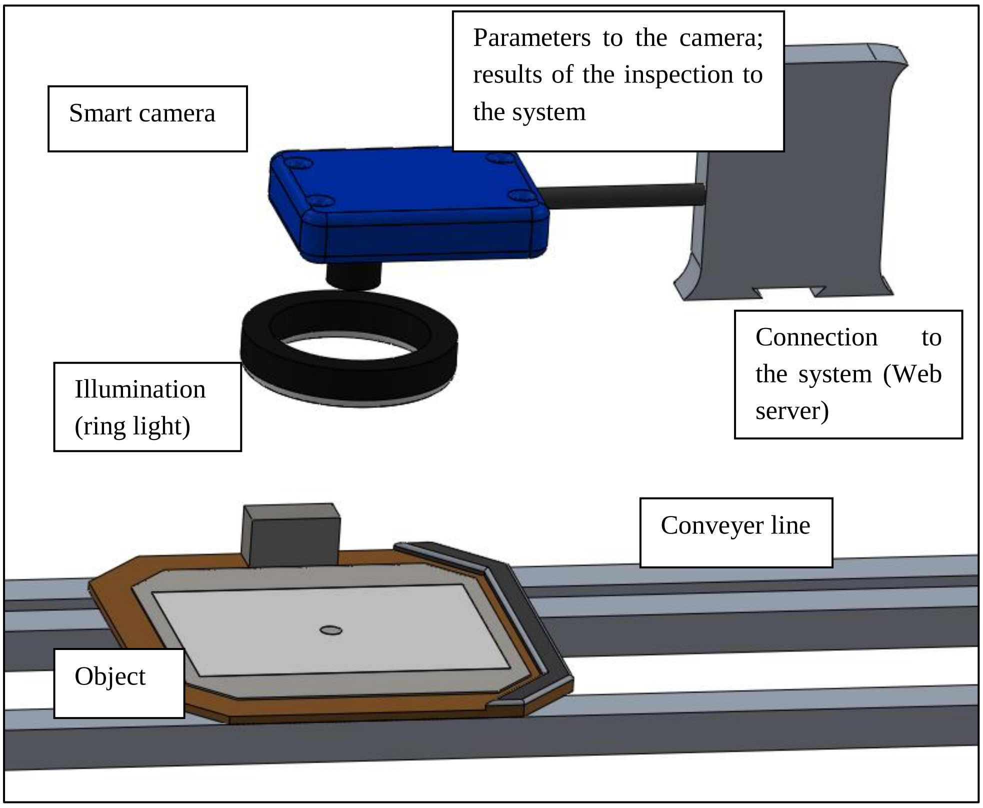


***Figure 2.2.*** *An example of a smart camera MV inspection.*

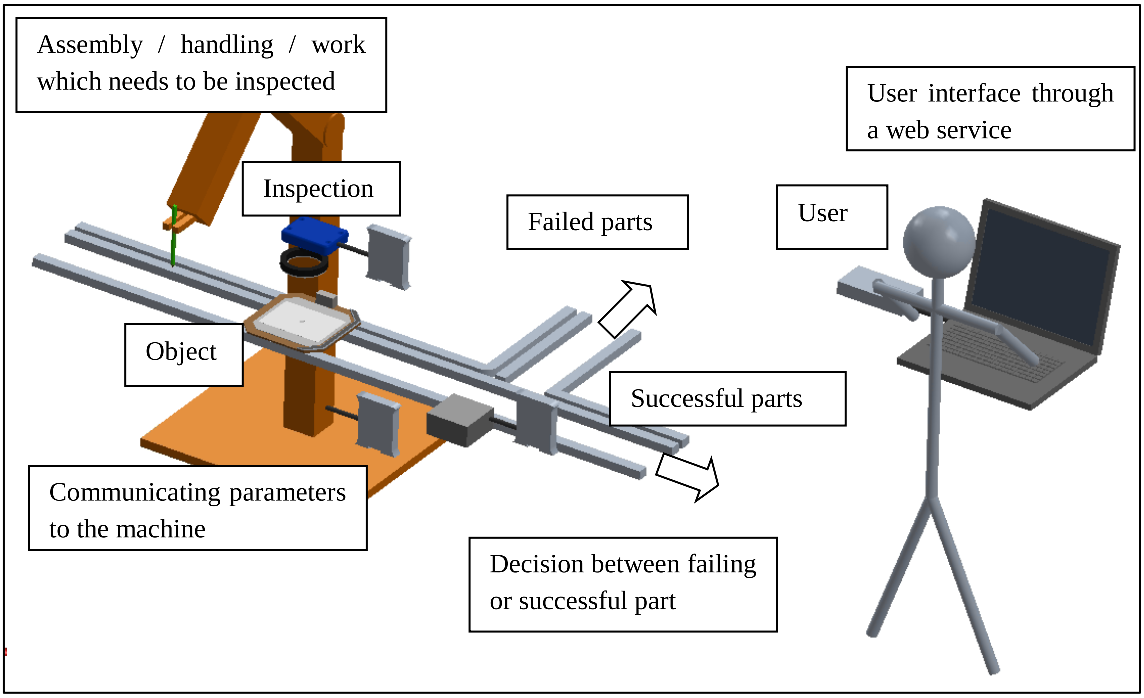


***Figure 2.3.*** *An example of a smart camera MV system.*

In the example smart camera MV system a conveyor line is transporting the part to the front of the camera. When the part arrives to the front of the camera, imaging trigger is triggered, and the camera takes a picture of the part. The processing unit is integrated inside to the camera so the camera is able to decide does the part fulfil the criteria without external processing unit. Light unit is illuminating the part to make the inspection easier. Usually smart cameras have integrated lighting control, so the illumination can be triggered only for the imaging time to save some energy and prevent component wearing. In the flash mode also a higher light intensity can be achieved. After processing the picture the camera sends information to web server. Camera is sending pass/fail signal. The conveyor line is receiving the pass/fail signal, and directs the parts accordingly. If the part didn’t pass the inspection, it’s possible that the camera will send control signal to the robot, which will change the action to the direction that the next part will more probably pass the inspection, for example by slowing down the processing speed.

There is no scientific approach in how to solve a concrete vision task in practise. Implementing a machine vision system requires balancing the project time and the budget with the needs of the system. In this chapter is described a roadmap to a successful industrial application. In [1] has been presented roadmap for solving concrete vision tasks. This thesis is focusing on smart cameras, and for smart cameras the approach is a little bit different than the approach for traditional MV system. For example the software is integrated to the smart camera, and that is the reason why before selecting the camera, different software options needs to be compared. Smart cameras are discussed in more detail in [2] as well as in Chapter 3 of this thesis.

Naturally each industrial application is different and that’s why the roadmap is just a suggestion how to proceed. It works as a background for the implementation part of this thesis and in the results part it is also evaluated how well this specific roadmap suited for an execution of an industrial application in university research environment. In Figure 2.4 is described the steps of the roadmap.

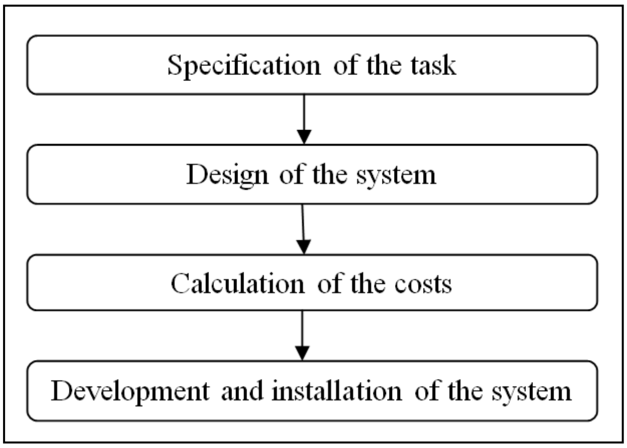


***Figure 2.4.*** *Roadmap to a successful industrial application.*

The subchapter 2.1 is dedicated to the specification of the task, 2.2 is dedicated to the design of the system, the subchapter 2.3 is dedicated to the calculation of the costs, and the subchapter 2.4 is dedicated to the development and installation of the system.

## 2.1. Specification of the task

One of the most essential parts in building an industrial application is understanding what kind of a problem the application is solving. If the specification of the task is done incorrectly, all the effort and resources used in solving the task might be wasted. In the specification part also the requirements of speed and accuracy needs to be defined, as well as the description of the environment. The environment can be laboratory conditions with low amount of impurities, vibrations, temperature variations, and with optimal unvarying illumination around the clock. On the other hand the environment can be challenging environment, and the whole machine vision system needs to be made adaptable for the disturbances coming from the environment. Naturally the more demanding the environment is, the more expensive the system is going to be. One of the specifications can be also making the system adaptable for changes. [3]

### 2.1.1. Task and benefits

The task and the benefits are important part of the specification. In this part any operation performed and any result generated by the system needs to be defined. It is important to know what accuracy is expected from the system, describe what the inspection is about, and which measurement needs to be performed. After gathering the information related to the task, the benefits can be evaluated. In general machine vision applications the benefits are higher precision of the operations and measurements, higher speed of the inspection, 100 % inline inspection of every passing part, making the inspection for objects impossible to be measured by humans, and safety aspects. In the business side, the sum of all the benefits of the machine vision application is justifying the expenses used in it. If to the benefits can be assigned monetary values, a return of the investment (ROI) can be calculated, and a breakdown point can be estimated.

### 2.1.2. Parts

In the part description several aspects needs to be known, for example is the part discrete or endless material (for example sugar), what are the maximum and minimum dimensions, are there any changes in shape, description of the features needed to be extracted, changes of these features when considering error part and common product variation, surface finishing, colour, corrosion, and changes due to part handling (for example finger prints or labels). If there is large variation in part types the software needs to be able to handle all the variations. In some cases it might be wise to allow the user to teach new type of parts to the system trough the user interface, instead of the need of heavy modifications done by machine vision specialist.

### 2.1.3. Part presentation

The crucial factors for part presentation are part motion (is the part moving or not and with what rate), positioning tolerances, and the number of parts in the view. If the part is stopped to the *field of view* (FOV), i.e. the part has *indexed positioning*, the time the part is stopped to the FOV needs to be defined. When the part is moving, the speed and acceleration needs to be known. With multiple parts the number of parts in view, overlapping parts, and touching parts needs to be known. With overlapping parts some features are not necessary visible, and some algorithms, for example for detecting the shape of the parts, are very hard to implement.

### 2.1.4. Performance requirements

In the performance requirements there are accuracy requirement and time performance requirement. The accuracy in MV application means the smallest detectable object and it will define the needed resolution of the system. In time performance requirements the cycle time, start of acquisition, maximum processing time, and number of production cycles from inspection to result using needs to be known. The time requirement affects especially to the system's processing power requirement.

If the VM application is high speed application, the frame rate needs to be considered. The frame rate requires overhead of 10-20 %, so for example if the application has objects going in front of the camera with speed of 20 pieces/sec, then the camera frame rate needs to be at least 22-24 fps (frames per second).

### 2.1.5. Communication interfaces and protocols

The information received by the MV system needs to be sent forward to be used in the process. Also the machine vision system needs to be configured, and there are various ways to exchange information between the MV system and the rest of the system. The data transmission can be done through several interfaces and protocols. In Table 2.1 are listed the most common wired communication protocols, and in Table 2.2 is listed the most common wireless communication protocols used in MV systems.

***Table 2.1.*** *The most common wired communication protocols. [2, p. 43.]*

| Protocol | Theoretical bandwith in bits per second (Mbit/s) |
|---|---|
| RS-232 serial link | 19.2 |
| USB 1.x Full-speed | 12 |
| USB 2.0 Hi-speed | 480 |
| USB 3.0 Hi-speed | 5 000 |
| FireWire or IEEE 1394a/b | 400/800 |
| Camera Link | 2 040, 4 080 or 5 440 |
| Ethernet | 10/100/1000 |
| GigE Vision (Gigabit Ethernet | 1 000 |

***Table 2.2.*** *The most common wireless communication protocols. [2, p.43]*

| Protocol | Theoretical bandwitdth (Mbit/s) | Wireless range (m) |
|---|---|---|
| WiFi IEEE 802.11a | 54 | up to 10 m |
| WiFi IEEE 802.11b | 11 | ~50 m indoor, ~200 m outdoor |
| WiFi IEEE 802.11g | 54 | ~27 m indoor, ~75 m outdoor |
| WiFi IEEE 802.11n | 150 | ~70 m indoor, ~250 m outdoor |
| Bluetooth | 1 | ~10-100 m |
| ZigBee (IEEE 802.15.4) | 0.25 | ~10-30 m indoor, up to 150 m outdoor |

The communication channels can be classified according to what bandwidth they have, are they using wired or wireless communication, how robust they are, and how compatible they are. [2, p. 42] For MV systems the most common communication channel is Ethernet port, through which can be used several different protocols like Modbus TCP or other TCP/IP protocols.

### 2.1.6. Installation space

Sometimes the installation space sets requirements which are effecting heavily to the system. If the installation space is very small, a very compact system might be required. The installation space also sets limits for the possible illumination options, and for minimum and maximum distances between the part and the camera. Also the distance between the camera and the processing unit needs to be considered, and it will effect to the data transmission protocols possible to use.

### 2.1.7. Environment

The environment might have varying lightning conditions, dirt or dust, shock or vibrations, and heat or cold the equipment needs to be protected from. In some cases protective glass is needed to be installed, and in some cases the availability of a power supply is a problem. In most of the industrial camera's specification sheets there are mentioned the shock and vibration resistance. Some cameras have also special housing, for example IP67 housing. IP67 means that the camera can withstand water and dust. In theory IP67 housing equipment can be sank to one meter deep water for 30 minutes. [4]

### 2.1.8. Checklist

CTMV has developed a checklist to be used in defining the requirements of a MV system. In the checklist there are the mentioned points compressed to a few pieces of paper, and it can be used to confirm that all the points have been considered in the system specification. The checklist can be found in the appendix of this thesis.

## 2.2. Design of the system

After defining the task and benefits, the designing of the system can be started. The chosen components should support each other so that there wouldn't be any bottle necks. For example if the camera has high resolution image sensor, the communication interface needs to be efficient enough to be able to transmit the formed data. In some special cases the bottle necks can be allowed, for example when the aim is low power consumption. [2, p. 43.]

### 2.2.1. Choosing between area camera and line scan camera

The basic camera types are line scan camera, and camera that images a quadrilateral area. The decision will effect to the hardware and software used in the system. Area cameras are more common and they will offer several benefits. They can record the wanted object fast and there is no need of synchronizing the camera with the speed of the conveyor line or with the motor that moves the object. The area cameras have more available software libraries, and they are cheaper. In some cases the line scan cameras offer higher resolution, and can sometimes record the view as a continuous image stream which can offer significant benefits for some specific systems for example in a case when the object is a continuous stream of substance. One classic application for line scan cameras is inspection of a rotating cylinder. Line scan cameras can reach remarkably higher frame rates than area scan cameras, and for example MIT (Massachusetts Institute of Technology) have built a line scan camera which can reach trillion frames per second. [5]

### 2.2.2. Choosing between a smart camera, compact machine vision system, and pc-based machine vision system

Machine vision systems can be divided in three segments: PC-based MV systems, compact MV systems, and smart cameras. All of them have advantages and disadvantages. The main advantages for smart cameras are simplicity in use, simplicity in the system design and development, very low output bandwidth requirement, better possibilities for longer cables or wireless communication (due to low amount of data to be transferred), low power consumption, easiness in maintaining data security, robustness, compactness in physical size (which might be very important for some industrial applications), possibility to process the raw video data (no need for complicated data compressions or transmissions) which increases the quality of the system, and in some cases lower costs due to smaller part count.

Because of processing power and memory restrictions, some of the smart cameras need to be optimized for some specific applications, which leads to application specific systems. In that kind of systems the flexibility is limited to certain kind of tasks. Usually the performance is also limited to the embedded processor(s), and memory capsules, and there is no possibility to replace the outdated processing or memory units. The software is preinstalled and might offer some restrictions in the available tools in the machine vision library.

The PC-based systems have usually higher flexibility and higher configurability than smart cameras. Usually the PC-based systems can be implemented in more various tasks, thanks to general purpose parts that can be purchased, replaced or serviced relatively easily. The PC-based systems have usually higher processing capabilities, and bigger amounts of memory, and are more suitable in more complex tasks. The downsides for these systems are bigger physical size, relatively complex system composition, and sometimes higher price due the higher part count. If there are available PCs to be used with a MV camera it means that no additional PC needs to be purchased, and it might affect to the cost of the system by bringing it down.

Compact MV systems are combination of these two systems. Compact MV system is basically a PC-based camera system but the processing unit is smaller, and can have dedicated processors for some certain kind of tasks. Sometimes the MV system might need to be able to process data intensive tasks and FPGA (Field-programmable gate array) processors are much more suitable in that kind of tasks than regular CPU (Central processing unit). Also the compact processing unit might have special connectors which are not available in regular PCs.

The upsides and downsides of all of these systems needs to be weighted and the decision should be based on that. In the future the processing power of smart cameras is increasing and the price is decreasing making the smart cameras more and more attractive option. [2]

### 2.2.3. Processing unit of the machine vision system

When talking about the processing unit of a machine vision system, it usually means the processor which extracts the relevant information from the image and creates the control or other signals to be sent forward. Sometimes the processor also does pre-processing for the image correcting barrel distortion, correcting colours, converting the pixels to real world units and other kind of pre-processing tasks. The pre-processing operations are usually data intensive tasks, and regular CPU might not be the most suitable to do such tasks. In Figure 2.5 are listed different processors (FPGA, DSP, CPU) and tasks the processors are most suitable to. FPGA is suitable for data intensive tasks for example pre-processing of the images. CPU is capable of performing huge amount of calculations in short period of time, and that’s why it’s the most suitable processor to perform complex algorithms. In general DSP’s (Digital signal processor) performance is in the midway of FPGA’s and CPU’s performance.

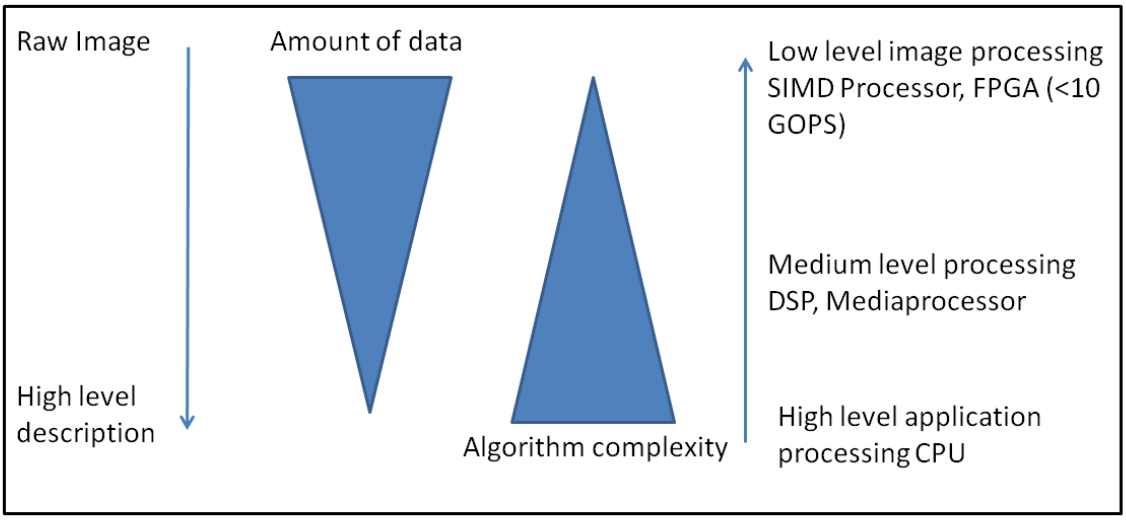


***Figure 2.5.** Processing task allocation according to different processors. [2, p. 36.]*

The processor of the MV system can be decided after the algorithms to be used are known. Usually regular CPU can do all the required tasks but in case of high speed high performance MV system there might be a need for special processors.

### 2.2.4. Field of view

The field of view (FOV) means the area of the object which will be imaged for the inspection or measurement. In Figure 2.6 is an example of FOV:

1. The object
2. Translated or rotated part (from moving)
3. The area which is needed to capture the translation/rotation of the part.
4. Margins / tolerance
5. Adaptation to the aspect ratio.

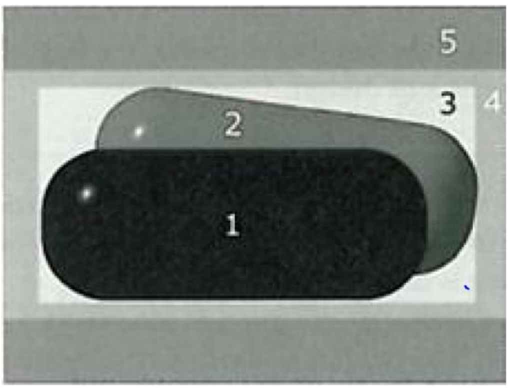


***Figure 2.6.** Example of the FOV. [1, p.43]*

The black part (area 1) is the actual part, and the grey one (area 2) indicates the maximum variations in the positioning of that part. The white area (area 3) is the area which is required to detect all the possible position variations. In the system there might be unexpected movements of the camera or the part, and it is good to insert some margins. Also the distortion of the lens is bigger in the edges of the image. The area under number 4 is the area to detect all the possible position variations with margins, and the area under number 5 is the area number 4 with adaptation to the cameras aspect ratio. The FOV can be calculated with the following equation:

$$\text{FOV} = \text{maximum part size} + \text{tolerance in positioning} + \text{margin} \\ + \text{adaptation to the aspect ratio of the camera sensor} \quad (1)$$

### 2.2.5. Resolution

In MV systems the required camera's sensor resolution can be calculated when the FOV, smallest feature that needs to be detected and used algorithms are known. The camera sensor resolution means the number of columns and rows that the camera provides (by the internal sensor). When measuring a resolution, one unit is called *a pixel*. Line scan cameras have the sensor resolution only in one dimension. When buying a camera, the camera's resolution is one of the most important factors when defining the performance of the camera but it is not the whole truth. Naturally many other components affect to the image quality as well, for example the size of the imaging cell, or the quality of the components used.

*Spatial resolution* tells the accuracy of the camera related to real world objects. It can be measured in mm/pixel. It means that in the picture the camera imaged, when moving one pixel to a certain direction, in real world it is moved so many mm. In some cameras the pixels are not squares, and in that case the spatial resolution needs to be calculated for horizontal and vertical directions.

*Measurement accuracy* tells the overall performance of the system, the smallest feature that can be detected. The contrast of the picture, and the software algorithm used are playing major role when defining the measurement accuracy. If the contrast of the picture is small, a single pixel feature might be impossible to detect; for detecting the feature it might require four or five pixels. In Table 2.3 are few the most common algorithms and accuracies they require (in pixels), and in Table 2.4 are the variables required in the resolution calculations.

***Table 2.3.*** *The most common algorithms and the required accuracy.*

| Algorithm | Accuracy in pixels |
|---|---|
| Edge detection | 1/3 |
| Blop | 3 |
| Pattern matching | 1 |

***Table 2.4.*** *Variables required in resolution calculations, and their units.*

| Name | Variable | Unit |
|---|---|---|
| Camera resolution | *Rc* | pixel |
| Camera resolution with safety tolerance | *Rc_s* | pixel |
| Spatial resolution | *Rs* | mm/pixel |
| Field of view | *FOV* | mm |
| Size of the smallest feature | *Sf* | mm |
| Number of pixels to map the smallest feature | *Nf* | pixel |

When the smallest feature needed to be detected and the used algorithms are known, the spatial resolution can be calculated in the following way:

$$Rs = \frac{Sf}{Nf} \tag{2}$$

The next equation shows how to calculate the required camera resolution:

$$Rs = \frac{FOV}{Rc} \tag{3}$$

The required spatial resolution is calculated in the following way:

$$Rc = \frac{FOV}{Rs} \tag{4}$$

If the FOV has been defined, the camera resolution can be evaluated to be:

$$Rc = \frac{FOV}{Rs} = FOV \times \frac{Nf}{Sf} \tag{5}$$

In addition a safety tolerance is needed. Some sources recommend the safety tolerance to be 100% [6] , so if the smallest requirement for camera resolution is for example 500 pixels, a sensor with 1000 pixels is used. The required camera resolution can be calculated with following equation:

$$Rc_s = 2 * Rc \tag{6}$$

The camera resolution calculation needs to be done for horizontal and for vertical directions. Also the aspect ratio of the camera has to be considered. If the smallest detectable feature is for example 0.5 mm (*Sf*) and the used algorithm is pattern matching, the spatial resolution (Rs) needs to be 0.5mm / 1 pixels = 0.5 mm/pixel. If the FOV is for example 140 mm x 80 mm, it means that the camera sensor resolution with safety tolerance (*Rc_s*) in x-axis needs to be 140 mm / 0.5 mm/pixel * 2 = 560 pixels. In y-axis the camera sensor resolution needs to be 80 mm / 0.5 mm/pixel = 320 pixels. When choosing the camera resolution it needs to be higher than 560 x 230 pixels. The next general sensor resolution is 640 x 480 pixels which seems to be suitable for this example application (pattern matching).

### 2.2.6. Camera sensor

With different camera sensors it's possible to detect objects or features human eye cannot detect. Thermal sensors are used in some special applications. Also by installing a filter it's possible to filter visible light away from the picture and adjust camera to detect only near infrared light. In Figure 2.7 is shown spectral response of silicon CCD sensor. In the same figure is also light frequency spectrum visible to human eyes. Silicon is the most common imaging sensor material and because it detects higher range than human eyes, regular silicon imaging cells can be used in detecting for example projected infrared patterns which human eye cannot detect.

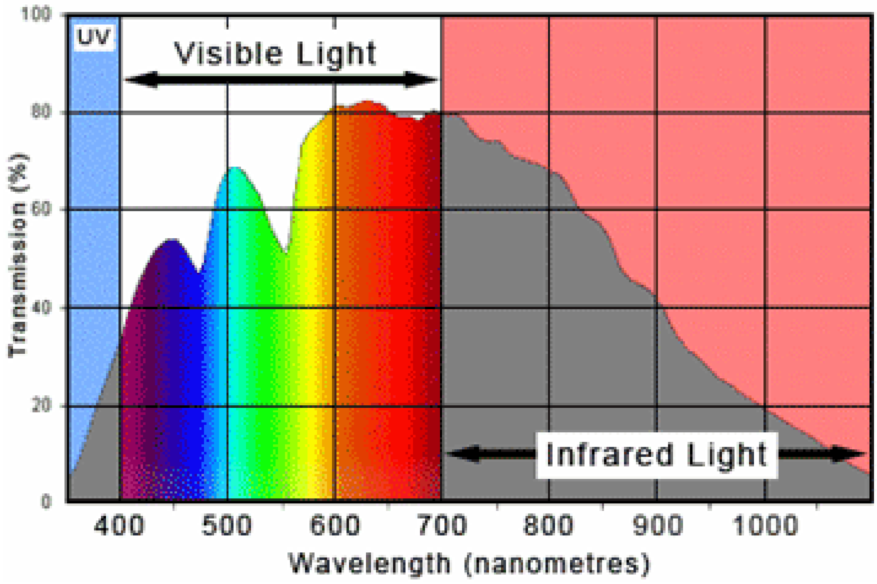


***Figure 2.7.*** *Spectral response of silicon CCD sensor. [7]*

In general imaging sensor is receiving photons (light particles) coming from the object. The photons are directed by the optical system to the image sensor. The most common image sensor sizes are 1/3", 1/2", 2/3", and 1". The number is not the exact size of the sensor but rather indicates that the sensor lies in the circle of the given diameter. With big sensor it is possible to have high contrast high quality images. In MV systems big sensors (over 1") are needed only in very high precision applications, for example when inspecting micro sized particles. In that kind of system also all other components must meet the quality demands (for example lenses). Bigger sensor requires bigger lens, and the systems with big sensors are significantly more expensive than systems with smaller sensors. The lens and the sensor size must be compatible. In the lens there is a marking what sensor size it is designed to. If the lens is specified for a sensor size of 1” and it is used with a 2/3” sensor, the sensor is illuminated poorly, and it reduces the image quality. On the other hand it is possible to use lens of 2/3” with 1” sensor.

The inspected parts will define does the sensor needs to separate colours, or can the senor be a monochrome sensor. Colour sensor is traditionally using colour filter (for example Bayer filter) which uses several pixels to detect colour. It means that monochrome cameras (gray scale cameras) are detecting individual pixels with higher accuracy. Also each pixel is recorded with certain amount of bits which means that if each pixel has lot of information the whole picture size can be very big. Monochrome pixel can be recorded for example with 8-bits which means that it can have values between 0-255. Colour pixel can be recorded for example with 32-bits (RGB colour: 8-bits for alpha value, 8-bits for red values, 8-bits for green values, 8-bits for blue values), so in this case colour pixel requires 4-times more space, which leads higher processing requirements and higher data transmission requirements. If the application doesn’t require colours it is better to choose monochrome camera to have higher quality with cheaper components.

With smart cameras it makes a difference does the imaging cell use CCD (Charge-coupled device) or CMOS (Complementary metal–oxide–semiconductor) technology. CCD (Charge-Coupled Device) imaging technology is older than CMOS imaging technology, and CCD based systems are generally bigger in physical size than CMOS based systems. To a CMOS chip it is possible to integrate the A/D conversion, signal processing, timing logic, exposure control, and most other required circuitry, resulting complete single chip cameras. CCD based cameras require usually three or more separate chips. In Table 2.5 is a comparison between CCD and CMOS sensors.

***Table 2.5.*** *Comparison between CCD and CMOS sensors.*

| **CCD** | **CMOS** |
|---|---|
| Excellent image quality | Medium to high image quality |
| High SNR (low noise < 40 electrons) | Lower SNR (>20 noise electrons) |
| Low FPN (dark non-uniformity <1%) | Higher FPN (requires on-chip correction) |
| Low dark current (<10pA/cm^2) | Higher dark current (nA/cm^2) |
| Rare technology | Mainstream technology |
| No on-chip ADC, signal processing, control | On-chip device integration -smart sensors |
| Serial scanning readout | Random access readout |
| Compolicated driving and interfacing | Simple data interface |
| Multiple high-voltage supplies | Simple supply operation |
| Higher system cost | Lower system cost |
| **Common characteristics** | |
| Spectral response (400-1000nm) | |
| Minimal pixel size (2-5 mikro mm) | |
| Charge storage per unit area | |
| Chip size and number of pixels | |

CCD cells are generally a bit bigger and a bit more expensive (not because of better components but because of smaller amount of manufacturers) and the image quality might be a bit better. Generally CMOS sensors are smaller and cheaper, and the image quality might be poorer. The image quality difference is so small that it doesn't make difference is the image cell CCD or CMOS.

High speed high precision colour imaging can be achieved by using 3-CCD cameras. In 3-CCD camera the three basic colours – red, green, and blue – are separated by a prism and simultaneously directed onto three CCD chips. This technique increases the resolution and the speed of the imaging. [2] [8]

### 2.2.7. Comparing different software platforms

Before choosing the actual camera it is good to compare different available software platforms, on which the application will be built. For regular MV systems the software platform can be chosen after choosing the camera. With smart cameras the software is already embedded to the hardware, and usually it's not possible to run other manufacturer's software in one's smart camera. It means that the software plays major role when selecting the hardware. If some manufacturer has well performing smart camera with poor software, the decision can favour other manufacturers with better software. It also means that for smart cameras the selection of the software platform is selected together with the camera.

When comparing the different software, it is good to have a list of the crucial algorithms needed in the application. Than it is easy to check does the software have the needed functions. Naturally the software needs to be compatible with the hardware. If the application is very complex might be that the software should provide a possibility for modifications and some degree of programmability. An application interface (API) offers the highest degree of programmability.

The organization which is implementing the MV system might have already some software licences or contacts to the producers, and already existing options might guide the direction of the project. The allocation of the resources has also effect to the project direction. If there are programming resources and lot of available time, good option might be to use free open source software libraries. If the implementation needs to be fast, might be better option to allocate the monetary resources to ready-made comprehensive software packages offered by the MV system manufacturers, rather than the salaries of the programmers. In that case the implementation is fast and the reallocation of the MV task might be easier; the learning curve of the software libraries offered by the MV system manufacturers is usually steep and there is no need of programming skills or deep knowledge of the subject. The manufacturers also offer good support materials and personal help, and it can contribute greatly to the success of the system. In Chapter 4 is evaluated few of the most popular MV software from the view point of the FAST laboratory's application.

### 2.2.8. Choosing the camera

At this point it is known is the camera going to be area camera or line scan camera, PC-based MV system, compact MV system, or a smart camera, the FOV, the sensor resolution, what kind of a imaging sensor the camera will have, and software preferences. In the specification part has been also decided the performance requirements, the information interfaces, the physical size, and does the camera need any protective housing. At this point the camera can be chosen.

In the markets there are hundreds of different MV cameras. It can be hard to decide which one to choose. There are few indicators according to which the buyer can rate the different camera manufacturers. The camera manufacturer should provide continuity for several years after purchasing the camera; there might be a need for spare parts, modifications, and support. If the camera manufacturer is fulfilling several different standards it's an indication of continuity. The shipment times and responsiveness can be also important. The more activity the camera manufacturer has in the geographical area where the application is going to be implemented, the easier is for the camera manufacturer to respond to the requests. In the Chapter 4 there has been evaluated few smart camera providers from the view point of the FAST laboratory's application.

### 2.2.9. Optics and lens design

Optics is the part of the camera that is directing the light coming from the object to the imaging sensor. The selection of the optics for MV system can be started by defining the focal length of the lens. The focal length of the lens can be chosen after the FOV, the camera sensor size and the *standoff distance* are known. Standoff distance means the distance between the camera and the object and the variable for standoff distance is *a*. In Table 2.6 is the variables needed for selecting the focal length.

***Table 2.6.*** *Variables that are needed when calculating the focal length of the lens.*

| Name | Variable | Unit |
|---|---|---|
| Focal lenth | *f'* | mm |
| Standoff distance | *a* | mm |
| Field of view, x-axis | *FOVx* | mm |
| Field of view, y-axis | *FOVy* | mm |
| sensor size, x-axis | sensor x | mm |
| sensor size, y-axis | sensor y | mm |

Focal length indicates how well the lens is magnifying the object. Lens with bigger focal length has usually smaller barrel distortion and higher depth of field, and that's why in MV systems it is often easier to use lenses with a bit bigger focal length. It means that the camera will be mounted a bit further away from the object. A general rule is that the greater the distance the better the quality. With greater distance the vibration of the camera has bigger effect to the picture, so the vibration should be minimized.

The most common detector sizes and their measures can be found from Table 2.7. The size of the detectors varies from manufacturer to manufacturer and in the calculations the detector size should be confirmed from the data sheet of the camera.

***Table 2.7.*** *Few of the most common sensor sizes and their measures.[6]*

| **Sensor size** | **2/3"** | **1/2"** | **1/3"** |
|---|---|---|---|
| **sensor x** | 8.8 mm | 6.4 mm | 4.8 mm |
| **sensosr y** | 6.6 mm | 4.8 mm | 3.6 mm |

The approximation for the focal length can be calculated by using the following equations:

$$f' = sensor\ x \cdot \frac{a}{FOV_x} \tag{7}$$

$$f' = sensor\ y \cdot \frac{a}{FOV_y} \tag{8}$$

After approximating the focal length, the actual focal length can be chosen. The most common focal lengths for standard lenses are 8 mm, 16 mm, 25 mm, 35 mm, and 50mm but there is huge variation of different lenses with different focal lengths and other properties. After choosing the actual focal length for the lens, the standoff distance has to be modified according to the selected one. The new standoff distance can be calculated with the following equation:

$$a = f' \frac{FOV_x}{detector\ x} \tag{9}$$

If for example the camera's sensor size is 1/3", the $FOV_x$ is 140 mm, and the standoff distance is 700 mm, according to the (*7)* the approximation for the focal length will be:

$$f' = 4.8\,mm \cdot \frac{700\,mm}{140\,mm} = 24.0\,mm$$

After calculating the approximation of the focal length the actual focal length can be chosen. The closest standard lens for the approximation is 25 mm. The new standoff distance for the selected focal length is:

$$a = 25mm \cdot \frac{140mm}{4.8\,mm} = 729.2\,mm$$

Magnification can be increased naturally by bringing the camera closer to the object, choosing a lens with bigger focal length, or adding extension tubes to the optics. When increasing the magnification, the depth of the field decreases. With macro lens (focal length from around 45 mm to 200 mm or more) can be achieved high magnification images. The differences between lenses can be huge and good quality lenses can be very expensive, especially if the lenses are high precision special lenses.

The lens mount is also important. It means how the lens is attached to the camera. Generally there are three different lens mounts: C-Mount, CS-Mount and Nikon F-Mount. All the mounts have different *lens flange focal distance* which is the shortest distance between the lenses mount face, and the image sensor. For C-Mount the flange distance is 17.526 mm, for CS-Mount it is 12.526 mm, and for Nikon F-mount it is 46.5 mm. The Nikon F-Mount is commonly used for line scan cameras.

In the optics there are also several other parameters. One of the most important ones is the *aperture.* Aperture is the hole through which the light travels to the image sensor. Aperture is generally indicated by focal length divided by the *f-number*, and it is usually written "f/x", for example *f/1.4*, *f/2*, or *f/8*. The "f" is the focal length, and the "x" is the f-number. F-number indicates the luminance (luminous flux) which means how well the resulting image is illuminated. The smaller the f-number is, the better the resulting image is illuminated. In the lens there might read 1/1.4 which means the same as f/1.4. F-number should not be confused with focal length. When the f-number increases the aperture size decreases. In Figure 2.8 is clarified the f-number's effect to the aperture.

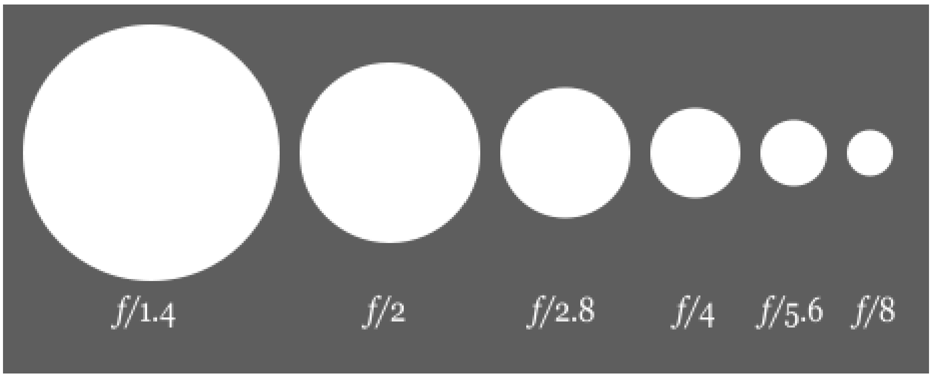


***Figure 2.8.*** *While f-number is increasing the aperture is decreasing.*

In some lenses the aperture size is adjustable. The size of the aperture is communicated in relation to the f-number of the objective (focal length). If the aperture is small, then only small amount of light travels through the hole to the light sensitivity cell. In very bright light this might be optimal setting. With a small aperture the depth of the field is increased which means that sharp area in depth direction is bigger. This is due to the collimation of the light rays: with small aperture the light rays which are allowed to travel to the imaging cell has to come from the same direction. If the aperture is big, the angle from which direction the light rays are travelling also increases. When the angle from where the light rays hit the imaging sensor is big, the sharp field is only seen in close depth area of the focal point.

Good picture requires enough light. The amount of light can be increased by increasing the size of aperture, or increasing the *exposure time*. Exposure time refers to the time during the picture is taken, and in high speed applications the exposure time needs to be very short. If object moves in the FOV while taking the picture, the resulting picture will be blurred. Exposure time is controlled by a shutter. When speaking about exposure time and shutter speed the terms work as synonyms. In many MV systems the maximum aperture size is f/1.4 which is relatively big, and usually the aperture is adjustable until f/16.

One option is to use telecentric lenses. Telecentric lens is a special lens which has entrance or exit pupil at infinity. It will provide orthographic projection having the same magnification with all distances. The lens should be the same size as the largest object to be imaged. Telecentric lenses are usually used in situations where the exact measurements of the objects are needed, and objects are moving within the FOV or even when the standoff distance is varying.

Successful picture is achieved by adjusting ISO sensitivity (pixel gain), aperture size, and exposure time. With higher ISO sensitivity less light is needed. If ISO sensitivity is too high it causes noise to the picture but in that case the exposure time can be very short. In Table 2.8 are the most important parameters when capturing an image.

***Table 2.8.*** *The most important parameters when capturing an image.*

| Name | Variable |
|---|---|
| Aperture (= focal length / f-number) | *f/x* |
| ISO sensitivity | *ISO xxx* |
| Exposure time | *t* |

In conclusion, the selection of the lens can be started by defining the focal length, and after that the aperture. These two parameters will define the depth of the field, and is the lens suitable for high speed application. With high depth of field, the aperture should be narrower, so the light received by the imaging sensor will be more collimated. If the application is high speed application, the aperture should be big, so lot of light can be travelled through the pupil, and the exposure time can be short. Telecentric lens can be used in situations when the exact measurements of the object are needed and the object is moving inside the FOV, and possibly the standoff distance is varying.

### 2.2.10. Choice of illumination

In any camera system the illumination plays an essential role. Human eyes are able to adapt to the changing environment by using different imaging units in different conditions (cone cells in light conditions, rod cells the dark conditions), and by the huge processing power of the system (pre-processing in the eyes, live and post processing in the brains). Machines are capable of imaging in dark or well illuminated conditions and able to process huge amount of data but still the adaptation to the changing conditions remains as a huge challenge. Rule of the thumb is that the more varying the conditions are, the more expensive the system is. If the machine is detecting a colour with a certain RGB value (Red-Green-Blue, a way the colours are expressed in digital form), a small change in the illumination will change the RGB values of the object, and the machine is not able to detect the object anymore. The different situations need to be predetermined and programmed to the machine, and only then the adaptation is possible. Programming all the possible situations might take huge amount of human working hours, computer memory and computing power of the system. The easiest way is to try to keep the environment as unvarying as possible.

The goal of the illumination is to create an optimal setup to detect the objects to be imaged as clearly as possible. The general rule is to maximize the contrast. Contrast can be maximized with three different ways: with the direction of the light, with the used light spectrum, and with polarization. The direction of the light is divided in back lights and front lights. Figure 2.9 is showing the hierarchy of the different light setups which are used in order to maximize the contrast. If with the illumination setup it's possible to maximize the contrast and separate the important information from the objects already before the image processing, the task performed by the imaging system and the processing unit can be significantly easier.

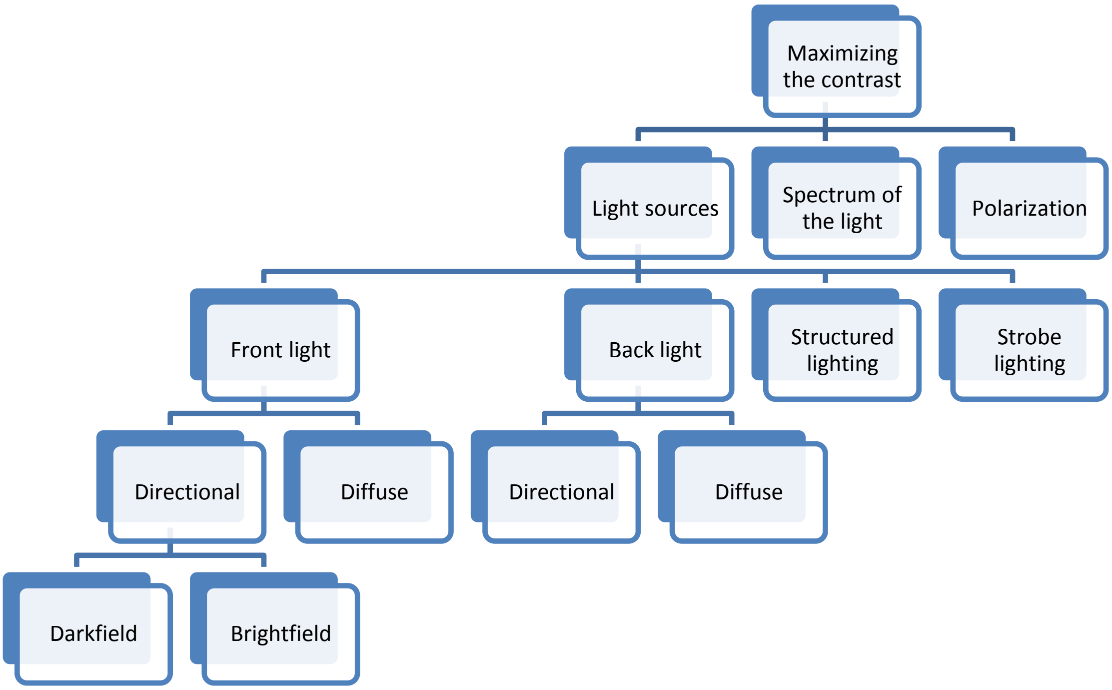


***Figure 2.9.*** *Different illumination setups. [1, p. 51-53.] [9]*

If the edges of the object needs to be detected, the backlight will offer huge contrast between the background (which will be seen as white), and with the object itself (which will be seen as black). Backlight is usually achieved by using back-illuminated panel with light sources of fluorescent tubes or LED lights. With this kind of setup it's easy to measure the tolerances of the object, or detect missing parts.

In front light the most common setups are diffused light, directed light, confocal front light, bright field, and dark field. Diffused field means that the light is provided from variety of angles, and the usual light source is a dome light. In domes the usual light source is LED lights. Directed light means light which is provided from range of angles. It can be done with a ring light or line light. Confocal front light means a light which comes directly from the direction of camera’s optical axis, and it can implemented with a beam splitter. Bright field means a light that is directed to the surface of the object, and most of the parts of the object will reflect the light to the camera. Parts that do not reflect the light back to the camera appears to be dark. With bright field can be detected for example scratches on the surface of an object. Dark field means similar setup than bright field with distinction that the light is directed in the way that the object will appear as dark, and for example the scratches on the surface of the object will appear as bright.

The most common light sources are fluorescent tubes, halogen lamps, xenon lamps, LED lights (Light-emitting diode) and laser diode. The comparison between the light sources can be found from appendices. The variables in the comparison are lifetime, variation of design, heat generation, reaction time, intensity, robustness, aging / drifting, maintenance, safety measures, and price-performance. LEDs are performing excellent or well in all areas. LED lights are luminescence radiators which mean that they don’t need heat to radiate light. One of the biggest advantages of LEDs is the luminous efficacy which means that LEDs are giving the highest output related to the energy input. LED’s performance is temperature dependent, and in cold temperatures LED is operating better than in high temperatures. The best performance of a LED is achieved in around -30 degrees of Celsius, and the LED performance starts to decrease after around 60 degrees of Celsius, naturally depending on the LED type. [10]

To increase the lifetime of the LED and make it operate more steadily (no heating or drifting), it is recommended that MV system would turn LED on only when needed. Usually MV system has a light controller which triggers the LED in a similar way than a normal camera triggers flash. In pulse mode LED can be triggered with ten-fold current over load to get almost ten-fold higher light emission intensity, depending on the LED type (white LED can release around 6 times higher light emission intensity). If the flash mode is operated correctly, it is possible that the LED won’t indicate any aging even after 10 million pulses. [1, p. 96.]

Usually finding the optimal setup is experimental process and the theory behind the lighting is supporting the experiments. In the experiments it’s good to write down what kind of a setup is used, and later when comparing the pictures it can be distinguished what kind of a setup produced the best contrast.

### 2.2.11. Mechanical design

When camera, lenses, standoff distance, and illumination have been decided, the mechanical design can be considered. Mechanical design means the mounting of the cameras and lights and other equipment. In mechanical design installation, operation, and maintenance point of views has to be considered. In some cases the devices needs to be protected from shocks or vibrations. In most cases it is beneficial to create robust but easily modifiable system. The operator shouldn't be able to disturb the process unintentionally but if the positioning needs to be changed the system should be easily detached. Also the possibility to change the standoff distance should be available.

### 2.2.12. Electrical design

In the electrical design the availability of the power source is important. The cable lengths need to be considered as well. Some data transfer cables have the maxim distances which should be respected.

### 2.2.13. Software structure

After all the aspects have been decided, and test pictures have been shot, it is possible to build the software side of the application. Typical processing sequence follows following pattern:

1. Image acquisition
2. Pre-processing
3. Feature localization
4. Feature extraction
5. Feature interpretation
6. Result generation
7. Handling interfaces

In Figure 2.10, Figure 2.11, and Figure 2.12 is shown flow chart of typical image processing sequence. In Figure 2.10 are image acquisition, pre-processing and feature localization steps. The image acquisition step is usually launched by external trigger impulse coming from the system. Almost all smart cameras have I/O connection for triggering the camera, but the triggering can be done also through Modbus or other Ethernet communication channel. If there are needed precise measurements from the picture, a calibration is needed. The calibration is done in the pre-processing step. In calibration the pixels can be transformed to real-world units, perspective errors can be fixed, and also the distortion of the lens can be fixed. The pre-processing step can require data intensive processing, and can be for CPUs time demanding task. FPGA processors can be tailored to perform data intensive tasks faster than regular CPUs. FPGAs are used in some high-speed applications. In feature localization the area of interest is defined. Lot of time can be saved when doing the inspection only for the required area.

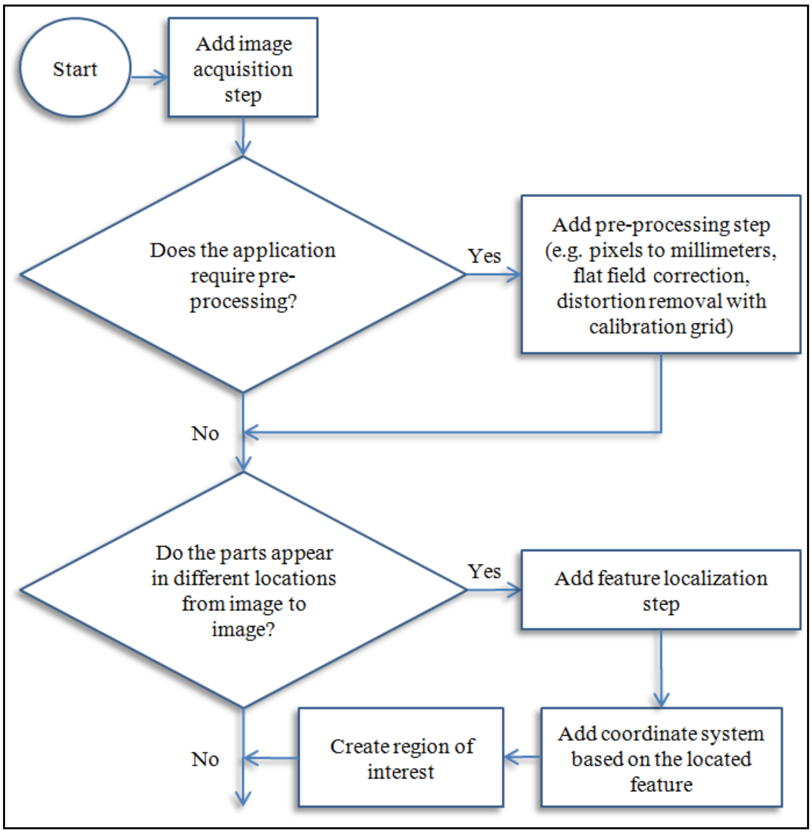


***Figure 2.10.*** *Sequence of typical image processing part 1.*

In Figure 2.11 are feature extraction and feature interpretation steps. The feature extraction step interprets the features seen in the ROI, and it will be much easier to implement if the contrast between the features and the background are well distinguished with the help of good illumination setup. In the feature interpretation step the wanted inspection is done (counting parts, detecting flaws...).

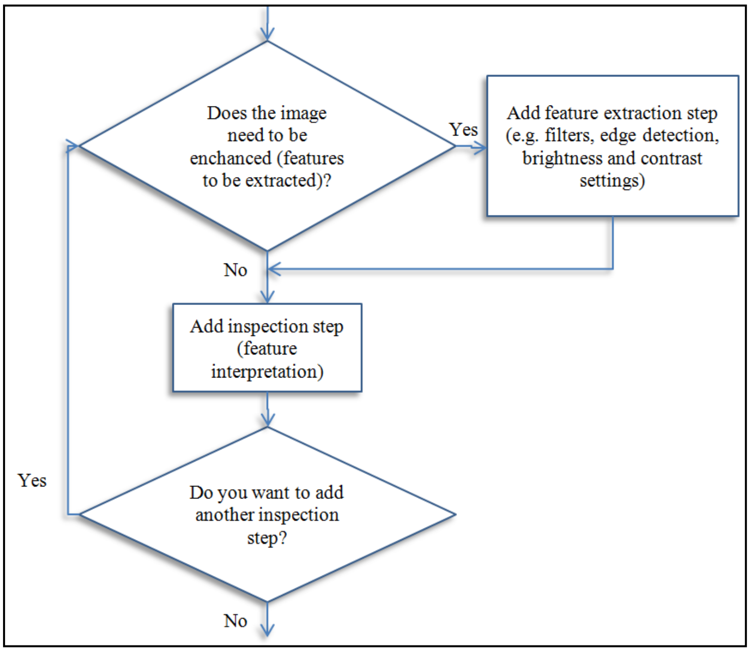


***Figure 2.11.*** *Sequence of typical image processing part 2.*

In Figure 2.12 are generation of results and handling interfaces steps. In some cases the results gained from the inspection needs to be further analyzed before the real results can be generated. The result can be as simple as pass or fail signal. The results are communicated forward in the system. In some cases it means sending simple signal to the sorting machine, and in some cases it means saving the data of the inspection to a register to be used later. The results are communicated through the handling interfaces.

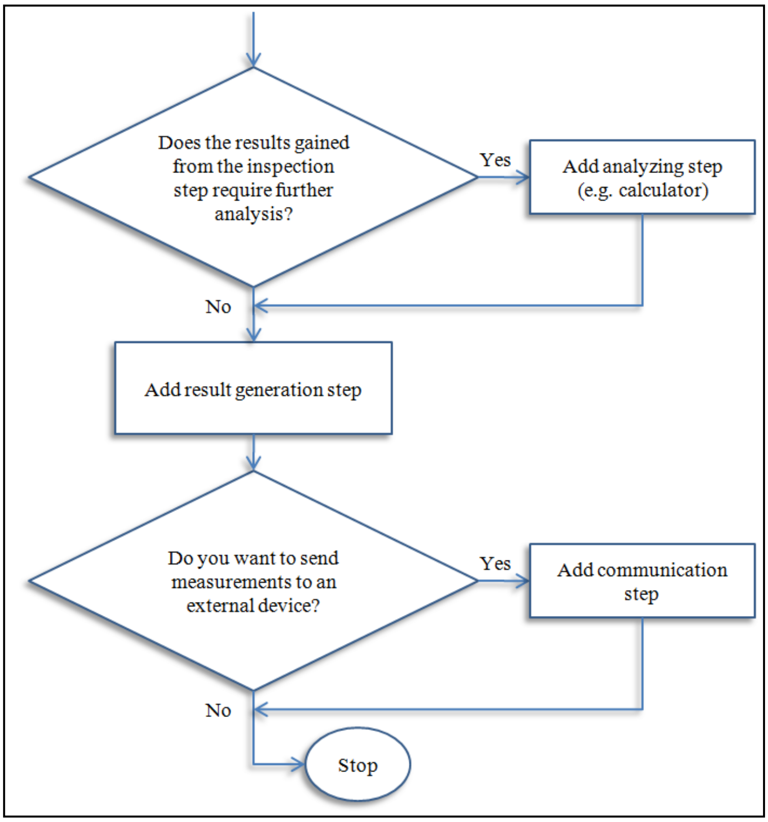


***Figure 2.12.*** *Sequence of typical image processing part 3.*

Also following aspects needs to be considered: triggering of the camera, visualization of live images, image saving, maintenance modus (calibration of camera, illumination, and contrast; overall easy calibration of the software), log files, detailed visualization of the image processing in user interface, and access to modification of crucial processing parameters trough user interface (like thresholds). Implementing the software can be very demanding, depending on the MV system, and might be wise to reserve enough time and resources for implementing this design step. The software robustness and real-time performance plays essential role in a machine vision system. [11] [12]

## 2.3. Calculation of the costs

Before launching the project, the project costs needs to be evaluated. The project costs can be divided to initial development costs, and to operating costs. The initial development costs include project management, base design, hardware components, software licenses, software development, installation, test runs, feasibility tests, and acceptance test, training, and documentation. The operating costs include maintenance (such as cleaning of the optical equipment), change of equipment (such as lamps), utility costs for instance electrical power or compressed air if needed, and costs for system modification due to product changes. If more MV systems are implemented with the same basis as the first system, the overall costs for the following system are reduced. There is no need for base design costs, for software only the run-time licenses not development licenses are needed, and training and documentation efforts will be significantly reduced. After the cost calculations can be moved to ROI calculations: If to the benefits can be assigned monetary values the ROI can be calculated, and a breakdown point can be estimated.

## 2.4. Project realization

The sequence of project realization follows usually the following pattern:

1. Specification
2. Design
3. Purchase of hardware and software
4. Development
5. Installation
6. Test runs
7. Acceptance test
8. Training and documentation

The specification and the design have been done already on the previous phases (Specification of the task, and Design of the system), and this part starts from the step three, purchase of the hardware and the software. After the purchase starts the actual development of the system. The system should be developed to be as ready as possible before installing it to the production environment. Finalizing the development of the system before testing it in the designated place is impossible because in the development phase there is needed information how the other industrial settings are affecting to the MV system and vice versa. Also test pictures from the actual industrial settings with the actual illumination are important for the development phase.

Before installing the MV system to the dedicated location it is recommended that the assembly and some testing of the system are already done in the place of the development. In that way can be checked that all the needed components are available, and there are no surprises when assembling the system. When the system is first time assembled to the production environment, lot of new information about the process can be received, for example is there any vibration or electrical interference. When the development of the system is done, test runs and acceptance tests are can be started. If the tests are successful, the training of the operational personnel can start. Also the documentation of the system should have been started when the project started, and should be finished before the end of the project.

After the project realization starts the operation phase. During the operation phase there are maintenance and support tasks. It is also possible that some minor modifications are done during the operation phase.

# 3. SMART CAMERAS

The development of the smart cameras has originated from the need of modular stand alone machine vision systems. A camera can take a live video feed size of several megabytes (MB) in a second. When the data processing is done in the point where the data is retrieved, the amount of information needed to be transferred is reduced drastically. At the best a smart camera will send only control signals average amount of few bites in a second. In some cases the amount of the transferred data can be so small that the transfer can happen wirelessly. When the data transfer is small also electricity is saved. In order to achieve small data transfer, the image processing needs to be done already inside the camera, or separate close-by processing unit.

Smart camera is relatively new concept and the exact definition for smart camera is yet to be formed. The two most common features in the definitions are compact vision system together with integrated image processing capability. The development of the semiconductor technologies is leading to smaller and smaller components, which is leading to more efficient and smaller camera systems. Nowadays regular consumer digital cameras have build-in image processing units but all experts in the field agree that those cameras shouldn't be called smart cameras. That's why a smart camera should be something more than just a camera with an image processing capability. Here are offered three definitions for a smart camera from different authorities. They all have similar characteristics but they are also complementing each other. The last definition offers an important point: that smart camera should be able to extract application specific information.

The first definition comes from the *Automated imaging association* (AIA) who recognizes three essential features for a camera to be smart:

(i) Integration of some key functions into the device (e.g., optics, illumination, imaging capture, and image processing).
(ii) Utilizing a processor and software in order to achieve computational intelligence at some level.
(iii) The ability to perform multiple applications without requiring manual actions. [2, p. 3.]

The second definitions comes from *European Machine Vision Association* (EMVA) who recognizes smart camera as following: "A smart camera with embedded intelligence, such as a microprocessor, DSP or FPGA, which can be programmed to make the camera behave like a configurable frame grabber-based PC-system. It includes the compute functionality required to execute vision algorithms within the camera body itself" [2, p. 343]

The third definition comes from researchers of the field. Yu Shi (National ICT Australia, Sydney, Australia) and F´abio Dias Real (LASMEA CNRS, Clermont-Ferrand, France) define a smart camera or an "intelligent camera," as "an embedded vision system that is capable of extracting application-specific information from the captured images, along with generating event descriptions or making decisions that are used in an intelligent and automated system". [2, p. 21.]

In historical sense the roots of smart cameras lie in PC-based camera systems. In the early years of machine vision systems there were no technology to build compact assemblies. When the computer technologies developed the processing units became smaller and smaller. In 1980's it was possible to install the imaging unit and the processing unit inside the same casing, and that was the birth decade for smart cameras [2, p. 284.] At that time the processing capability was very low, and even for the most advanced machine vision systems it took several minutes to do simple tasks. For example for Cognex's early MV system DataMan it took 90 seconds to read number 6. [13] When the processors were integrated inside the same housing with the camera, the processing was even slower.

## 3.1. Architecture of a smart camera

The applications for machine vision systems are varying a lot. The application will usually define the structure of the system. Even though there is vast number of different machine vision systems they all share some basic components. A usual machine vision system consists of illumination, optics, image capture unit, early state image processing (for example lens distortion correction), image processing, communication interface, and data transfer. In a smart camera the image processing step is called *Application Specific Information Processing* (ASIP). In Figure 3.1 is a general architecture of a smart camera.

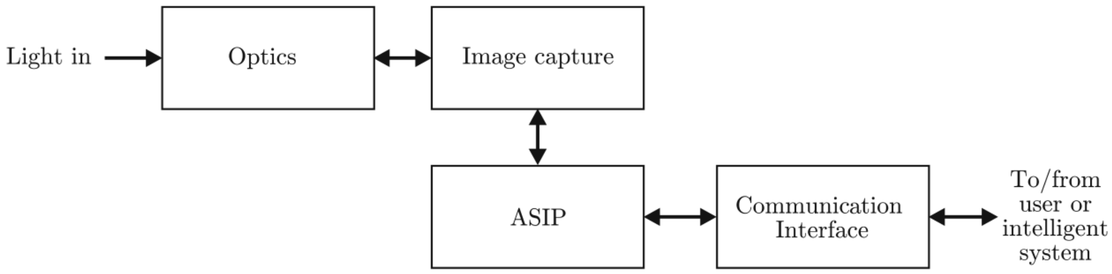


***Figure 3.1.*** *Typical architechture of a smart camera [2, p.20.].*

## 3.2. Classification of smart cameras

Vision systems are generally classified into a three different groups: PC-based vision systems, compact vision systems and smart cameras. Smart cameras can be divided to embedded smart cameras and stand-alone smart cameras. The division between different vision systems and smart camera types can be seen in Figure 3.2, and the characteristics and applications for the smart camera types can be seen in Table 3.1. In Figure 3.2 when moving from up to down, the level of integration between ASIP and image capture is decreasing while the level of system complexity is increasing. Complexity refers to configuration complexity, and smart cameras are normally easier to configure than more complex systems. [2, p. 31.]

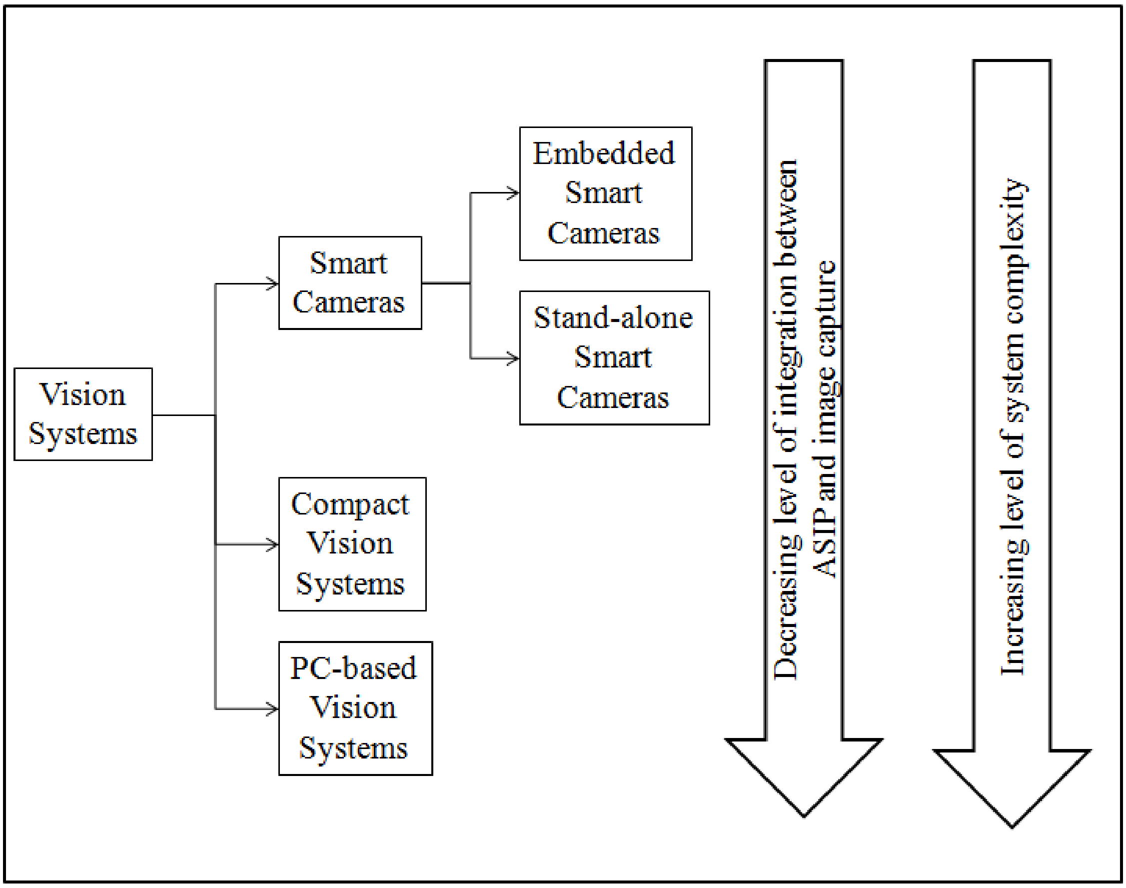


***Figure 3.2.*** *A classification of smart cameras. [Modified from 2, p. 30.]*

***Table 3.1.*** *Characteristics and applications for different types of smart cameras. [modified form 2, p. 31]*

| Type | Characteristics | Applications |
|---|---|---|
| Embedded smart cameras | Camera is embedded in another device such as a mobile phone | Optical mice, fingerprint readers, smart camera phones |
| Stand-alone smart cameras | "Normal" smart cameras, all in one camera casing. Sometimes called as a "camera with a PC inside". | Industrial machine vision, human-computer interfaces |

Size is one of the biggest advantages of smart cameras. When the image capture, the processing unit and all required vision system components are installed inside the same housing, the size can be reduced drastically. CCD (Charge-Coupled Device) imaging technology is older than CMOS imaging technology, and CCD based systems are generally bigger in physical size than CMOS based systems. To a CMOS chip it is possible to integrate the A/D conversion, signal processing, timing logic, exposure control, and most of the other required circuitry, resulting complete single chip cameras. CCD based cameras require usually three or more separate chips. The comparison between CCD and CMOS technologies can be found in this work in subchapter 2.2.6 Camera sensor.

## 3.3. Smart camera applications

Smart cameras are used in security application to do intelligent gesture and pattern recognition, in automotives to assist the driver and increase the safety of the vehicle, in human-computer interaction to recognize the gestures made by human, and in various industrial applications. This thesis is focusing on industrial applications and industrial application will work as a focus also in the applications introduced in this chapter.

Nowadays smart cameras can perform almost any task which other MV systems can perform. The decision between PC-based MV system, compact MV system and smart camera MV system is not so much based on the application which should be performed but rather other kind of factors like physical size requirement, simplicity requirement, development time requirement, robustness, electricity consumption requirement or flexibility requirement. Smart cameras are more suitable in applications where several cameras are operating independently and asynchronously, or in applications where distributed vision is required (for example in several points of a production line). In Figure 3.3 are smart camera sales revenues of 2007 divided between different smart camera applications (according to Automated Imaging Association, AIA). The most popular smart camera applications are automated mechanical and electronic assembly verifications, surface flaw detection, character recognition, part recognition, location analysis, 2D symbol reading, 2D and 3D metrology and robot guidance.

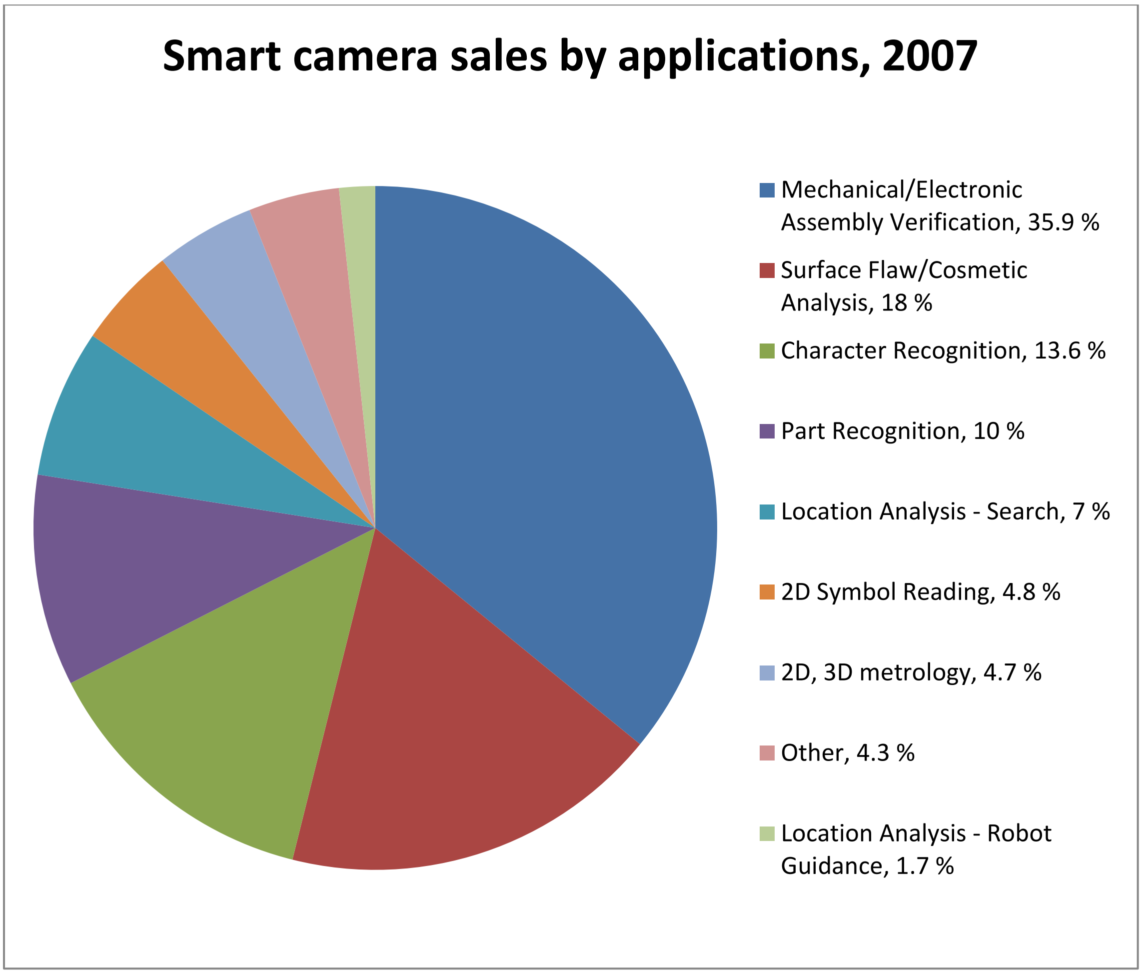


***Figure 3.3.*** *Smart camera applications. [2, p. 350.]*

The MV markets can also be divided according to end-user industries. *European Machine Vision Association* (EMVA) has been creating annual reports of the European MV markets since 2005. Figure 3.4 shows how the total turnover is divided between different end-user industries in Europe in 2009.

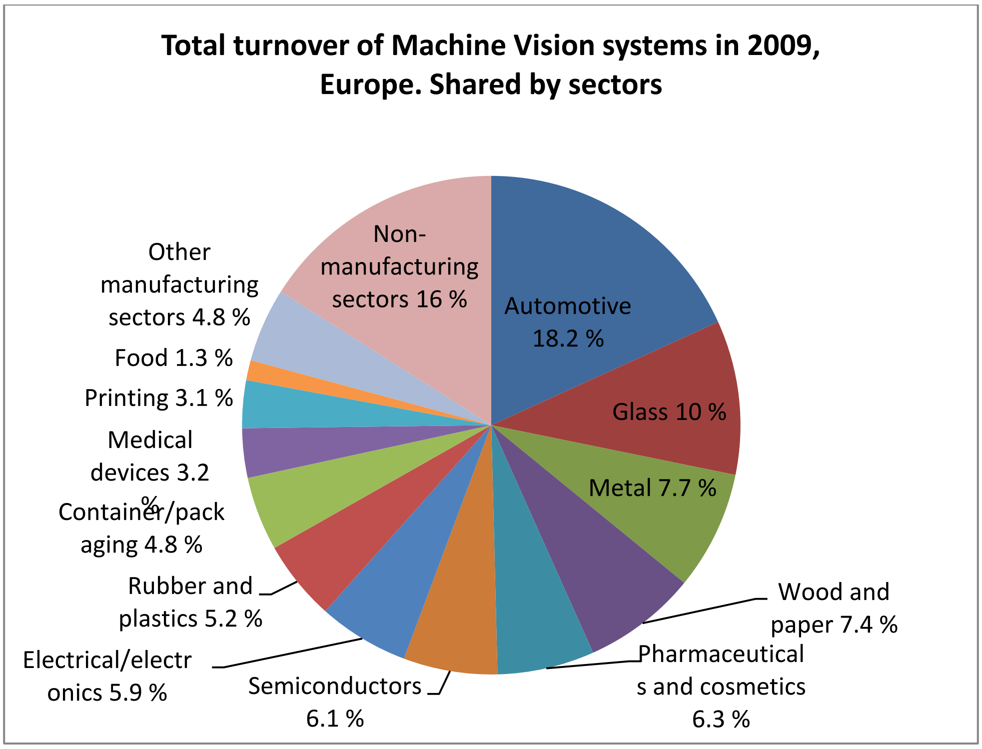


***Figure 3.4.*** *Industrial sectors for machine vision systems in 2009, Europe. [14]*

## 3.4. The smart camera markets of the world

There has been made lot of studies related to the MV markets but most of the studies are done by commercial companies and the research reports are expensive and not available to be used in this study. EMVA has been creating annual reports about European vision technology markets, and in 2008 and 2009 the smart cameras contributed about 4 percent of the European MV industry's incomes. [14] In Figure 3.5 is shown the total turnover of machine vision technology in Europe, during years 2008 and 2009.

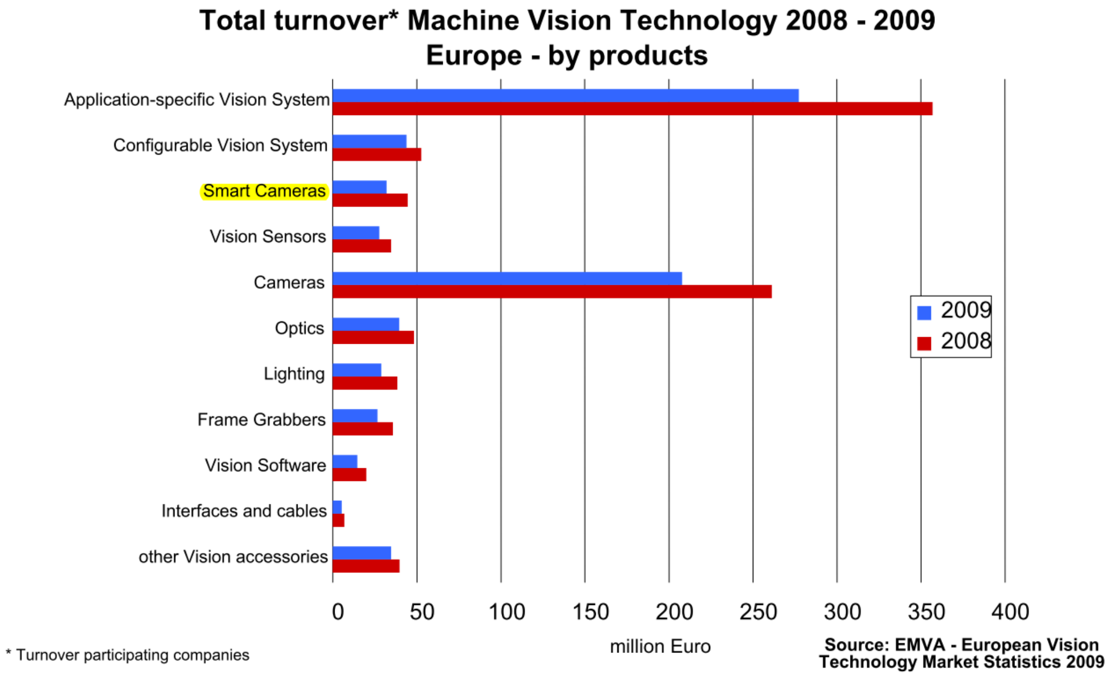


***Figure 3.5.*** *Total Turnover of Machine Vision Technology during 2008-2009 in Europe. Divided between different product categories. [14]*

After 2009 the development of the smart cameras have been very fast, and the prices of the smart camera systems have been going down, making the smart camera system to be more attractive option for the buyers. The price of the smart camera systems will keep on getting lower while the performance will keep on getting higher, and that’s why in the future the market share of the smart cameras can be expected to rise.

To get deeper insight to the market situation in the world it is vital to understand the reasons behind the buying decisions. Traditionally the MV applications are installed to manufacturing facilities to assist in automation tasks. It means that in the places where the level of automation is high, the MV systems are needed. In the countries where workforce is cheap and automation is not advanced, the need for MV systems is low. In Figure 3.5 is European machine vision technology turnover during the year 2008 divided between different product categories. From the figure can be estimated that smart cameras are contributing approximately 4 % of the whole turnover.

In 2007 a business research & consulting firm *Frost & Sullivan* revealed some statistics related to the MV market shares around the world (Figure 3.6).

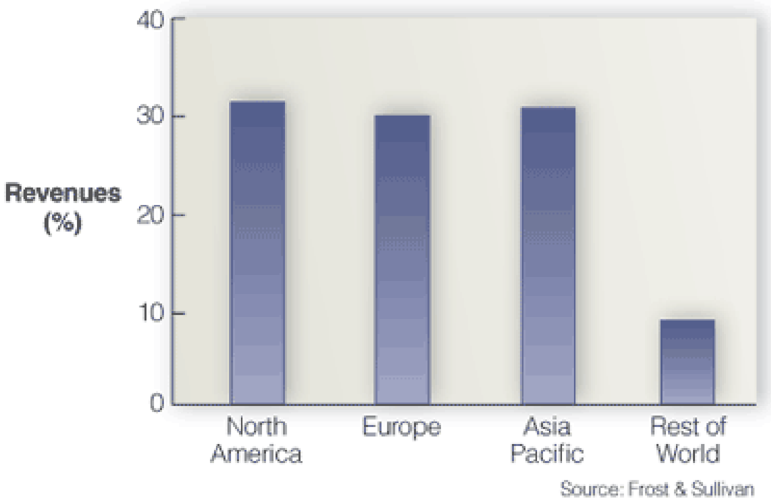


***Figure 3.6.*** *MV market shares of different areas of the world in 2007.[15]*

From Figure 3.6 can be seen that in 2007 the markets were divided quite equally between North America, Europe and Asia Pacific. Current statistics are different than the statistics of 2007 due to fast growth of developing nations but the newest statistics were not available to be used in this study. The GDP growth rate of Asia Pacific has been very big for recent years and it seems to continue that way.

When considering the MV markets especially interesting country is China. China is the second biggest economy in the world and China's GDP growth is very fast (Figure 3.8). When China's economy grows, also the automation level increases. It means that MV market will grow faster than the GDP. In 2007 the *Automated Imaging Association* (AIA) estimated the China's MV market growth rate to be close to 19.3 % a year. [16] Teledyne Dalsa has approximated the China's annual automation related sales growth rate to be close to 25 %. [17]

The biggest economies in the world by the GDP PPP are listed in Figure 3.7 , and the growth rate of the countries can be found in Figure 3.8.

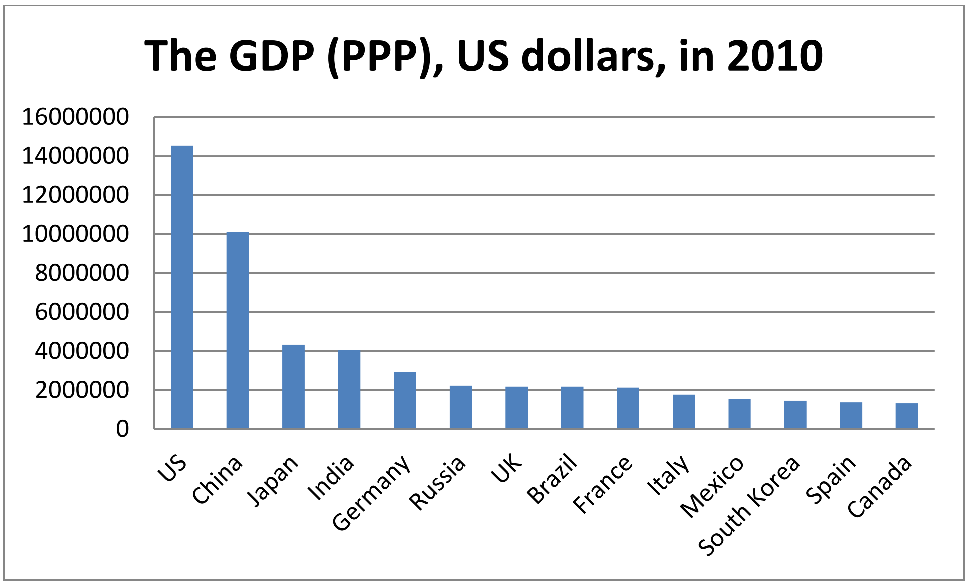


***Figure 3.7.*** *The GDP (PPP) of the biggest economies of the world, 2010. [18]*

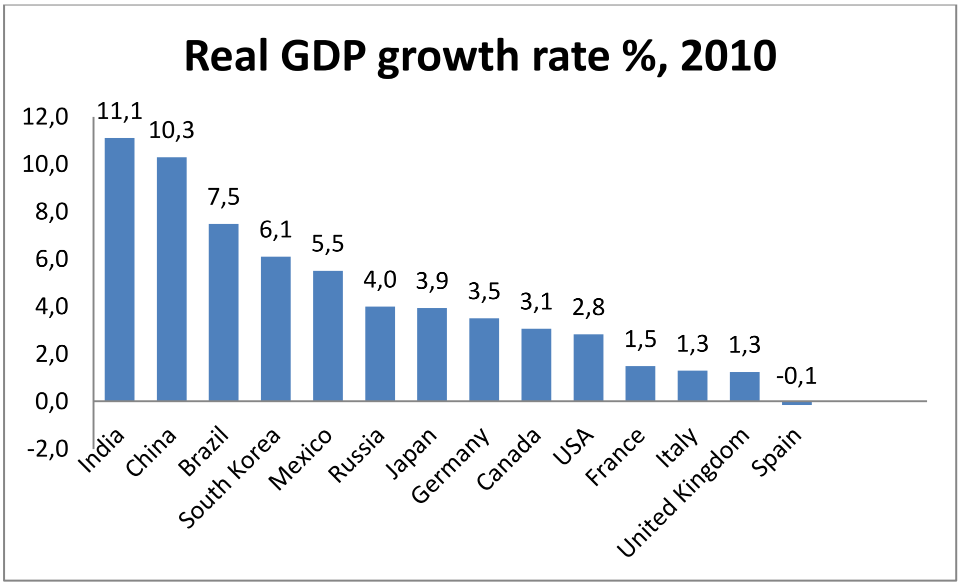


***Figure 3.8.*** *Real GDP growth rate % of 2010. During 2011 the growth rate has been increasing, the West European countries making an exception. [18]*

From Figure 3.7 can be pointed out that most of the biggest economies in the world are also the biggest buyers of MV systems (India is an exception). When the country has big growth rate (Figure 3.8) the country is especially interesting for MV companies because of possibility of expanding the revenues and profits. The GDP growth rate of 2010 is affected heavily by the recession and in many parts is slower than the growth rate of 2009. During 2011 the growth rate has been increasing, Western European countries making an exception. The year 2012 is still a mystery because of unstable situation of the world's economy. The growth rate in Europe has been slowing down few recent years but the developing nations (China, Brazil, South Korea) can be expected to keep on growing, and to offer good markets for automation related industries.

## 3.5. State-of-art of Smart Cameras

Nancy Ide and Jean Veronis define the phrase “The state of the art” as “The level of knowledge and development achieved in a technique, science”. [19] During the recent years the development of processors and other components have allowed the smart cameras to do more complex and accurate tasks in shorter period of time, while the overall system costs have been reducing. The challenge in defining the state of the art for smart cameras is because of the wide product category. Smart cameras can be used in high speed applications, and on the other hand smart cameras can be used to perform complex object recognition tasks. One camera might require a processor that is capable of data intensive processing tasks and the second one might require a processor which is capable of doing millions of calculations in a second. In third case the requirement might be the size and the price of a single unit. That’s why one smart camera might have very different architecture than the other and the both are presenting the latest technological edge of smart camera technology. Here are presented industrial smart camera models, and research related smart camera models. There are also other kind of smart cameras: for example mobile phones with a camera can be called smart cameras because they are capable of extracting application specific data. Mobile phones have several advantages like cheap price, wireless power and wireless communication channels, and sometimes other sensors like accelerometers, gyroscopes, and GPS receivers. Mobile phones with camera are discussed for example in [20] and in [21] . Generally those cameras are not suited for industrial needs, and that’s why those cameras are not discussed here.

### 3.5.1. Industrial smart cameras

In Table 3.2 are presented the most advanced industrial smart camera models in the world. In the table are the manufacturers, models, release or update date, and the reason why the smart camera series is mentioned. Release date will give indication of how new technology is used in hardware components, and in some cases the original release date is relatively old and an update have provided newer processors, better casings or other improvements. All the smart cameras in the table, except Vision Component’s VC nano 3D, have IP67 housing.

***Table 3.2.*** *The most advanced industrial smart camera models.*

| **Smart camera manufacturers** | **Model** | **Release / update date** | **Special** |
|---|---|---|---|
| Cognex | Insight 7000 series | 2/2012 | Company purely specialized in machine vision |
| National Instruments | NI 177x series | 10/2011 | Powerful and easy to use |
| Teledyne Dalsa | BOA pro | 10/2011 | Specialized in semiconductors and sensors |
| Ximea | Currera-R series | Updated 8/2011 | Powerful, cheap, compatible |
| Sick | IVC-3D | Updated 12/2009 | 3D camera |
| Vision Components | VC nano 3D | 6/2009 | 3D camera |

In one smart camera series can be over 10 different models to be suited to different purposes. Some models have bigger frame rates and smaller amount of pixels, other models have smaller frame rates and bigger amount of pixels. Some of the models have colour sensors, some don't. Due to that reason only the series are presented here. The 3D cameras in the table (Table 3.2) are relatively old but justified their presence by offering functionality that other smart cameras didn't have, the 3D imaging possibility. The suitability of these cameras to Fast laboratory's application is presented in sub-chapter 4.2.8 Choosing the camera.

### 3.5.2. Research of smart cameras

The research of smart cameras is focused on the advantages of smart camera systems (the size of the system, energy efficiency, networking of several smart cameras), or increasing the hardware and software performance of smart cameras so the system can perform the same tasks as more complex and bigger systems (3D feature tracking and stereo vision, object tracking, demanding quality inspection tasks). In [22] is presented methods to save energy by sending the microprocessor to idle state in several cases: at the end of processing a frame, when the scene is empty, or even in cases where an object is in the scene but there is no need to process the scene. In [23] is presented a solution where energy is saved by down-sampling the image in hardware level, and sending only relevant data from the image sensor to main memory. The research in [23] indicated that the solution provided 54.14% decrease in energy consumption, and 121.25 % increase in battery-life compared to performing software-level down-sampling and processing whole frames. In [24] the energy consumption problem for a wireless smart camera was tackled by installing a solar panel to the proximity of the camera, and tailoring the smart camera to perform the environmental data gathering task as energy efficiently as possible. In [25] is presented an innovative low-cost and highly compact smart camera which bill of material is under 25€. The energy efficiency is commonly utilized in battery run systems which are paired together with wireless communication channel. These totally wireless smart cameras are connected together to create well functioning smart camera networks. The smart camera networks are used for example in demanding object recognition tasks where the information of the cameras are combined to build more accurate understanding of the objects. In [26] and [27] are discussed more on smart camera networks.

The state-of-art smart camera system doesn't need to be wireless or energy efficient: in [28] is presented high performance smart camera system for print inspection. The system is used for detecting printing flaws of prints including techniques against counterfeiting (for example banknotes or postal stamps). It means that the system needs to perform in high speed (50 sheets per second), and high accuracy. Every single product needs to be inspected with different views and different spectral bands (for example with visible colour, infrared, and ultraviolet). In object detection 3D based algorithms are significantly more robust than 2D based algorithms for instance due to ground plane assumptions. If the processing of the images is done in the proximity of the imaging devices, the need for data transfer, part count, and energy consumption is significantly lower when compared to traditional solutions. That is the reason why smart cameras are ideal solutions in many 3D mapping and stereovision tasks. In [29] is presented 3D feature tracking system using wide-baseline stereo smart cameras.

## 3.6. The future of smart cameras

Dr. Ahmed Nabil Belbachir, the editor of the book Smart Cameras commented in Computer Vision Central's interview: "Cameras are getting more compact, low-cost, emerging for a wide range of applications such that the number of cameras installed and operated is increasing very fast. On the other hand the capacity of memory devices is increasing rapidly at low-cost prices. As a consequence, there are and will be a huge number of cameras (in the order of billions) operating and delivering zettabytes or yottabytes of data for the next five decades. Therefore, applications and research related to smart cameras is expected to rapidly grow in the next years." [30]

In the future cameras are moving towards the smart camera concept; the camera will have dedicated processing unit to extract the application specific information. There is no need to transport all the data the camera is recording; the wanted information can be extracted from the images and sent forward. The image stream can consist of hundreds of mega bytes in a second but the wanted information can be as simple as telling what object is in the field of view. If the camera sends signals telling what object is in the image field every time the object changes, the sent data stream can be as low as hundreds of bites in a minute. The data transmission can be done wirelessly with low energy consuming technology like ZigBee, and memory can be saved in logging the results.

This kind of technology saves energy, and makes the applications simpler and more robust.

Also 3D mapping technologies have developed a lot during recent years. Nowadays 3D mapping can be created with stereovision and laser scanners but also with time of flight cameras (ToF). ToF cameras use similar technology than regular cameras in addition that each pixel is projecting light beam, and measuring when the reflection of the light beam is returned to the pixel. The technology will add a one more dimension to the image stream, the depth. Some companies call their depth cameras RGBD cameras, where D stands for the depth. The price of ToF technology has been reducing all the time, and company called 3DV (bought by Microsoft) has developed a web camera called "Z-Cam" which provides the depth dimension in addition to the normal web camera features. They announced in 2008 that the price of the camera will be as low as US$69.99. [31] When the technology improves and the prices are reducing, it's possible that future cameras can embed 3D mapping option. Microsoft bought the 3DV company and released Kinect sensor, 3D camera which uses different 3D mapping technology, and for that reason ZCam was never released for commercial markets.

# 4. DESIGNING THE QUALITY INSPECTION APPLICATION FOR FAST LABORATORY PRODUCTION LINE

In this chapter the theory behind building a MV application introduced in Chapter 2 (Theoretical background for building a machine vision inspection), is put into practice. The flow of this chapter follows the same structure of Chapter 2 and starts by specification of the task and carries on by the design of the system and cost calculations. The implementation of the system is in Chapter 5.

## 4.1. Specification of the task

In this thesis work the implementation will be done for a production line of Sony SRX-611 robots. Robots are simulating assembly task by drawing the pictures of the installed components. The machine vision system will be part of asset aware manufacturing schema, so the information offered by the cell can be used also in various other ways, to support the vision of the factory of the future. Even though the assembly line is just simulating the real task, the process requires tool changing, gripping action of the robot, and coordinated movement of the robot arm, and the difficulty level of the simulation corresponds to the difficulty level of the task the system is simulating. Also the machine vision task requirements are as demanding as the requirements of an industrial machine vision application with an exception of more steady and easily predictable environment.

The goal of the assembly line is to apply the most sophisticated and advanced assembly line control mechanisms up to date. The control mechanisms will include real time monitoring system executed trough a web servers. The line will have automated auxiliary systems, and advanced safety measurements both in mechanical and software side. The machine vision system is integrated to the assembly line using the same control and monitoring mechanisms as the rest of the production line.

### 4.1.1. Task and benefits

The task is to do quality inspection for the end product of a manufacturing line, and offer information which can be used to increase the quality, and to define does an individual end product pass the quality criteria. The MV system will send pass/fail signal to the system accordingly. If there is a fail signal, also the reasons why the particular part didn't pass the inspection will be sent forward. The MV system will also create a log file to which all the relevant information will be saved.

At the moment the quality inspection in the system is done visually by humans. So far the visual inspection has been adequate but the goal of this MV system is not just offer information related to the quality, one of the goals of the project is also to demonstrate that it is possible to implement MV system to the current production line, which is using web services as the control platform, and which is actualizing asset aware manufacturing schema. The focus is on the research side which is hard to evaluate in monetary terms and that's why the ROI of the project is hard to calculate. If the implementation is possible it will supplement the overall goal of the eSONIA project and offer concrete example how to implement MV using web services.

### 4.1.2. Parts

The parts are paper sheets in size of A6 in which are drawn different cell phone components with different colours. The parts are discrete and have several different shapes. In the beginning three colours, red, green and blue, are used. For the drawn cell phone there will be three different frames, three different keyboards, and three different screens. These components offer 729 (9x9x9=729) different product variations. In Figure 4.1 are the frame variations, in Figure 4.2 are the keyboard variations, in Figure 4.3 are the screen variations, and in Figure 4.4 is an example of the drawn object. In the future the MV system will be physically relocated to a different production line, and the second line has also several different parts which are different to the first objects by shape, and colour, and they will have also the depth dimension. The MV system needs to be able to adapt to these variations.

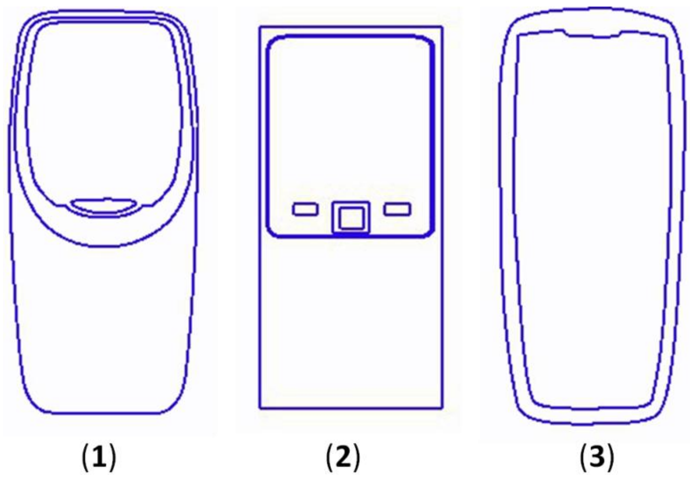


***Figure 4.1.*** *Frame variations.*

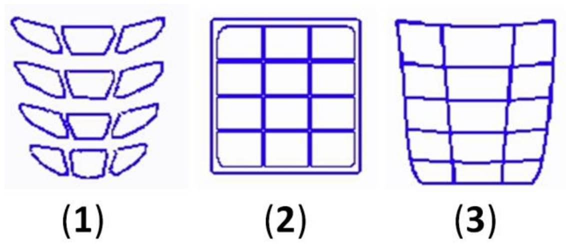


***Figure 4.2.*** *Keyboard variations.*

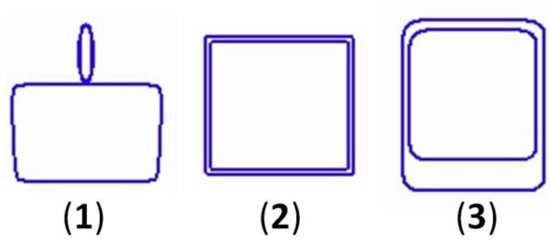


***Figure 4.3.*** *Screen variations.*

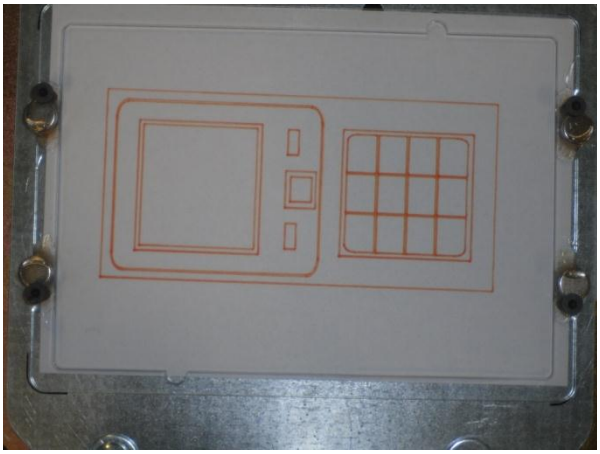

***Figure 4.4.*** *An example of the object.*

The maximum dimension of one part is 120mm, and the smallest detectable feature is 0.5m wide. The MV system should be able to detect which product variation is in the picture, and compare it to the template of the variation. The MV system should detect how the object is differing from the template, and report the results. To be able to do as comprehensive quality inspection as possible, all possible quality defects needs to be predefined.

The MV system needs to detect is the wanted feature there (in this application a frame, a keyboard and/or a screen) and is the predefined colour correct. The positioning and form of each feature needs to be exact, and the line intensity should be uniform. There is a possibility that the paper moves during the process, so the predefined feature will be deformed or incorrectly positioned. If the pen is running out, the line will be fainter, and might be that at some point the line is missing totally. In the paper there might be also extra markings which are not supposed to be there. In some cases the robot which is moving the paper away from the pallet fails to pick up the paper, and the same paper travels several times trough the whole process. In that case the same picture might be drawn several times to the paper. Because of the amount of the product variations, the user interface should be built in a way that the user can easily teach new templates for the system. Also the most common parameters should be able to adjust without bigger effort.

### 4.1.3. Part presentation

Parts will be presented to the MV system by indexed positioning, which means the part is stopped to the front of the camera by a mechanical stopper. The stopper has RF reader from which can be read what kind of product should be in the front of the camera. That information can be used in the template comparison algorithm. The stopper has also inductive sensor which will send a signal when a pallet is stopped to the front of the camera. The signal from the inductive sensor can be used in triggering the camera, and that can be the starting point of the inspection cycle. In an optimal case the camera will send signal when the image acquisition is done so the pallet can carry on in the production line.

### 4.1.4. Performance requirements

The smallest detectable object is 0.5 mm wide. This fact together with the FOV will define the resolution of the camera which will be calculated later. At this point can be estimated that because of relatively small FOV (140mm x 80mm) and relatively big spatial resolution, the camera sensor resolution requirement isn’t too high. More exact calculations will be made later in the part “4.2.5 Resolution”.

The drawing process will take in the fastest case around 15 seconds, so the cycle time for the inspection is very long and will set up relatively low computational power requirements. The biggest accuracy requirements are set up by the algorithms of the system, and those will be the most challenging part in the implementation of the system. There is high amount of detectable features, and those features should be extracted with high precision which will be a demanding task.

### 4.1.5. Communication interfaces and protocols

The communication interface should be compatible with the local area network the factory is using, and the easiest way to connect the MV system to the network would be connecting it to Ethernet switch using static IP address. That’s why the MV system should have an Ethernet port. The protocols should be compatible with S1000 Smart Remote Terminal Unit. Most probably the communication between the camera and the S1000 is done using Modbus TCP protocol which means that the MV system should be able to create Modbus server and be able to read and write to a holding register in the server.

### 4.1.6. Installation space

The camera system will be installed inside of a robot cell of Sony SRX-611 SCARA robot. The MV system is inspecting the drawings just before the robot picks them up. The robot is occupying the most of the space inside the cell but there is still left relatively large space for the MV system. In the XY-dimensions there is 500 mm x 200 mm space, and in Z dimension (height) there is 1 m space, which means that the camera system can be physically very large, and the distance from the object has lot of freedom and can be adjusted easily. The distance between the object and MV system is defining some requirements for the lenses, and because this specific case has lot of freedom with the distance, choosing of the lens is done by balancing the quality, price and availability of the lenses. In Figure 4.5 is a picture of the installation space with a reference camera, ring light and the pallet.

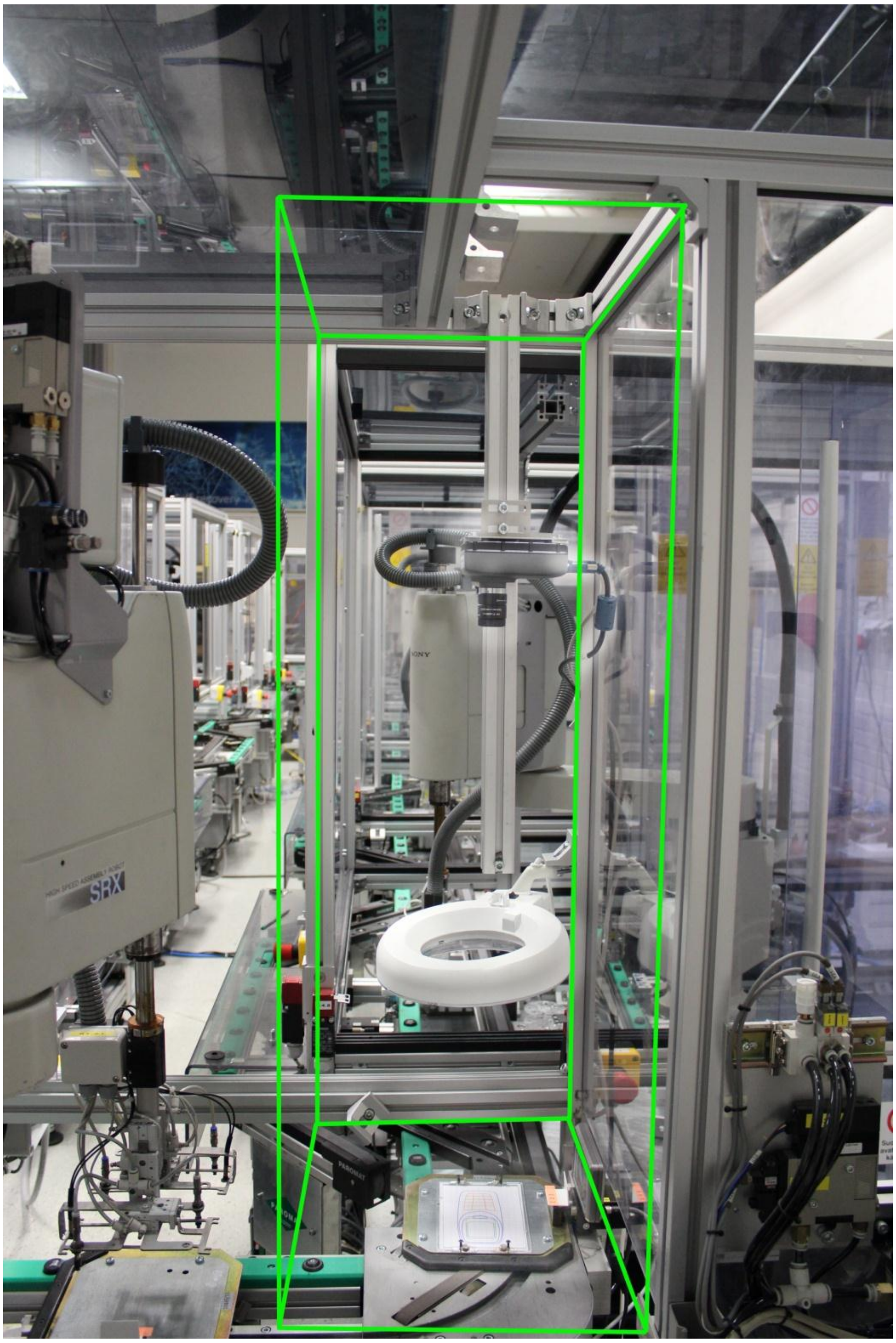


***Figure 4.5.*** *The installation space of the camera system.*

### 4.1.7. Environment

The environment of this specific application is not demanding due to laboratory conditions. There is no dirt or dust in the laboratory, and the MV system don’t require protective casing. The robot is causing some vibration to the frame the camera is attached to but the vibration is so small that it can be ignored. Rapid physical movements are not expected. The laboratory has steady temperature throughout the whole year, and power supplies are easily available. The illumination of the laboratory is normal fluorescent light in the ceiling, and windows in the ceiling level, which are allowing diffused sunlight to hit the target.

### 4.1.8. Checklist

The filled checklist can be found from appendices of this thesis (Appendix 1).

## 4.2. Design of the system

In this part is the design of the FAST laboratory's quality inspection application. It will consist of choosing the suitable hardware and software components to perform the inspection. The components should support each other so that there wouldn't be any bottle necks. For example if the camera has high resolution image sensor, the processor should be efficient enough processing power and memory to deal the amount of acquired data.

### 4.2.1. Choosing between area camera and line scan camera

The FAST laboratory production line has conveyor belt which is transporting pallet forward. In theory it would be possible to implement the quality inspection with a line scan camera. On the other hand area camera will offer several benefits: those are cheaper, there are more available software libraries and hardware components, it's possible to stop the line to make the inspection, and the department has available area cameras to be tested with the line before making the purchase decision. For these reasons area camera is selected.

### 4.2.2. Choosing between a smart camera, compact machine vision system, and pc-based machine vision system

The MV system will be part of eSONIA project and it needs to suit to the vision of the future's factory. It means that the system needs to be easily plucked in and out, small in physical size, easily re-programmable and configurable, possibly to be able in wireless communication, robust, and it needs to be energy efficient. A smart camera will suit to the task better than a PC-based system. A compact vision system would be almost as good option as smart camera, and it would offer higher flexibility but it would have bit more complicated system design, bigger physical size, and more complex configurability and re-programmability. Because of all these factors a smart camera is chosen.

### 4.2.3. Processing unit of the machine vision system

Because of the slow speed of the manufacturing line, also the processing power requirement is low. The processing power can be estimated more carefully after building the application but in practise all the available cameras in the market released in the time span of the last 5-years should be able to process the pictures in 15 seconds. There are no high speed pre-processing needed and that's why regular smart camera processor is suitable for the job. Smart camera prices are high, and the performance is increasing drastically every year, so 5-years old smart camera might be quite expensive but offer only very low performance. For that reason when buying a smart camera, also the release date is important. The author of this thesis would not recommend buying older than three years old camera.

### 4.2.4. Field of view

The object size is 120 mm x 60 mm. The pallet is moving forward in the production line in small rails, so there will be no possibilities for the pallet to move in Y-dimension. The pallet is stopped to the front of the camera by a stopper, so the object cannot be moving also in X-dimension. Also the Z-dimension is fixed. The object doesn't have possibility to rotate. It means that the object will be in the front of the camera with tolerance of maximum few millimetres. For those reasons the margins can be quite small. Margins with 20 mm to X- and Y-dimensions were selected, so the object and the margins were together 140 mm x 80 mm. When adapting to the aspect ratio the 140 mm were the dominant dimension. With aspect ratio of ¾ the FOV is 140 mm x 105 mm. After selecting the camera the actual aspect ratio is known, and at that point the actual Y-dimension can be calculated. In Figure 4.6 is the FOV taken with 1280 x 1024 resolution monochrome camera.

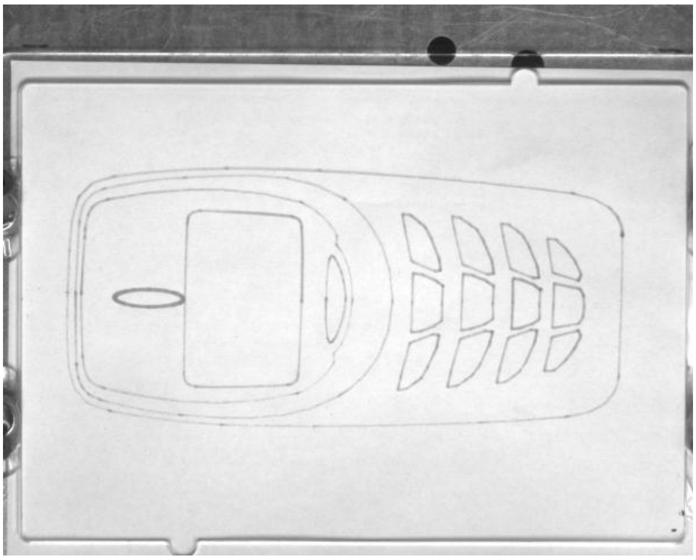

***Figure 4.6.*** *The field of view with margins and adaptation to the aspect ratio (taken with 1280 x 1024 monochrome camera).*

### 4.2.5. Resolution

The line thickness of the drawing (object) is 1 mm. In some of the parts the lines are 0.5 mm away from each other. It means that the smallest detectable feature is 0.5 mm. In the inspection there is a change that blob algorithm is used, and blob algorithm requires 3 pixels. The initial values can be seen in

***Table 4.1***. *Initial values for calculating the resolution of the camera.*

| Name | Value | Unit | Variable |
|---|---|---|---|
| Size of the smalles feature | 0.5 | mm | Sf |
| Algorithm used: Blob | 3 | pixel | Nf |
| Field of view, X-dimension | 140 | mm | FOVx |
| Field of view, Y-dimension | 80 | mm | FOVy |
| Camera resolution | ? | Rc | pixel |

By using the equation (5) the camera resolution for x-dimension can be calculated to be:

$$Rc = FOVx \cdot \frac{Nf}{Sf} = 140\ mm \cdot \frac{3\ pixel}{0.5\ mm} = 840\ pixel$$

And by using the same equation (5) the camera resolution for y-dimension can be calculated to be:

$$Rc = FOVy \cdot \frac{Nf}{Sf} = 80\ mm \cdot \frac{3\ pixel}{0.5\ mm} = 480\ pixel$$

The camera resolution needs to be higher than 840 x 480 pixels. The next general sensor resolution is 1280 x 1024 pixels which seems to be suitable for this application.

### 4.2.6. Camera sensor

The inspection application doesn't require so high precision that it would need bigger than normal sensor. The regular sensor of 1/3", 2/3" or 1" is suitable. The parts have different colours, so it is important that the sensor is a colour sensor. It would be possible to distinguish two colours from each other by using different colour LED lights or different colour filters but the application has three different colours, so the better option is to have a colour camera. In the future there is a possibility that the camera is used in other application as well, and those applications have most probably different colours, so from that view point as well, it is important that the camera has colour sensor.

### 4.2.7. Comparing different software platforms

In Table 4.2 is the list of needed algorithms for the FAST laboratory application. In practise all the available MV libraries have these algorithms, so the decision is not based on the available algorithms but rather to the easiness of use.

***Table 4.2.*** *List of needed algorithms.*

| Needed algorithm |
|---|
| Edge detection |
| Pattern matching using geometrical reference |
| Pattern matching using pixel value comparison |
| Defect detection by using golden template |

There are lot of different available software libraries for MV systems. In Table 4.3 is a list of the most well known MV libraries.

***Table 4.3.*** *Software libraries for MV systems.*

| Software name | Note |
|---|---|
| Adaptive Vision Studio | |
| Aforge.NET framework | |
| AQSENSE SAL3D | |
| Cognex In-Sight Explorer | For smart cameras |
| Cognex Vision Pro | |
| Digital Optics VPP | |
| EVT EyeVIsion | |
| Festo CheckKon | |
| Festo CheckOpti | |
| Integrating Vision Toolkit | |
| Intopii Pinta | |
| IVC studio | |
| Keyetech | |
| libdmtx | |
| Mathworks Matlab | |
| Matrox Imaging Library | |
| Matrox Design Assistant - IDE | For smart cameras |
| MvTec ActivVision Tools | |
| MVTec HALCON | The biggest vision library |
| NeuroCheck | |
| Neurotechnology SentiSight | |
| NI LabVIEW | Programmin environment |
| NI Vision Builder AI | For smart cameras |
| NI Vision Development Module | |
| Open Computer Vision Library | |
| OpenCV | Open source software |
| RoboRealm | |
| SANXO Modular-X | |
| STEMMER IMAGING Common Vision Blox | |
| Tordivel Scorpion | |
| Voyant Vision | |

In the MV software important properties are efficiency, available tools, and easiness to use. The comparison between software is difficult to implement. In the interviews for this thesis interviewees commented on different smart camera MV software libraries and the comments are just representing opinions of one single person. The interviewees commented on five different imaging libraries: OpenCV, NI Vision Builder AI, MVTec's Halcon, Festo's MV libraries and Cognex's Insight-Explorer. The following summary of the MV libraries is formed by researching literature related to the subject, the web pages of the manufacturers, articles related to the products, and interviewees comments.

OpenCV requires lot of programming, so it is usable if the user knows how to do programming with C++. OpenCV is open source project so using it doesn't require licence fees. The OpenCV project was launched by Intel (processor manufacturer) and it focuses mainly on real-time image processing. It might not be the best option for an industrial application. FAST laboratory's application requires to be flexible and fast to implement so OpenCV might not be the best choice for this specific case.

MVTec's Halcon is the biggest and most comprehensive MV library available. Learning to use Halcon requires time and programming background. Some companies focused on implementing MV systems prefer building their application by using Halcon because it offers the needed flexibility, tools, and efficiency. The person implementing the FAST laboratory's application doesn't have programming background so learning to use Halcon might require too much time. For that reason the Halcon might not be the best choice for this specific case.

Festo's MV libraries are called CheckKon and CheckOpti. Festo's MV libraries are offering the basic tools and normal usability. In some cases there have been problems for example in the camera triggering. The tool set isn't so advanced as other MV libraries. Festo is planning to release some new smart camera models in the beginning of 2012. At that point it is possible that Festo is also launching MV library updates or totally new MV library. Festo's current MV library doesn't seem to be the most suitable for the FAST laboratory's application.

Cognex is one of the biggest MV manufacturers in the world. For smart cameras Cognex is offering In-Sight Explorer. In In-Sight Explorer there is interface called *Easy Builder* which is relatively easy to use. From Easy Builder it is possible to change to Spreadsheet view in which is easy to change the parameters used in the application. Overall opinion about Cognex's software has been positive. The tool selection is good and tools are effective. Also the usability is good and the parameters are easily adjustable. Cognex seems to be suitable for the FAST laboratory's application.

National Instrument's software for smart cameras is called Vision Builder Automated Insection (AI). Vision Builder AI is one of the easiest MV software to use. Also Vision Builder's tools are effective. NI offers also possibility to program own tools by using NI's LabVIEW programming environment. Tampere University of Technology has purchased campus licence for NI's software and it means that if NI's smart camera is purchased to the FAST laboratory, there are no extra costs for purchasing LabVIEW licence or extended driver licence. All-in-all NI's software seems to be suitable for the FAST laboratory's application.

### 4.2.8. Choosing the camera

At this point is known that the camera is going to be smart camera with at least 840 x 480 pixels. It is also known that the objects have different colours, so the camera must be a colour camera. The objects are coming to the front of the camera in every 15$^{th}$ second, so the frame rate requirement is very low. In practise even the lowest frame rate in the markets is suitable for this application. In Table 4.4 is the list of the camera requirements.

***Table 4.4.*** *List of the camera requirements.*

| **Camera requirements** |
|---|
| Smart Camera, imaging area (not line scan) |
| Resolution at least 840 x 480 pixels |
| Colour sensor |
| No sensor size requirement |
| No frame rate requirement |
| No processing power requirement |
| No random-access memory requirement |
| No storage memory requirement |
| Ethernet and I/O interfaces |
| Modbus |
| TCP/IP possibility |
| Release date preferably as close as possible to the current date but at least within 3 years. |

There is a huge amount of different smart camera manufacturers. The most suitable smart cameras and their manufacturers are compared in this section. There are several advantages in buying the camera from well-known big manufacturer: they will provide continuity for several years after the purchase of the system so spare parts and support can be guaranteed; the software is developed with bigger budget for wider audience, and the software has been tested over the years in thousands of different applications, so the software will be more flexible, and the tool set will be wider. Also the R&D budget for the hardware is bigger, which usually provides higher quality products.

Most of the smart camera manufacturers are also manufacturing other industrial applications. The MV business is not big when compared to the overall automation industry but it is increasing all the time.

Companies that are providing only imaging solutions are rare. Cognex is the biggest MV provider in the whole world, even though it's drastically smaller than Festo or National Instruments (NI) due to the fact, that most of Festo's and NI's revenue is formed from other solutions than MV solutions. Cognex is focusing purely on MV side. Cognex is offering complete MV systems, and it is popular in all areas of automation industry. The prices of the cameras vary lot so the most sensible way of expressing the price level is categorizing the products in different product pricing categories. In Table 4.5 are presented the different product pricing categories.

***Table 4.5.*** *Product pricing categories for smart cameras. The price includes the smart camera hardware, and included basic MV software.*

| Product pricing category | Description (€) |
|---|---|
| Very low cost | 0.1 - 100 |
| Low cost | 100 - 1500 |
| Average pricing | 1500 - 4000 |
| High pricing | 4000 - 10 000 |
| Very high pricing | 10 000 - |

In Table 4.6 are compared two Cognexs smart camera options, and in Figure 4.7 are the pictures of the smart cameras. In the following tables red colour indicates unsuitable specification, and blue colour indicates specification which was not available in the data sheets of the device.

***Table 4.6.*** *Cognex smart camera options. [32] [33] [38] [34]*

| Smart camera model | In-Sight 1403C | In-Sight 5400C |
|---|---|---|
| Resolution | 1600 x 1200 | 640 x 480 |
| Frame rate | 7 fps | 60 fps |
| Colour sensor | yes | yes |
| Sensor | 1/1.8" CCD | 1/3" CCD |
| Processing power | not defined | not defined |
| Random-access memory | 128 MB | 32 MB |
| Storage memory | 64 MB | 64 MB |
| Ethernet | yes | yes |
| Digital inputs | 1 | 1 |
| Digital outputs | 2 | 2 |
| Modbus | yes | yes |
| TCP/IP | yes | yes |
| Release date | 2009 | 2004 |
| Pricing category | High pricing | Average pricing |


***Figure 4.7.*** *Cognex In-Sight Micro 1403C (on the left) and In-Sight 5400. [32]*

The In-sight 5400C smart camera is released over 7-years ago, and it makes the camera very old. The In-Sight 1403C is released over 3 years ago, it is expensive, and Cognex don't have office in Finland, so it is provided only through resellers. Usually resellers cannot provide so comprehensive support as the manufacturer itself. Also the spare parts and delivery times are longer due the communication channel. Even though the camera is old, it has several benefits: Cognex's software is one of the best in the markets, and Cognex's online training and support materials are very comprehensive. Because of the high price and low performance the Cognex's cameras are not the best option for FAST laboratory's application.

Festo is a big player in automation industry. Festo's worldwide revenue in 2010 was 1.8 billion Euros which is over double the size of NI, the second biggest company which is providing smart cameras, and over 8-times more than Cognex's revenue. [35] [36] Even though Festo is a huge player in automation industry, its smart camera selection is not as advanced as NI's or Cognex's. Festo offers tailored smart cameras for specific applications. In Table 4.7 are the specifications of one of the Festo's smart cameras, and in Figure 4.8 is the picture of the smart camera.

***Table 4.7.*** *Suitable Festo's smart camera. [37] [38]*

| Smart camera model | SBOC-C colour |
|---|---|
| Resolution | 752 x 480 |
| Frame rate | 60 |
| Colour sensor | yes |
| Sensor | 1/2" CMOS |
| Processing power | Not defined |
| Random-access memory | Not defined |
| Storage memory | Not defined |
| Ethernet | yes |
| Digital inputs | 2 |
| Digital outputs | 3 |
| Modbus | yes |
| TCP/IP | yes |
| Release date | 3/2009 |
| Price | High pricing |

***Figure 4.8.*** *Festo's smart camera option. [37]*

The customization of Festo's MV systems is great and the customer can choose quite specifically which components the smart camera will have. In the data sheet there is no information about the processing power, and might be that the processing power in the smart camera is outdated, or might be that Festo has updated some specific components of the camera, and the processing power is up to date.

Festo don't offer trial software for the MV systems, and for that reason it is hard to evaluate the software performance. In the interviews for this thesis one interviewee commented that Festo's tool library is constricted and the software itself hard to use. Festo is planning to launch new selection of smart cameras on the beginning of 2012, and that selection will probably offer good cameras for the implementation part of this thesis but the current selection is not the most suitable one.

NI is offering vast and advanced selection of smart cameras. NI has several smart cameras that are fulfilling the requirements of FAST laboratory's application. In Table 4.8 are compared two NI's smart camera models. The first one (NI 1774C) is representing the new generation of the NI's smart cameras, and the second one (NI 1742) was chosen to be in the table because it was available to testing in the FAST laboratory. The second model is an old model of NI's smart cameras, and it doesn't have adequate resolution, or a colour sensor, so building the application by using the camera will be challenging but will offer insight to the NI's products. The software used in the NI 1742 is the newest NI smart camera software (Vision Builder AI 2011), so it will be the same software that would be in the newest model. In Figure 4.9 are the pictures of the cameras.

***Table 4.8.*** *Comparison of two NI smart camera models. [39] [40]*

| Smart camera model | NI 1774C | NI 1742 |
|---|---|---|
| Resolution | 1280 x 960 | 640 x 480 |
| Frame rate | 17 fps | 60 fps |
| Colour sensor | yes | no |
| Sensor | CCD | CCD 1/3" |
| Processing power | 1.6 GHz Intel Atom | 533 MHz PowerPC |
| Random-access memory | 512 MB | 128 MB |
| Storage memory | 2 GB | 128 MB |
| Ethernet | yes | yes |
| Digital inputs | 4 | 2 |
| Digital outputs | 4 | 2 |
| Modbus | yes | yes |
| TCP/IP possibility | yes | yes |
| Release date | 3.10.2011 | 2007 |
| Price | Average pricing | Average pricing |


***Figure 4.9.*** *NI 1774C (on the left) and NI 1742 smart camera models. [39]*

The NI 1774C is the most recent smart camera release in the MV markets, and it will offer several benefits: the software and the hardware are utilizing the latest technologies in the markets. The new line of NI smart cameras has high performance, high amount of

RAM, and high amount of storage memory. The FAST laboratory has already licences for the all NI's software, so the licence expenses will be less than when using some other software licences. In most cases the licence expenses are included to the camera price but in some cases buying some extra toolkits, or drivers will bring some extra expenses. In NI's case also the licenses for software development environment (LabVIEW), and extra drivers are already owned by the FAST laboratory, so if NI's system is implemented there will be no software licence costs.

NI has department in Finland which offers the needed support and training. The shipment days are short, and NI's personnel have possibility to travel to the FAST laboratory in 3 hours, so if needed there is also possibility for on-sight support. NI offers comprehensive online training and support materials. NI is big manufacturer so the NI will offer continuity with high probability for several years after buying the camera.

Teledyne Dalsa is specialized in digital imaging and semiconductors. Originally it was providing imaging sensors for other companies to be used in their products but nowadays Dalsa is also providing its own cameras. When Dalsa is designing and manufacturing its imaging cells and other semiconductors by itself, Dalsa's cameras have better possibility to implement system integration without any bottlenecks along the way. Dalsa has also opportunity to produce smart cameras more precisely according to the need, so the smart cameras Dalsa sells should have all the latest components. Also Dalsa offers high amount of product variations to meet the customer's specific needs.

In 2010 Dalsa's smart camera BOA won the "Best in the test" competition organized by *Test & Measurement world* magazine. Test & Measurement world says:

"The BOA vision system is a highly integrated smart camera with all of the elements of an industrial machine-vision system. Powerful and quick to deploy, the BOA is ideal for automated quality-inspection applications and factory automation. An all-in-one machine-vision system, BOA is easy to use and flexible, and Dalsa says it is the first smart camera in its class to incorporate multiple processing engines, and also the first to offer truly embedded application software, easily set up through a standard Web browser. BOA offers advanced vision capabilities that are easy to integrate at an affordable price, while consuming very little space and power. The ultra small BOA has been specifically designed for industry. Its 44-mm cube form factor is designed for tight-fit applications, integrating easily into existing production lines, machinery, or moving equipment." [41]

In Table 4.9 are specifications of Dalsa's BOA Smart Camera. Dalsa offers several versions of the BOA Smart Camera, and the latest version is called BOA Pro. BOA Pro has higher resolution and different processors than the older version of BOA. The BOA smart camera is offered with a range of sensor resolutions, and different performance grades. That is the reason why in the table there has been shown several numbers for example to the resolution. In Figure 4.10 is the BOA Smart Camera.

***Table 4.9.*** *Specificationf of BOA Smart Camera from Teledyne Dalsa. [42]*

| Smart camera model | BOA |
|---|---|
| Resolution | From 640 x 480 to 1600 x 1200 |
| Frame rate | Up to 60 fps |
| Colour sensor | yes |
| Sensor | 1/3" CCD |
| Processing power | Old model: DSP + CPU; Newest model: ARM + DSP |
| Random-access memory | 256 MB |
| Storage memory | 256 MB |
| Ethernet | yes |
| Digital inputs | 4 |
| Digital outputs | 4 |
| Modbus | yes |
| TCP/IP possibility | yes |
| Release date | 2011 |
| Price | Average pricing |


***Figure 4.10.*** *BOA Pro Smart Camera. [42]*

In most of the aspects BOA smart camera seems to be good option for FAST laboratory's application. Teledyne Dalsa is US based company and it doesn't have office in Finland, so the purchase must happen trough resellers. It will increase the delivery times with the components or with the spare parts, and also the support might not be as extensive as with manufacturers who have offices located in Finland.

Test & measurement world “Best in Test 2010” competition had also one other smart camera as one of the finalists: Matrox Iris GT. The magazine says:

“Matrox Iris GT is a smart camera for machine-vision applications. Powered by an Intel 1.6-GHz Atom processor, it runs Windows CE 6.0 and features an integrated graphics controller with VGA output, a 256-Mbyte DDR2 memory, and a 1-Gbyte flash disk. For connecting to external devices, the camera includes a 10/100/1000 Ethernet port, a USB 2.0 port, an RS-232 serial port, an optocoupled trigger input, and strobe output. It also supports Ethernet/IP and Modbus over TCP/IP communications to interact with PLCs and other automation equipment. Iris GT is available in three monochrome CCD sensor configurations: 640x480 at 110 fps, 1280x960 at 22 fps, and 1600x1200.

Iris GT comes with Matrox Design Assistant, an integrated development environment. Users interactively create a flow chart of the application instead of writing programs or scripts. An integrated HTML editor and layout tool gives users the flexibility to create custom Web-based operator views for application monitoring.” [41]

In Table 4.10 are Matrox Iris GT 1200C smart camera’s specifications, and in Figure 4.11 is the picture of the camera.

***Table 4.10.*** *Matrox Iris GT 1200C smart camera specifications. [43]*

| Smart camera model | Matrox Iris GT 1200C |
|---|---|
| Resolution | 1280x960 |
| Frame rate | 22.5 fps |
| Colour sensor | yes |
| Sensor | 1/3" CCD |
| Processing power | 1.6 GHz Intel Atom |
| Random-access memory | 512MB DDR2 |
| Storage memory | 2 GB flash |
| Ethernet | yes |
| Digital inputs | 4 |
| Digital outputs | 4 |
| Modbus | yes |
| TCP/IP | yes |
| Release date | Oldest: 2008<br>Newest: 2011 |
| Price | Average pricing |


***Figure 4.11.*** *Matrox Iris GT smart camera. [43]*

Matrox's camera seems to be suitable for FAST laboratory's application. In the interviews Matrox's imaging library didn't receive as high comments as other MV software libraries. Also Matrox don't have branch in Finland which increases the delivery times and the available support.

*Ximea* is focusing on building high performance hardware, and their smart cameras have very high resolution, very high processing power, very high RAM, and very high storage memory. Ximea's smart cameras are so powerful that it is possible to install Windows or Linux operating system for the smart camera, and run any MV manufacturer's software with the operating system. Ximea is offering drivers for over 15 different imaging libraries, and this kind of approach brings several benefits: If an old application needs to be run with new camera, it is possible to buy Ximea's high performing smart camera and install the drivers and imaging libraries of the old camera's manufacturer, and then run the old application in the new Ximea's smart camera. With this kind of approach Ximea is promising out-of-the-box compatibility. Because Ximea is focusing on the hardware side there in the camera prices there is no addition from the software development. Ximea can offer the cameras in $1/4^{th}$ or $1/3^{th}$ of the price of traditional MV manufacturer's cameras. The software needs to be bought separately, and if the implementing organization has already ready licences from one MV manufacturer, Ximea's camera might be a very good choice. The implementation might need more work than traditional smart camera's implementation, and the support might not be so extensive. In Table 4.11 are Ximea's Currera RL50C smart camera's specifications, and in Figure 4.12 is the picture of the camera.

***Table 4.11.*** *Ximea's Currera RL50C smart camera's specifications. [44]*

| Smart camera model | CURRERA RL50C |
|---|---|
| Resolution | 2952x1944 |
| Frame rate | 15 - 200 fps |
| Colour sensor | yes |
| Sensor | CMOS |
| Processing power | Intel Atom Z530 1.6GH |
| Random-access memory | 1 GB |
| Storage memory | 4GB, Micro SD Card Slot |
| Ethernet | yes |
| Digital inputs | 4 |
| Digital outputs | 4 |
| Modbus | yes |
| TCP/IP | yes |
| Release date | 2010 |
| Price | Average pricing |


***Figure 4.12.*** *Currera RL50C smart camera. [44]*

Ximea's camera seems to be suitable for FAST laboratory's application. The question is how well different software libraries can be implemented to the camera. Ximea is operating in Germany which is relatively close to Finland. The hardware parts are possibly fast and easy to receive but because Ximea is not developing software, the software support might not be so extensive as for some other smart camera manufacturers.

All in all the best option for FAST laboratory's application seems to be NI's 1774C smart camera. It has very high hardware and software performance together with easiness to use. The price is also competitive. NI has office in Finland in Espoo, 2.5 hours away from FAST laboratory, so it's possible that after the purchase NI's personnel can offer on-site support. FAST laboratory has already NI's licences so there will be no extra costs in any additional software licences. The production engineering department of TUT has already one NI's smart camera (NI 1742) so the NI's software library can be tested already before the purchase. Also MV courses of production engineering are using NI's cameras and software in the teaching, so the students have experience in NI's products. It makes the NI 1774C suitable to be used in the teaching environment as well as in the research environment.

The second option for FAST laboratory's application would be Teletyne Dalsa's BOA smart camera. BOA has received several positive reviews and price is very competitive. The third option would be Ximea's Currera smart camera. Ximea's cameras are high performing and low cost smart cameras, and because FAST laboratory has already NI's licences in use, it would be possible to run NI's software in Ximea's camera.

#### 4.2.9. Optics and lens design

The selection of optics can be started by calculating the approximation for the focal length. Then will be chosen the next standard lens focal length. Then the standoff distance will be calculated again using the chosen focal length. Because there will be used several initial values, also there will be several results. The results will give the standoff distance for the camera with a certain tolerance. The system has very big adjustable standoff distance. If the tolerance fits inside to the adjustment range can be stated that the chosen focal length will be suitable for the camera system.

***Table 4.12.*** *Initial values for the focal length calculations.*

| Name | Variable | Unit | Value |
|---|---|---|---|
| Focal lenth | $f'$ | mm | ? |
| Standoff distance | $a$ | mm | 100 - 1000 |
| Field of view, x-axis | $FOVx$ | mm | 140 |
| Field of view, y-axis | $FOVy$ | mm | 80 |
| sensor size, x-axis | sensor x | mm | 4.8 - 8.8 |
| sensor size, y-axis | sensor y | mm | 3.6 - 6.6 |

***Table 4.13.*** *Few of the most common sensor sizes and their measures. [6]*

| Sensor size | 2/3" | 1/2" | 1/3" |
|---|---|---|---|
| **sensor x** | 8.8 mm | 6.4 mm | 4. 8 mm |
| **sensor y** | 6.6 mm | 4.8 mm | 3.6 mm |

With FOV of 140 mm x 80 mm the x-dimension is dominant when compared to y-dimension. It means that only x-dimension is needed to calculate. In standoff distances the further away the camera is, the better the quality is. Because the tolerance for the standoff distance is very big (100 – 1000 mm) the initial value for standoff distance can be chosen to be further away from the object but still leave some tolerance if adjustments are needed. With this reasoning standoff distance of 700 mm was chosen. The approximation for focal length can be calculated by using the equation (7), and it will be calculated for the three most common sensor sizes. For the 1/3” sensor the focal length will be:

$$f' = 4.8\,mm \cdot \frac{700\,mm}{140\,mm} = 24.0\,mm$$

For the 1/2” sensor the focal length will be:

$$f' = 6.4\,mm \cdot \frac{700\,mm}{140\,mm} = 32.0\,mm$$

And for the 2/3” sensor the focal length will be:

$$f' = 8.8\,mm \cdot \frac{700\,mm}{140\,mm} = 44.0\,mm$$

If we choose a lens with 25 mm focal length, the new standoff distances can be calculated with the equation (9) . For the 1/3” sensor the new standoff distance will be:

$$a = 25mm \cdot \frac{140mm}{4.8\,mm} = 729.2\,mm$$

For the 1/2” sensor the new standoff distance will be:

$$a = 25mm \cdot \frac{140mm}{6.4\,mm} = 546.9\,mm$$

And for the 2/3” sensor the new standoff distance will be:

$$a = 25mm \cdot \frac{140mm}{8.8\,mm} = 397.7\,mm$$

With all sensor sizes a lens with 25 mm focal length seems to be suitable for the application.

### 4.2.10. Choice of illumination

The illumination is very important part of the MV inspection. The importance of a correct illumination is stressed in situation where the object is 3-dimensional. With 3-dimensional object if the light is directed only from one side, the object will cast a shadow to the other side. The MV application might not be able to distinguish which line is the edge of the object and which line is the shadow. If there is done measurements of distances the results will be incorrect. Also the shadows will create problems for template matching because the object will look different than the template.

The first application in FAST laboratory is inspection of 2-dimensional object (paper sheet) so the lighting is not so critical. In template matching there are 2 different tools: one to match the pixels, and second to match the geometric forms. If the matching is done according the intensity values of the pixels, uneven one-sided lighting might disturb the inspection. On the other hand if the template matching is done according the geometric forms, one-sided lighting won’t disturb the inspection.

The best lighting option for inspecting 2-dimensional multicoloured figures from a paper sheet is white ring light directed directly from above. With that kind of a light the light will be cast to the paper evenly and all the colours will be seen. In general LED lights are the best for MV inspections, and the light colour should be white. White LED can be produced with lot of several techniques, for example with red-green-blue LED combination, or phosphor coating. Red-green-blue combination white LED has advantage of possibility of changing the colour by changing the power of different colour LEDs. This option is not needed in the camera at the moment, and that’s why any ring light that produces white light is sufficient for the application.

In the future the same hardware will inspect also 3-dimensional objects. That’s why it’s better to choose illumination that is suitable for inspecting also 3-dimensional objects. Directly above directed white LED ring light is good choice also for illuminating 3-dimensional objects.

The robot cell to which the MV system is installed needs to be protected from daylight. The protection don’t have to be 100% but the affect of the daylight needs to be minimized so that it don’t offer extra brightness to the paper sheet, or it won’t offer reflections to the camera that would disturb the process. In some cases when the affect of the daylight is not taken into account the inspection might work differently during the day and night, and that’s why it’s important to get the illumination as steady and balanced around the clock.

### 4.2.11. Mechanical design

The mounting of the camera is relatively easy. The robot cell has metal frames composed from individual metal pipes. The camera can be attached to one metal pipes with a mounting plate. A mounting plate for the camera can be seen in Figure 4.13, and the other mechanical design can be seen from Figure 4.14. The mounting plate got tolerance for adjustments in xy-plane, and the aluminium pipe profile got tolerance for adjustments in z-dimension. The structure has been supported with aluminium pipes, and the wires are going inside the aluminium pipe.

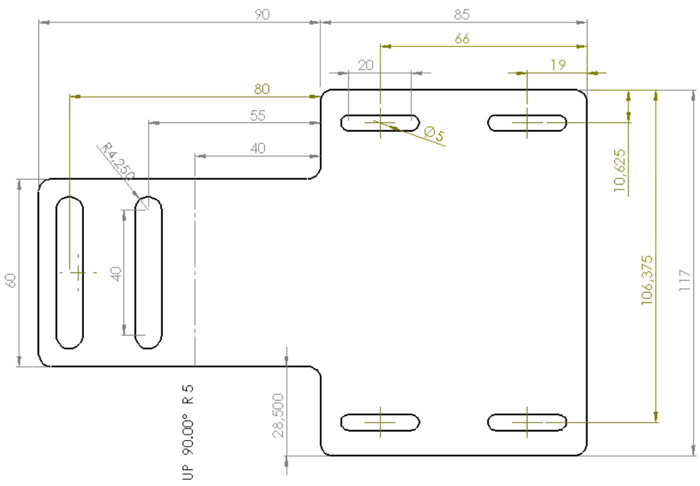


***Figure 4.13.*** *Mounting plate for NI 1742. The same plate could be used for NI 1774C when the slits with 5 mm diameter were extended to 10 mm.*

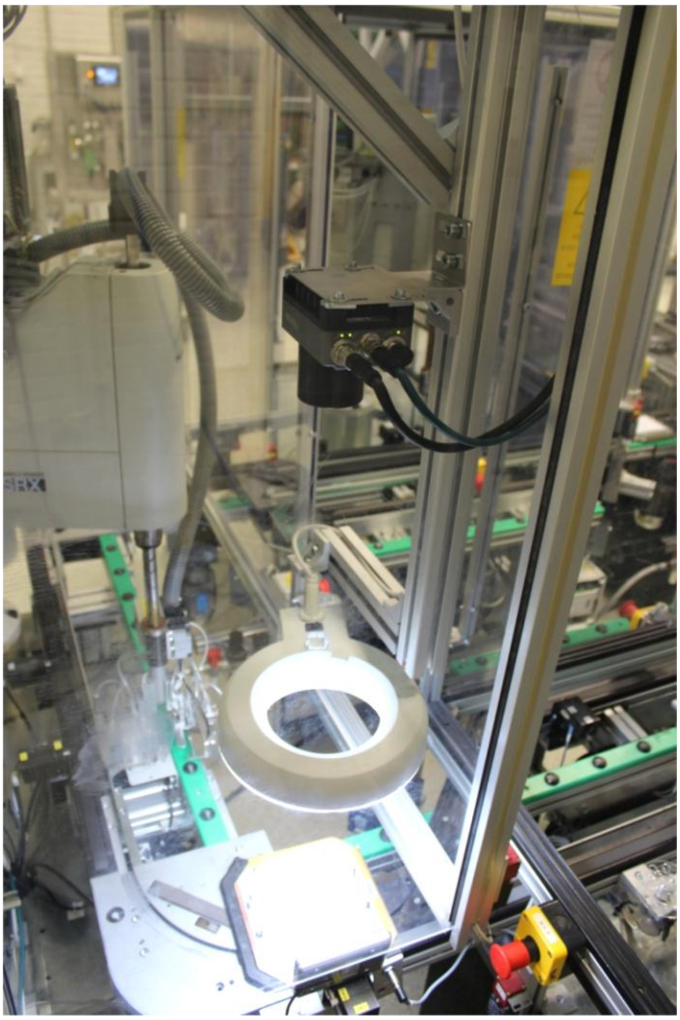

***Figure 4.14.*** *NI 1774C camera mounted to the production line.*

### 4.2.12. Electrical design

The camera system can use the same electrical wirings as the robot cell. Also the Ethernet can be plugged to the same switch as other devices in the robot cell. The wires can be easily put inside the slits of the aluminium profile.

### 4.2.13. Software structure

The software structure usually follows the following pattern:

1. Image acquisition
2. Pre-processing
3. Feature localization
4. Feature extraction
5. Feature interpretation
6. Generation of results
7. Handling interfaces

The design of the software is explained in detail in subchapter 5.1.1.

## 4.3. Calculation of the costs

Table 4.14 presents the sources from project costs but the values are left unassigned because the cost calculation and ROI are not essential for a university project.

***Table 4.14.*** *Cost calculations for the project.*

| Initial development costs | Operation costs |
|---|---|
| Project management | Maintenance |
| Base design | Change of equipment |
| Hardware components | Utility costs |
| Software licenses | System modification costs |
| Installation | |
| Test runs | |
| Feasibility tests | |
| Acceptance test | |
| Training | |
| Documentation | |

# 5. PROJECT REALIZATION

In this chapter is described the MV project realization. The chapter follows the theoretical part written in chapter 2 concerning the project realization part. The implementation was done during November and December 2011, and January 2012. The sequence of project realization follows the following pattern:

1. Specification
2. Design
3. Purchase of the hardware and the software
4. Development
5. Installation
6. Test runs
7. Acceptance test
8. Training and documentation

The specification and the design have been done already on the previous phases (Specification of the task, and Design of the system), and this part starts from the step three, purchase of the hardware and the software. The purchase of the hardware was done by the department during November 2011 and it was very straightforward. Tampere University of Technology had already campus licenses for the software so a separate purchase of the software was not needed. The installation part was also very straight forward because the design steps were well executed and installation space, mounting plates, and everything related to the installation were available. This chapter focuses more in detail to the remaining implementation steps: development, test runs, acceptance test, and training and documentation.

## 5.1. Development

In the development there are three main parts where to concentrate: developing the software, the user interface, and building the communication between the system and the MV inspection.

### 5.1.1. Software

The software structure follows the flow chart of Figure 5.1. The inspection starts with communication step. NI 1774C camera is running Modbus TCP server which has a holding register. The device the camera is communicating with is called S1000. In this specific communication the camera works as Modbus slave, and S1000 as Modbus master. It means that camera has register from where it can receive values, or to which it can update values. From 50 values of the register 15 values are updated by S1000 and 35 values are updated by the camera. S1000 is scanning the register of the camera with interval of 1000ms, and with every loop it updates new values if needed, and receives updated values if those are changed. The values in the register can be seen in Table 5.1 and Table 5.2. In Figure 5.1 there are guard conditions. The information flow follows the default conditions automatically if any other path is not accessible. If any other path is open, the inspection follows that path. Only one path can be followed. For example the guard condition can be "trigger = 1". It means that initially the variable called trigger has value 0 (and inspection follows the default path), and when S1000 updates the trigger value to be 1, the information flow follows the changed path. In the flow chart can be seen that in the communication step the default path leads back to the communication step itself. There is a delay of 1000 ms to the end of the communication step. The communication reads the holding register values with scanning interval of 1000ms, and when the trigger value is set to be 1 it will carry on in the path.

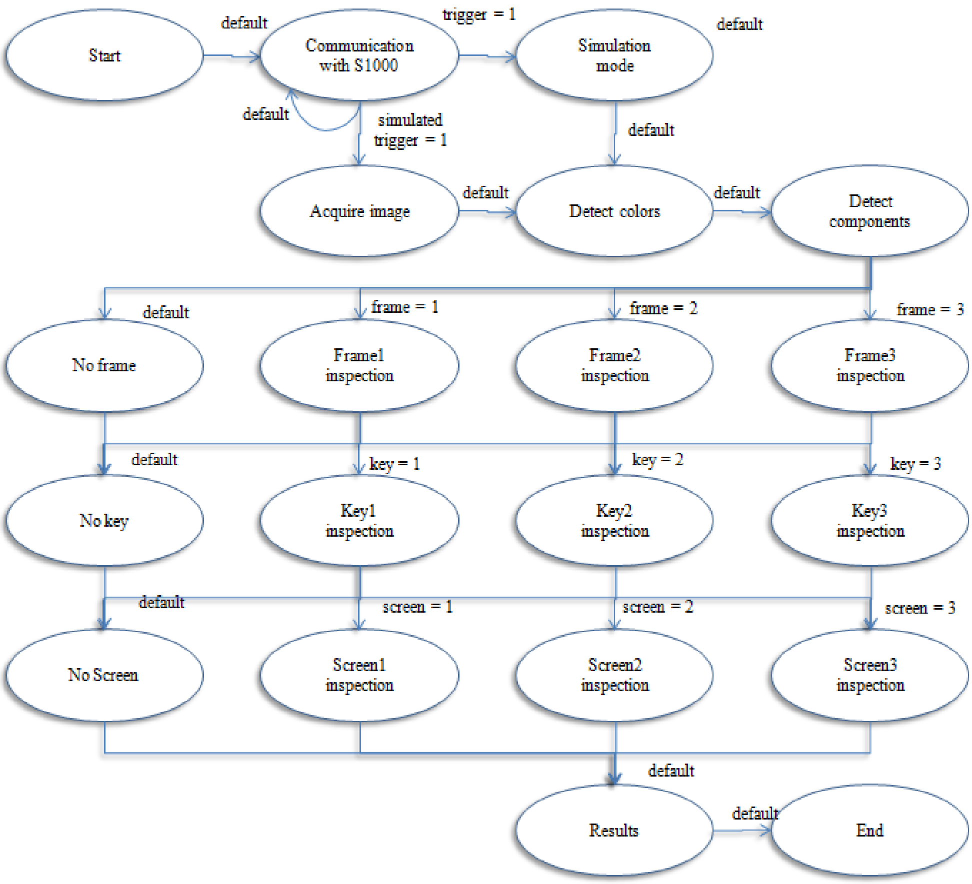


***Figure 5.1.*** *Software structure of the implemented quality inspection application.*

***Table 5.1.*** *Holding register values of NI 1774C updated by S1000.*

| Name of the variable | Register address | Description |
|---|---|---|
| trigger | 0x0 | With value 1 the application will launch, and automatically set the trigger value back to 0. |
| frame | 0x1 | No color (0), color 1, color 2, or color 3. |
| frameColor | 0x2 | No key (0), key 1, key 2, or key 3. |
| key | 0x3 | No color (0), color 1, color 2, or color 3. |
| keyColor | 0x4 | No screen (0), screen 1, screen 2, or screen 3. |
| screen | 0x5 | No color (0), color 1, color 2, or color 3. |
| screenColor | 0x6 | No frame (0), Frame 1, Frame 2, or Frame 3. |
| inspectionLevel | 0x7 | With 0 the component parameters needs to be predefined. With 1 the camera will detect the components automatically. |
| palletNo | 0x8 | Pallet number in the pallet's RFID tag |
| allowedFrameOcclusion | 0x9 | Missing lines percentage, which is allowed. |
| allowedKeyOcclusion | 0xA | Missing lines percentage, which is allowed. |
| allowedScreenOcclusion | 0xB | Missing lines percentage, which is allowed. |
| allowedFrameExtraLines | 0xC | Allowed difference with the template. |
| allowedKeyExtraLines | 0xD | Allowed difference with the template. |
| allowedScreenExtraLines | 0xE | Allowed difference with the template. |

***Table 5.2.*** *Holding register values of NI 1774C updated by NI 1774C.*

| Name of the variable | Register address | Description |
|---|---|---|
| waitForCamera | 0x20 | No use in current inspection. If needed camera can signal with this variable that the conveyor line should wait for the camera to |
| noFrameError | 0x21 | 0 = error, 1 = successful |
| goodAmountOfFrames | 0x22 | 0 = two or more frames, 1 = successful |
| frameCorrect | 0x23 | 0 = error, 1 = successful |
| frameColorCorrect | 0x9 | 0 = error, 1 = successful |
| frameOcclusionPercentage | 0x25 | Missing line percentage |
| frameOcclusionAcceptable | 0x26 | 0 = Too many lines missing, 1 = Occlusion |
| frameExtraLinesPercentage | 0x27 | How big area is covered with extra dark lines |
| frameExtraLinesAcceptable | 0x28 | 0 = Too big area 1 = Extra lines acceptable |
| noKeyError | 0x29 | 0 = error, 1 = successful |
| goodAmountOfKeys | 0x2A | 0 = two or more keys 1 = successful |
| keyCorrect | 0x2B | 0 = error, 1 = successful |
| keyColorCorrect | 0x2C | 0 = error, 1 = successful |
| keyOcclusionPercentage | 0x2D | Missing line percentage |
| keyOcclusionAcceptable | 0x2E | 0 = Too many line missing, 1 = Occlusion |
| keyExtraLinesPercentage | 0x2F | How big area is covered with extra dark lines |
| keyExtraLinesAcceptable | 0x30 | 0 = Too big area 1 = Extra lines acceptable |
| noScreenError | 0x31 | 0 = error, 1 = successful |
| goodAmountOfScreens | 0x32 | 0 = two or more screens, 1 = successful |
| screenCorrect | 0x33 | 0 = error, 1 = successful |
| screenColorCorrect | 0x34 | 0 = error, 1 = successful |
| screenOcclusionPercentage | 0x35 | Missing line percentage |
| screenOcclusionAcceptable | 0x36 | 0 = Too many line missing, 1 = Occlusion |
| screenExtraLinesPercentage | 0x37 | How big area is covered with extra dark lines |
| screenExtraLinesAcceptable | 0x38 | 0 = Too big area 1 = Extra lines acceptable |
| inspectionPassed | 0x39 | Did the quality meet the criteria |
| frameOK | 0x3A | Frame passed the inspection |
| keyOK | 0x3B | Key passed the inspection |
| screenOK | 0x3C | Screen passed the inspection |
| timeOfLastIteration | 0x3D | Time of last iteration |
| timeOfLastInspection | 0x3E | Active time when camera as inspecting during last iteration |
| timeOfLastWaiting | 0x3F | Time the camera was waiting a signal to start the inspection |
| timeOfAllIterations | 0x40 | Time of the iterations camera has done after launching the inspection |
| timeOfAllInspections | 0x41 | Active time the camera has been inspecting after launching the inspection. |
| timeOfAllWaitings | 0x42 | Time the camera has been waiting for the trigger signal totally. |

The communication state has 6 steps. In the beginning all the variables are set to 0. The variables are listed in Table 5.3. If the variables are not set to 0 old values from previous inspections might cause problems. The second block is updating the status “waiting for the trigger signal” to the user interface. The third step is reading the values from the holding register, and the fourth block creating decision does the conditions for triggering the inspection meet. The fifth step is saving the values from previous steps as variables to be used later in the inspection. The state has also delay block of 1000ms and the purpose of the delay block is to set up the scanning interval before reading the values again, and prevent the inspection for using all the available memory and processing power while looping the state.

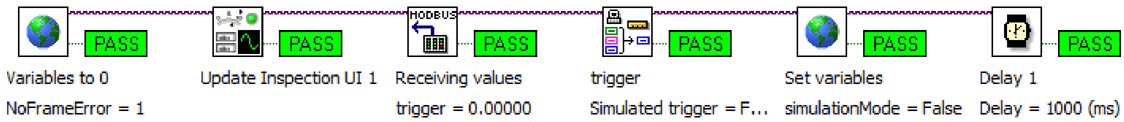


***Figure 5.2.*** *Communication state.*

***Table 5.3.*** *Variables used in the inspection.*

| Variable values received from S1000 | Variable values gained from inspection | Errors and other variables |
|---|---|---|
| S1000Frame | detectedFrame | framePath |
| S1000Key | detectedKey | keyPath |
| S1000Screen | detectedScreen | screenPath |
| S1000FrameColor | detectedFrameColor | previousPalletNo |
| S1000KeyColor | detectedKeyColor | noFrameError |
| S1000ScreenColor | detectedScreenColor | noKeyError |
| allowedFrameOcclusion | frameOcclusion | noScreenError |
| allowedKeyOcclusion | keyOcclusion | goodAmountOfFrames |
| allowedScreenOcclusion | screenOcclusion | goodAmountOfKeys |
| allowedFrameExtraLines | frameExtraLines | goodAmountOfScreens |
| allowedKeyExtraLines | keyExtraLines | timeInspected |
| allowedScreenExtraLines | screenExtraLines | timeInspectedTotal |
| inspectionLevel | | timeIterationTotal |
| palletNo | | timeWaited |
| | | timeWaitedTotal |

If the trigger value has been changed from 0 to, 1 the guard condition for moving to the second stage is fulfilled and the inspection moves to “Acquire image” state (Figure 5.3). The image is acquired with exposure time of 140ms and with gain value of 87. The illumination is done with ring shaped fluorescent light which has frequency of 50 Hz. With exposure time of 140ms the light will flash about 6 times. With high exposure time can be ensured that the illumination is in the same level in all taken pictures. Separate gain values for different colour filters has been predefined through *Measurement & Automation explorer* to be 1.682 for red channel, 0.992 for green channel and 1.703 for blue channel. With these values the background paper will appear as white and all different colours can be easily distinguished. The values received from S1000 are written to the screen, and to the UI, so the user knows that the transfer of the information was successful and the comparison of the inspection results is easier.

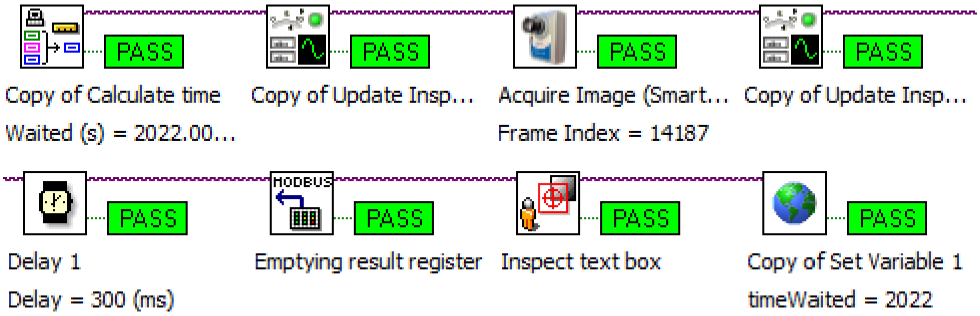


***Figure 5.3.*** *Acquire image state.*

Alternative for the "acquire image" state is "simulate acquisition" state where the image is retrieved from a file saved in the cameras memory. The simulated acquisition can be triggered from the user interface. After image acquisition the application will detect the colours of the components. The first step in defining component colour is finding the component. It will be done with "detect line" tool which is inserted to the area of the component. When line is detected 4x4 pixels area is separated and the histogram of the area is measured. The same procedure is repeated for all the components (frame, key and screen). After the histogram measurements a calculator will compare the red, green and blue values and return the highest value for each component. The value is saved as a variable (detectedFrameColor, detectedKeyColor, detectedScreenColor) to be used later in the inspection.

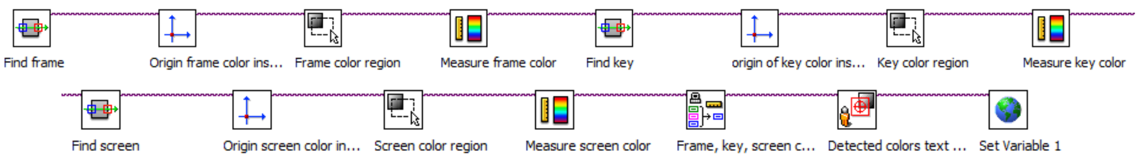


***Figure 5.4.*** *Detect colors block.*

In the previous version of the inspection the user could choose what level of inspection would be performed. The slowest inspection takes around 8 seconds which is fast enough, and that's why all the lighter inspections were deleted, and currently the user can choose only one possible inspection where components are detected, and missing lines and extra lines are calculated.

After detecting the colours the inspection detects the components present in the picture. In "detect components" step the inspection will set areas of interests for the frame, key and screen, and try to match all the frame, key and screen variations inside the ROIs. The match is done with geometric matching tool which finds lines in the picture and compares the lines with lines in given template. The matching is done as quickly as possible to save inspection time but still the matching needs to be accurate enough to detect only components which are in the picture. Because for example the frames have similar features, it is possible that the matching tool will confuse the frames. In Figure 5.5 is shown the “Curve” tab from the setup of the geometric matching tool. The settings for the curve can be seen from the figure. The step sizes are set to be bigger than the suggested values to fasten up the inspection. In “Main” tab is the name of the inspection, and inspection ROI (frame area set in previous tool). In the “Template” tab is shown the template used in the inspection. In this inspection an image which has been validated visually adequate is used as a template. It is possible to use an image of the original curves the robot was set to draw. In this way could be inspected how well the robot has succeeded in drawing the curves. The problem is that the geometric matching tool will accept only image files as templates, and that’s why the curves need to be converted to an image file where the line intensity, image scale, and image rotation might vary from the acquired image. If the purpose of the inspection is to verify that the components posses all the needed lines, it is better to use one robot drawn picture as the template. If the purpose is to validate the accuracy of the robot, it is better to use a template built from the original .svg file (the file that has the curves the robot was programmed to draw).

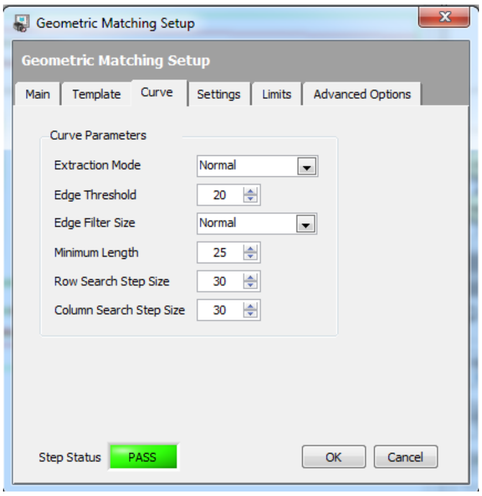


***Figure 5.5.*** *Setup for the geometric matching tool.*

In the settings tab (Figure 5.6) is defined how easily the matching tool will succeed in matching. The minimum score range is from 0 to 1000. In the “Detect components” step the minimum score is set to be 900, so the component may have small defects but only the correct component is detected. The component might have also some rotation or occlusion. If the occlusion is set to be higher than 30 the inspection might detect frame 3 and frame 1 when the actual component is frame 1. With the occlusion of 30 the component might lack some lines but it will still be detected.

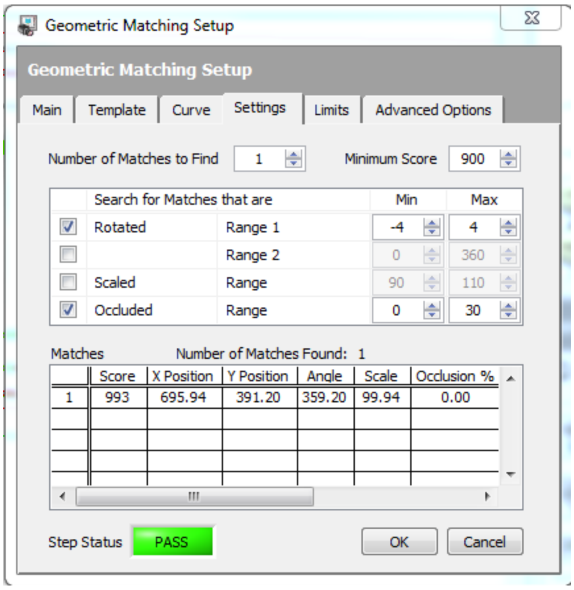


***Figure 5.6.*** *The settings tab of the geometric matching tool.*

In the "Limits" tab it is set that the minimum number of the matches to be found is exactly 1. In the "Advanced Options" tab (Figure 5.7) is set that the algorithm used is "Edge Based". When some lines might be missing the edge based algorithm founds match better than feature based algorithm. The search strategy is set to be aggressive so the matching is done as fast as possible. The contrast reversal is original because the images can appear only in white background. There is no need for computing target template curve score so the target template curve score box is unchecked.

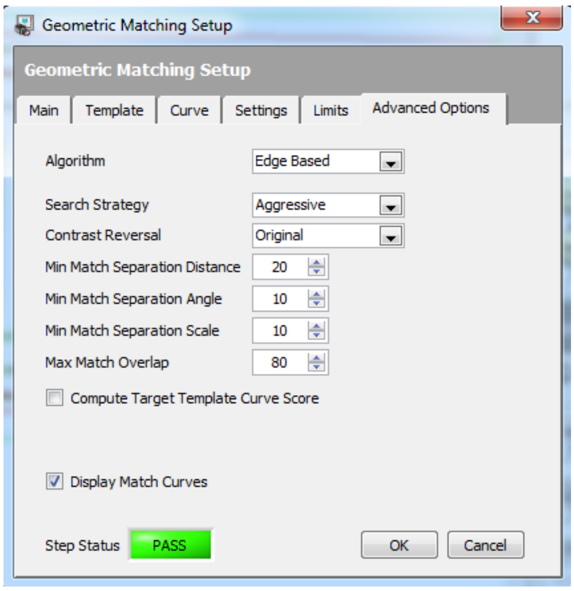


***Figure 5.7.*** *The "Advanced Options" tab in the geometric matching tool.*

If some of the components will match the result is saved to variables to be used later in the inspection. If the S1000 sent only 0 values for the components to be inspected, the inspection will inspect the components it found from the picture. If the S1000 set frame, key and screen values to be something else than 0, the inspection will follow those values. The found components are displayed to the screen. The inspection will notify if several frames, keys or screens are detected and the inspection will fail.

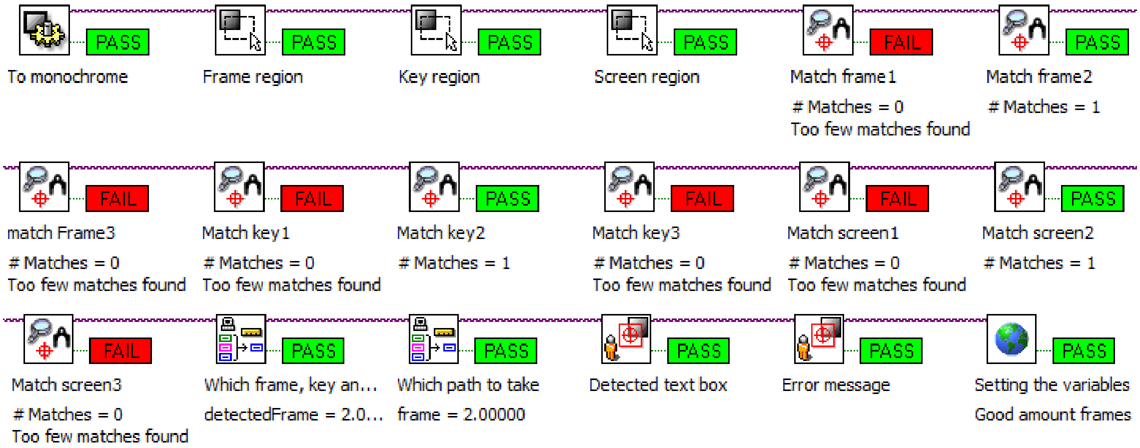


***Figure 5.8.*** *Detect components block.*

After detecting the components comes individual component inspections. If the components were predefined by S1000, the inspection will inspect the components the S1000 updated to the holding register, and if not, the inspection will inspect the components found in “Detect Components” step.

The individual component inspection sequence can be seen in Figure 5.9. The occlusion inspection (detecting missing lines) is done with geometric pattern matching tool. To the tool is uploaded a template, and the tool will inspect how well the given picture will match the template. The approved minimum match score is set to be 800 and the occlusion is set to be 50, so the inspection will recognize the component even it would have several lines missing. The calculated occlusion percentage of the match will increase when more lines are missing. The occlusion percentage is saved as a variable, and used in results part. Also extra lines in the picture are inspected. The geometric matching tools will save the exact coordinates of the component, so “Detect defects” tool can compare a template and the acquired picture pixel by pixel. If in the picture there are 50 units (the scale is from 0-255) darker pixels than in the original template, a defect is marked to the screen. In this way are extra markings or lines can be detected. The results are saved as variables to be used later in the inspection.

The inspection of all the components will follow the same pattern. After inspecting the frame the inspection moves to key inspection, and after that to screen inspection.

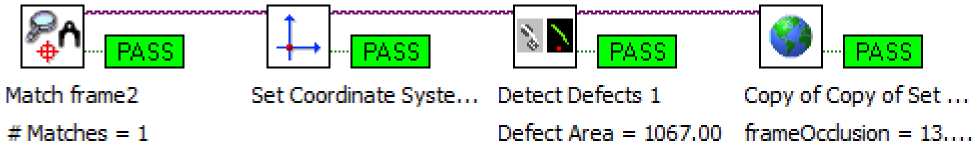


***Figure 5.9.*** *Inspecting occlusion and extra lines of individual components.*

After all the components have been inspected the inspection moves to results state. In the results state all the gained information is processed and updated to the user interface and to the Modbus TCP register. The data is also logged to the camera's memory.

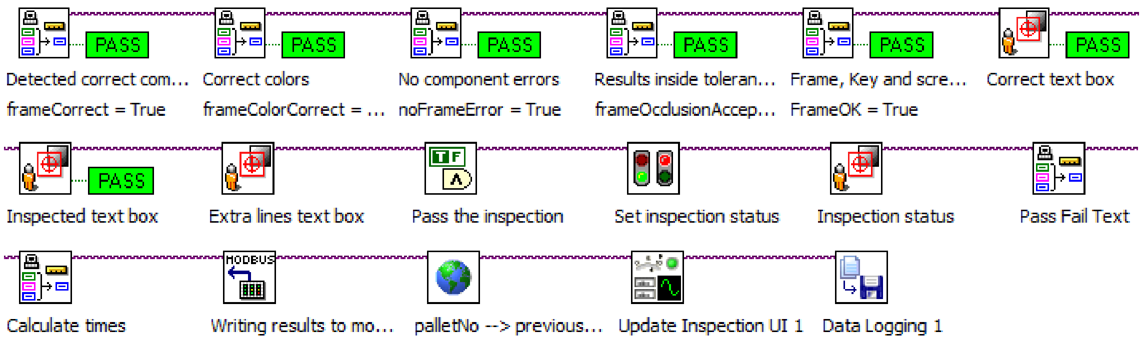


***Figure 5.10.*** *Results block.*

### 5.1.2. The user interface

The assembly line has several machines, and most of them communicate by using web services. Inico's S1000 is a programmable remote terminal unit (RTU) device which is capable of communicating with robots, conveyor line and other devices by using digital or analogue inputs and outputs, Modbus, RS-232 or wireless technologies. S1000 can host a web page which works as an UI for configuring and controlling the devices. The same S1000 which is controlling the conveyor line is also controlling the camera.

The camera itself has a possibility to host a web server. The web server is launched automatically when the application is launched. It will consume some memory and processing power, and if there is a need to increase the processing speed, the web server can be turned off. The web server hosts a web page at the address of the cameras IP (http:192.168.1.8). To be able to open the application the web server is hosting, a LabView run-time engine add-on is needed to be installed to the browser. When the web page is accessed with a computer with privileges to view or control the inspection, the needed add-ons are installed automatically. Figure 5.11 and Figure 5.12 are showing the UI which is composed of 5 different parts.

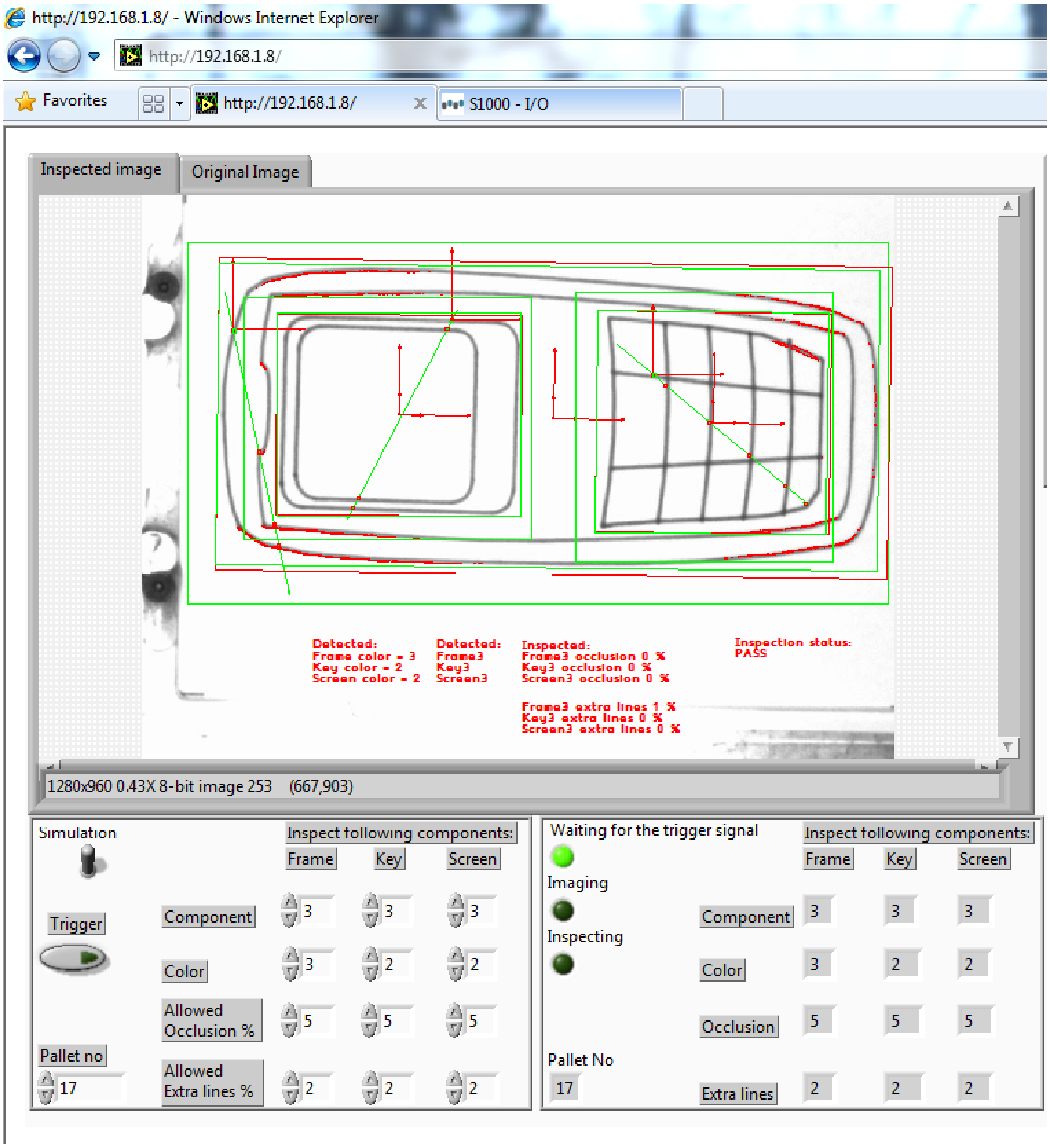


***Figure 5.11.*** *Left side of the inspection interface through Internet Explorer 32-bit.*

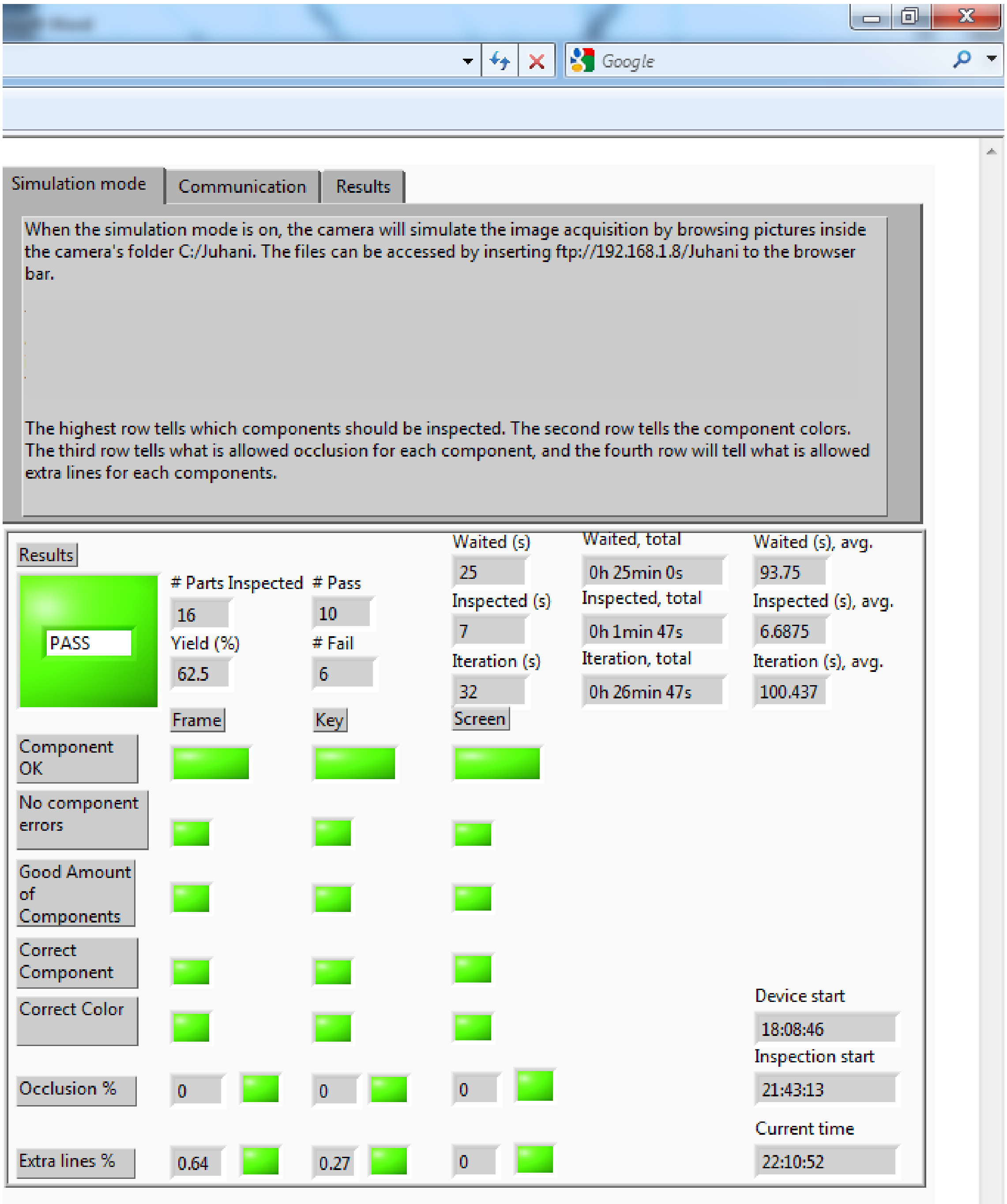


***Figure 5.12.*** *Right side of the inspection interface through Internet Explorer 32-bit.*

The first and the biggest part is the picture box (Figure 5.11). The picture box has two tabs: The inspected image, and the original image. The second part is the simulation controls (Figure 5.11). There are 15 controls from which can be defined which components to search, which colours the components should have, and what are the tolerances for occlusion and extra lines. From a switch can be defined that the camera is in simulation mode, and from a trigger button the simulation mode can be triggered. When the simulation mode is on the camera is simulating the inspection by browsing pictures in the cameras folder. If 0 is inserted to components and the component colours, the inspection will automatically detect the components in the picture, and do the inspection for the detected components.

The third part is indicator part (Figure 5.11). It indicates the state of the inspection, and which values the inspection has received. If the simulation mode is on, the values are received from the simulation controls. If the simulation mode is not on, the values are received from the dedicated S1000.

The fourth part of the UI is the results (Figure 5.12). In the results there are 44 indicators from which 28 are communicating the results of one single inspection, 4 are communicating general statistics of all inspections, and 12 are communicating time variables related to the inspections. The fifth part of the UI is instructions (Figure 5.12). The instruction sheet has several tabs, and the user can gain some general knowledge about the inspection by browsing and reading the tabs.

### 5.1.3. Communication

The communication between the system and the camera happens through S1000. The camera is running a Modbus TCP server which has holding register. S1000 scans the holding register with frequency of 1000 ms. S1000 has capability to read or write to the register. The input values coming from S1000 are written to the holding register for the places 1-32, and the outputs from the camera are read from the holding register from the places 33-67. In the S1000 is running a web server which hosts a web page in the IP address of the S1000. S1000 is running also a web service called "InspectionService", and any machine in the intranet can subscribe to that service. Every time the camera has finished an inspection the web service publishes the results in the form defined in the inspection service's .wsdl file (Web Services Description Language). The published message can be seen by anybody who has subscribed to the service. More information on the web services in factory environment can be found from [45] .

## 5.2. Test runs

The system was tested and benchmarked in three ways: running the inspection in NI1774C using ready taken pictures, running the inspection in work laptop using the same inspection and same pictures, and running the inspection in the production line. Also older National Instrument's smart camera (NI 1742) was tested but because of lack of performance the camera couldn't run the inspection.

The NI1774C used in average 8.57 seconds in processing an image. It detected the component colours, detected the components, calculated the occlusion for each component, and calculated the extra lines in each component area. After that it logged the results to a separate .csv file. When the web server and the UI was disabled, and all the delay blocks were deleted (1.3 s), the average inspection took 6.95 seconds. In Appendix 2 are presented the used pictures and the results the inspection gained after inspecting the pictures. Almost every single picture produced by the production line passed the inspection. The most general quality errors of the inspection line were drawing too many components to a single picture, a robot cut a corner, and small missing lines. Most of the defects were software based errors which were easy to fix. Because of low amount of defects some artificial defects needed to be made, and those were created by inserting white paper over the drawing. In this way the camera was picturing white area where there should be colour, and was reporting the area as a missing line. Part was rejected if any component had more than 5% of missing line, or 2 % difference with the template the component was compared to. The results were very close to the expected results and are indicating that the system works well and is fulfilling the expectations.

## 5.3. Acceptance test

The acceptance tests were performed on 2.2.2012. The whole production line was initiated and the system was tested with several pallets. The camera was able to perform the inspections like intended, and the dedicated RTU S1000 was publishing the inspection results. It was possible to follow the inspection in real-time from any computer in the same local area network by typing the camera IP to the address bar.

## 5.4. Training and documentation

This thesis works mostly as the documentation of the inspection. Inspection manual and more detailed instructions for using the different defect detection tools were also written, and those can be found from the FAST laboratory.

# 6. CONCLUSIONS

The thesis if offering valuable information how to control and communicate in industrial environment by using web service based technologies. The advantage in this approach is interoperability of the inspection service; prior knowledge of the technologies used in the service is not needed. The required information can be received by requesting and reading the wsdl (web service definition language) file of the service. The request and reading can happen with any XML based service. The implementation uses flexible software and the modularity of the system is highlighted: the whole system can be physically relocated, or rebuilt in a short period of time. All the communication happens through Ethernet which reduces the amount of wiring. The INICO S1000 controller works well with the smart camera but uses old communication standard (Modbus TCP) which requires regular scanning but on the other hand it proves the retrofit of the system. The web service could have been built directly to the server of the smart camera, and it would have reduced the part count. The whole assembly line is using similar INICO S1000 controllers so by using a similar device the compatibility was ensured. Also implementing the web service to the web server of the camera would have required bigger efforts in building of the program, and the program would have used some of the memory and the processing power of the camera, and for these reasons the approach would have been unpractical.

Due to research environment some system requirements were more easily reached. In real industrial application the testing of the system would have been more intensive and the cost calculations and ROI would have needed bigger attention. Currently the machine vision system publishes the inspection results in high detail and utilization of these results requires more research and investments through running big patch sizes, analyzing the results, and modifying the system to be able to react to noticed quality flaws. The inspection could also inspect the accuracy of the robots and performance of the algorithms that are decoding the svg files to perform robot arm movements. Now the focus is on detecting the flaws deriving from incorrect communication, failure of the feeding and exit point of the conveyor line, mechanical failures, or faulty markers. This thesis proves the web service based approach to be practical and further research in real industrial environment would be needed, so the robustness of the system could be proven and the advantages of the approach could be fully utilized.

The state of the art pays attention to the research field and to the industrial field. Industrial smart camera manufacturers have been focusing on improving the performance by improving processing power, memory, and other components. Protective IP67 casing has been added to most of the industrial smart cameras (National Instruments, Cognex, Sick, Teledyne Dalsa, Ximea) allowing them to be used in harsh environment. Naturally the development of the used algorithms and usability of the systems is continuously increasing.

The research of smart cameras is focused on the advantages of smart camera systems (the size of the system, energy efficiency, networking of several smart cameras), or increasing the hardware and software performance of smart cameras so the system can perform the same tasks as more complex and bigger systems (3D feature tracking and stereo vision, object tracking, demanding quality inspection tasks). New innovations have been released especially on power consumption allowing the smart cameras to be battery operated and communicate through wireless channels. Some research groups have found ways to reduce the bill of materials of a smart camera to very low, and it indicates that in the future the price of industrial smart cameras might be decreasing dramatically. When smart cameras are getting smaller and cheaper, it makes the camera to more attractive option to solve the vision tasks. Sold units of smart cameras can be expected to get high simultaneously boosting the smart camera related research. In object detection 3D based algorithms are significantly more robust than 2D based algorithms for instance due to ground plane assumptions. If the processing of the images is done in the proximity of the imaging devices, the need for data transfer, part count, and energy consumption is significantly lower when compared to traditional solutions. That is the reason why smart cameras are ideal solutions in many 3D mapping and stereovision tasks. The technology for inexpensive 3D smart cameras already exists but their arrival of to the markets is yet to be seen. As a market point of view China is especially interesting for smart camera applications due to highly growing economy, and even more rapidly growing automation sector.

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# APPENDIX 1: CHECKLIST FOR DESIGNING A MACHINE VISION SYSTEM

## General

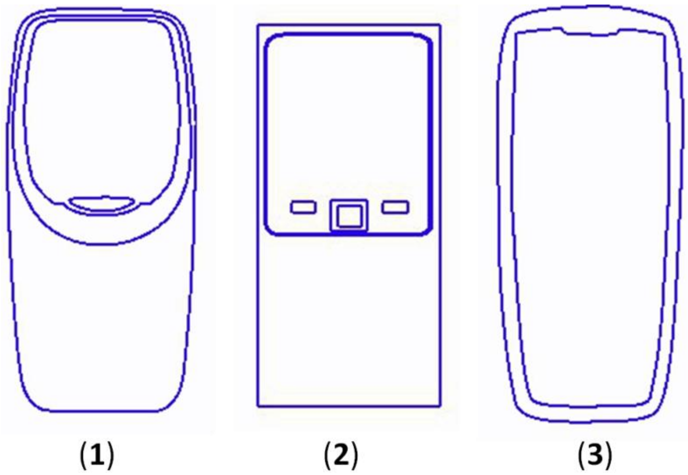
| | |
|---|---|
| Date: | 15.2.2012 |
| Company: | FAST Laboratory |
| Contact person: | |
| Department: | Production Engineering |
| City: | Tampere |
| Zip code: | 33720 |
| Street: | Korkeakoulunkatu 5 |
| Phone: | |
| E-mail: | |

## Task

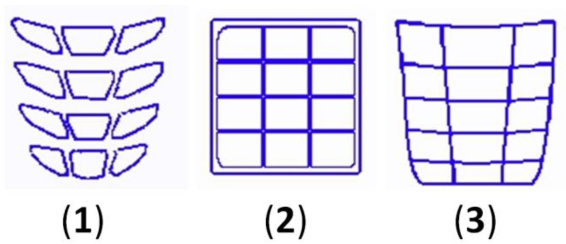
| | |
|---|---|
| Description of the task and benefits: | The task is to do quality inspection for the end product of a manufacturing line, and offer information which can used to increase the quality, and to define does an individual end product pass the quality criteria. The task will supplement the overall goal of eSonia project, the factory of the future. |
| Size of the smallest feature to be detected: | 0.5 mm |
| Required accuracy: | 3 pixels |
| 100% inspection: | Yes |
| Offline inspection: | Yes |
| Retrofit: | Yes |
| Random control: | no |
| In-line inspection: | Yes |
| New design: | Yes |

**Parts**

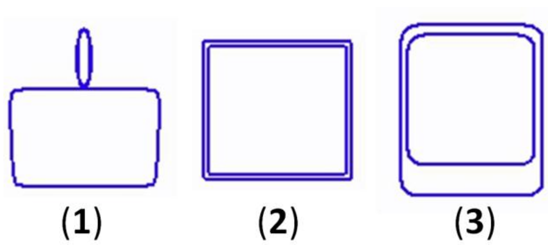
Description of parts:



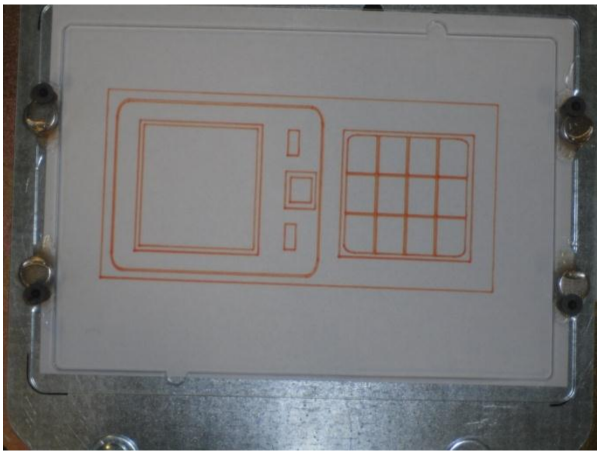

*Frame variations.*




*Keyboard variations.*




*Screen variations.*



*An example of the object.*

| | |
|---|---|
| Discrete parts: | Yes |
| Dimensions (min,max): | Min: 0.5 mm ; Max: 120 mm |
| x-dimension: | 0.5 mm to 120 mm |
| y-dimension: | 0.5 mm to 60 mm |
| z-dimension (depth): | 2 mm |
| Surface finish: | No |
| Color: | Red, Green, Blue |
| Corrosion, adhesives: | No |
| Changes due to handling: | No |
| Number of part types: | 3x3x3x3=81 |
| Difference of parts: | Shape and colour |
| Batch production: | No |
| Can production change be addressed: | Yes |

## Part presentation

| | | | |
|---|---|---|---|
| Indexed positioning: | yes | Time of non-movement: | 20 s |
| Tolerances in positioning: | | | |
| x-dimension: | 5 mm | | |
| y-dimension: | 5 mm | | |
| z-dimension: | 2 mm | | |
| Rotation about x: | - | | |
| Rotation about y: | - | | |
| Rotation about z: | 5 degrees | | |
| Number of parts in view: | 1 | | |
| Overlapping parts: | no | | |
| Touching parts: | no | | |

## Time requirements

| | |
|---|---|
| Maximum processing time: | 20 seconds |
| Processing time is variable in tolerances: | 5 - 20 seconds |

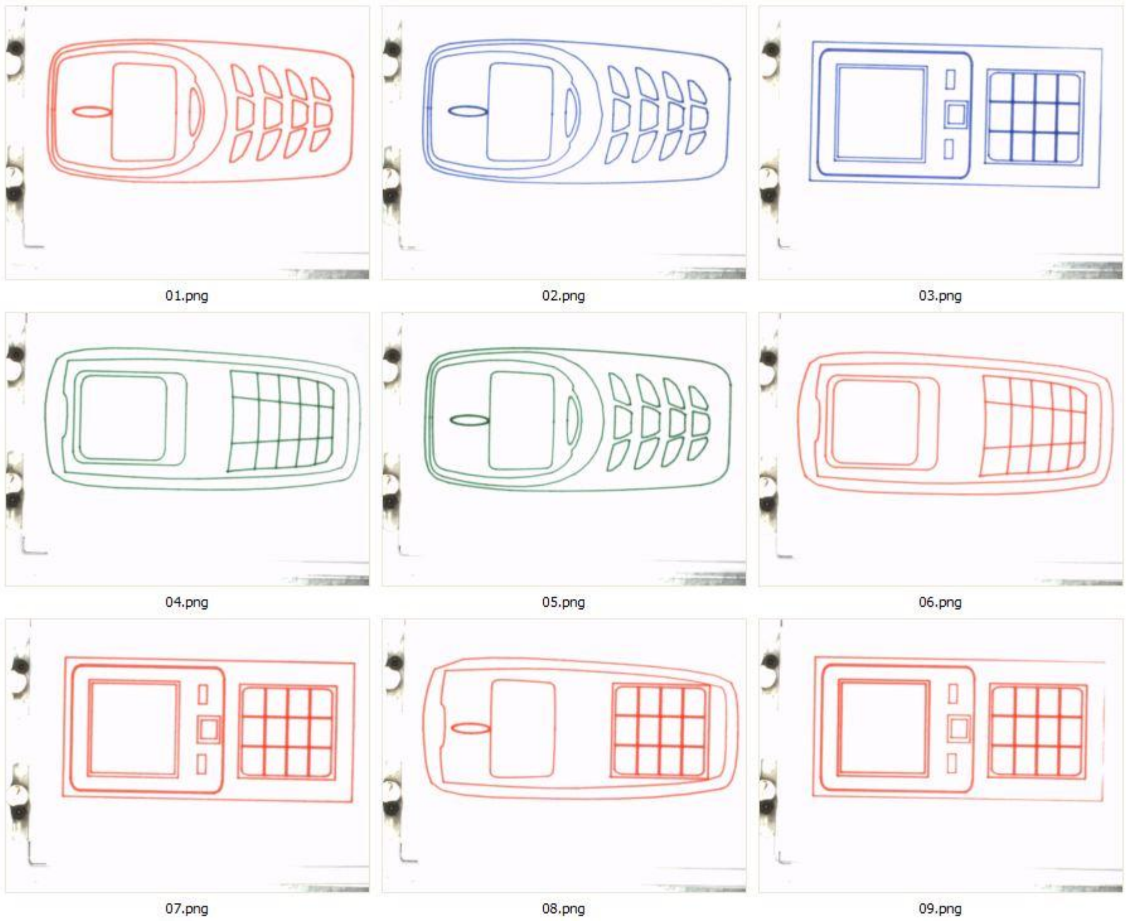
## Information interfaces

| | |
|---|---|
| Manual trigger: | No |
| Automatic trigger: | Yes |
| What information has to be passed by interfaces: | Components, component colours |
| What interfaces are necessary: | Digital I/O |
| | TCP/IP |
| | Fieldbus |
| Requirements for user interface: | Visualization of components |
| | Visualization of received values |
| | Visualization of results |

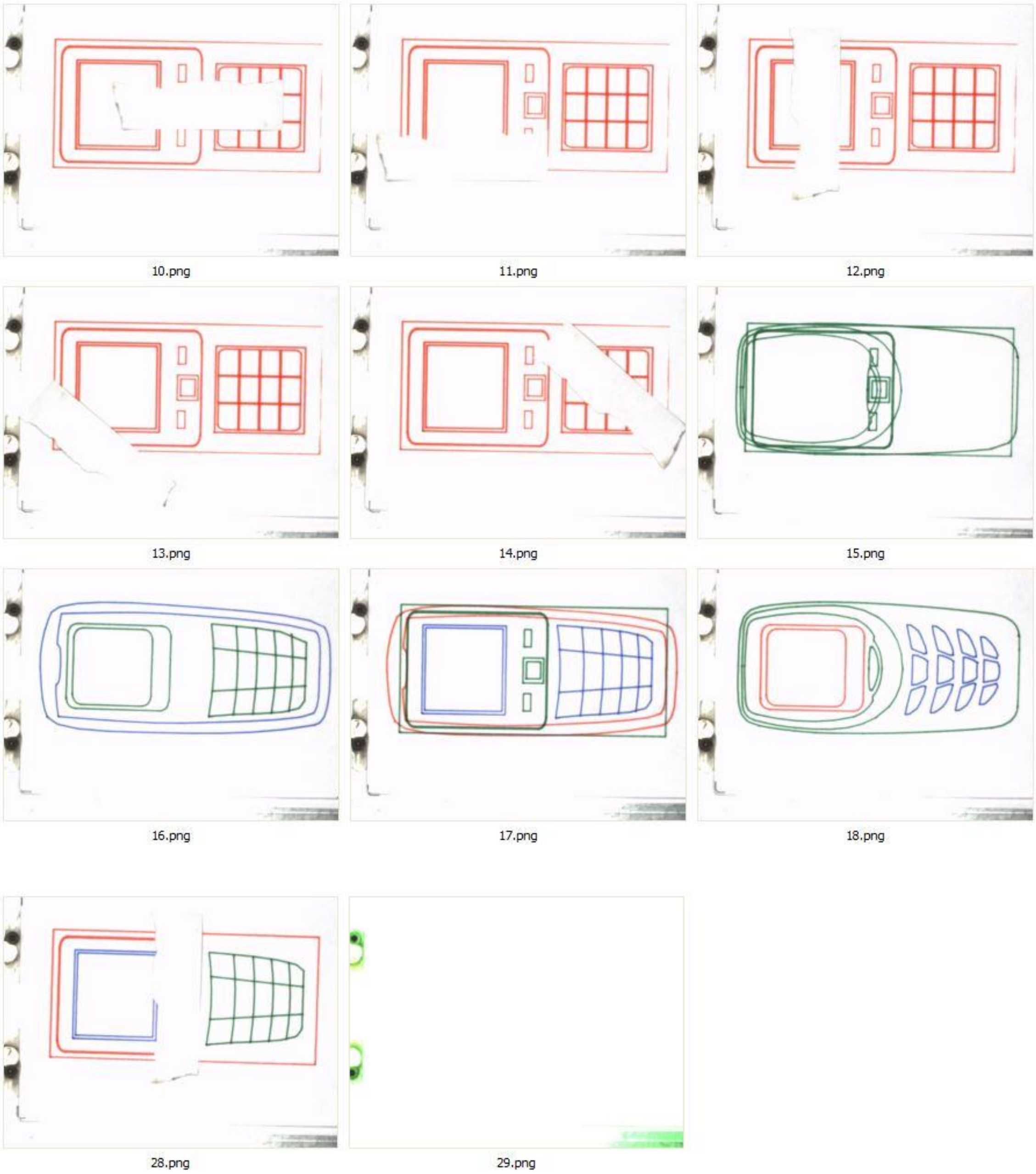
## Miscellaneous

| | |
|---|---|
| Installation space: | |
| x-dimension: | 500 mm |
| y-dimension: | 200 mm |
| z-dimension: | 1000 mm |
| Maximum distance between camera and PC: | Smart Camera |
| Ambient light: | Sun through windows, |
| | light tubes in the ceiling |
| Protection class: | From ambient light |
| Dirt or dust: | No |
| Schock or vibration: | No |
| Variations in temperature: | No |
| Electromagnetic influences: | No |

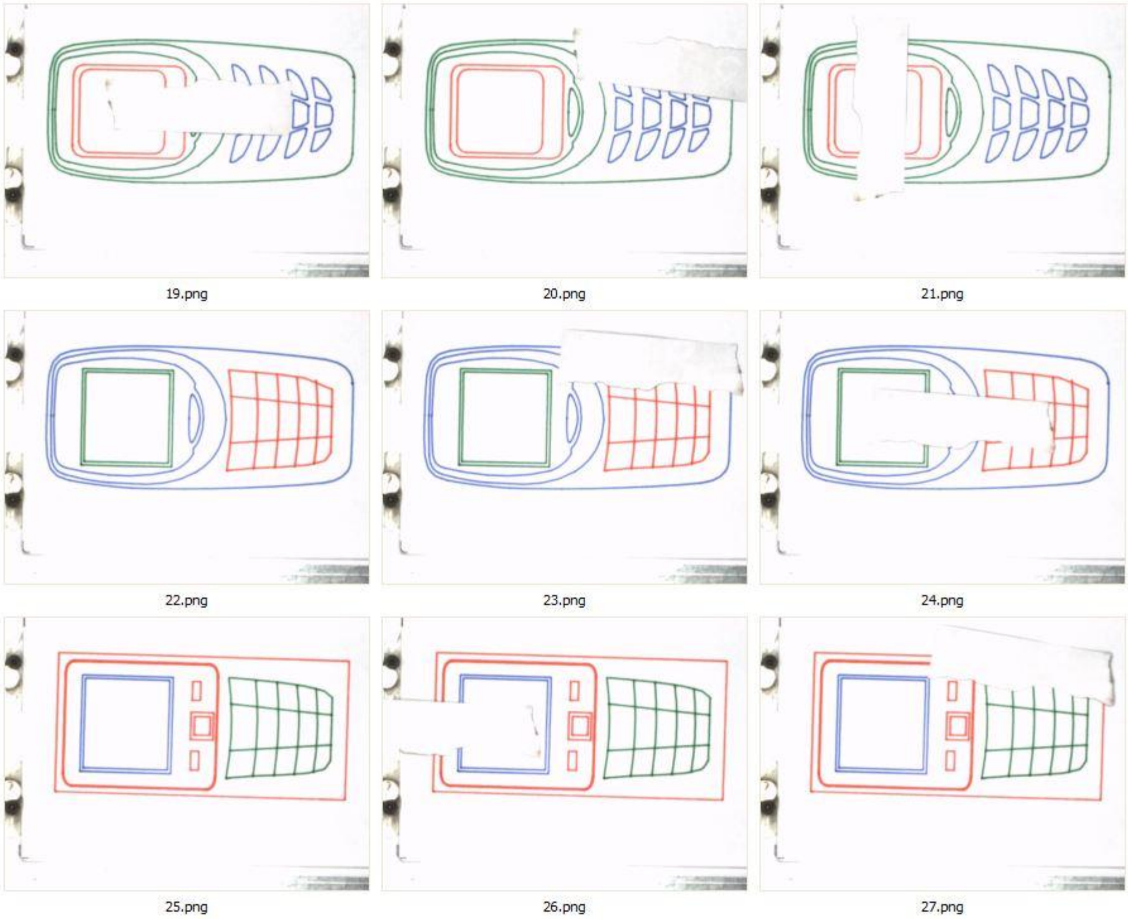
# APPENDIX 2: TEST RUN PICTURES AND RESULTS




*Pictures used in test runs, part 1.*




*Pictures used in test runs, part 2.*




*Pictures used in test runs, part 3.*

*Results of the test runs, part 1.*

| | | Time (s) | | | Detected component | | | Detected color | | | No dublicates | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| File | Status | Active | Idle | Total | Frame | Key | Screen | Frame | Key | Screen | Frame | Key | Screen |
| 01.png | Pass | 7.236 | 1.4 | 8.6 | 1 | 1 | 1 | 1 | 1 | 1 | TRUE | TRUE | TRUE |
| 02.png | Pass | 7.285 | 1.3 | 8.56 | 1 | 1 | 1 | 3 | 3 | 3 | TRUE | TRUE | TRUE |
| 03.png | Pass | 8.124 | 1.4 | 9.49 | 2 | 2 | 2 | 3 | 3 | 3 | TRUE | TRUE | TRUE |
| 04.png | Pass | 7.322 | 1.3 | 8.59 | 3 | 3 | 3 | 2 | 2 | 2 | TRUE | TRUE | TRUE |
| 05.png | Pass | 7.373 | 1.2 | 8.56 | 1 | 1 | 1 | 2 | 2 | 2 | TRUE | TRUE | TRUE |
| 06.png | Pass | 7.582 | 1.4 | 8.94 | 3 | 3 | 3 | 1 | 1 | 1 | TRUE | TRUE | TRUE |
| 07.png | Pass | 7.81 | 1.4 | 9.18 | 2 | 2 | 2 | 0 | 1 | 1 | TRUE | TRUE | TRUE |
| 08.png | Pass | 7.585 | 1.4 | 8.96 | 3 | 2 | 1 | 1 | 1 | 1 | TRUE | TRUE | TRUE |
| 09.png | Pass | 7.979 | 1.5 | 9.44 | 2 | 2 | 2 | 0 | 1 | 1 | TRUE | TRUE | TRUE |
| 10.png | Fail | 6.453 | 1.5 | 7.98 | 2 | 0 | 2 | 0 | 1 | 1 | TRUE | TRUE | TRUE |
| 11.png | Fail | 7.028 | 1.4 | 8.42 | 2 | 2 | 0 | 1 | 1 | 1 | TRUE | TRUE | TRUE |
| 12.png | Fail | 7.71 | 1.4 | 9.08 | 2 | 2 | 2 | 0 | 1 | 1 | TRUE | TRUE | TRUE |
| 13.png | Fail | 7.397 | 1.4 | 8.76 | 2 | 2 | 2 | 1 | 1 | 1 | TRUE | TRUE | TRUE |
| 14.png | Fail | 6.837 | 1.4 | 8.21 | 2 | 0 | 2 | 0 | 0 | 1 | TRUE | TRUE | TRUE |
| 15.png | Fail | 6.238 | 1.4 | 7.63 | 3 | 0 | 0 | 2 | 0 | 0 | FALSE | TRUE | TRUE |
| 16.png | Pass | 7.64 | 1.2 | 8.83 | 3 | 3 | 3 | 3 | 2 | 2 | TRUE | TRUE | TRUE |
| 17.png | Fail | 7.07 | 1.3 | 8.36 | 5 | 3 | 2 | 1 | 3 | 3 | FALSE | TRUE | TRUE |
| 18.png | Pass | 7.689 | 1.3 | 9.03 | 1 | 1 | 3 | 2 | 3 | 1 | TRUE | TRUE | TRUE |
| 19.png | Fail | 7.116 | 1.4 | 8.49 | 1 | 1 | 3 | 2 | 3 | 1 | TRUE | TRUE | TRUE |
| 20.png | Fail | 7.586 | 1.3 | 8.84 | 1 | 1 | 3 | 2 | 3 | 1 | TRUE | TRUE | TRUE |
| 21.png | Fail | 6.895 | 1.3 | 8.24 | 1 | 1 | 0 | 2 | 3 | 1 | TRUE | TRUE | TRUE |
| 22.png | Pass | 7.545 | 1.3 | 8.82 | 1 | 3 | 2 | 3 | 1 | 2 | TRUE | TRUE | TRUE |
| 23.png | Fail | 7.072 | 1.5 | 8.52 | 1 | 3 | 2 | 3 | 1 | 2 | TRUE | TRUE | TRUE |
| 24.png | Fail | 7.139 | 1.3 | 8.43 | 1 | 3 | 2 | 3 | 1 | 2 | TRUE | TRUE | TRUE |
| 25.png | Pass | 7.236 | 1.5 | 8.69 | 2 | 3 | 2 | 1 | 2 | 3 | TRUE | TRUE | TRUE |
| 26.png | Fail | 7.374 | 1.4 | 8.79 | 2 | 3 | 2 | 2 | 2 | 3 | TRUE | TRUE | TRUE |
| 27.png | Fail | 7.532 | 1.3 | 8.8 | 2 | 3 | 2 | 1 | 2 | 3 | TRUE | TRUE | TRUE |
| 28.png | Fail | 5.941 | 1.2 | 7.13 | 0 | 3 | 2 | 1 | 2 | 3 | TRUE | TRUE | TRUE |
| 29.bmp | Fail | 5.941 | 1.2 | 7.13 | 0 | 0 | 0 | 0 | 0 | 0 | TRUE | TRUE | TRUE |

*Results of the test runs, part 2.*

| | | Missing lines (%) | | | Occlusion acceptable | | | Difference with template | | | Extra lines acceptable | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| File | Status | Frame | Key | Screen | Frame | Key | Screen | Frame | Key | Screen | Frame | Key | Screen |
| 01.png | Pass | 0 | 0 | 0 | TRUE | TRUE | TRUE | 0 | 0 | 0 | TRUE | TRUE | TRUE |
| 02.png | Pass | 0 | 0 | 0 | TRUE | TRUE | TRUE | 0.798 | 0 | 0 | TRUE | TRUE | TRUE |
| 03.png | Pass | 0 | 1.173 | 0 | TRUE | TRUE | TRUE | 0 | 0 | 0 | TRUE | TRUE | TRUE |
| 04.png | Pass | 0 | 0 | 0 | TRUE | TRUE | TRUE | 0 | 0 | 0 | TRUE | TRUE | TRUE |
| 05.png | Pass | 0 | 0 | 0 | TRUE | TRUE | TRUE | 0.122 | 0 | 0 | TRUE | TRUE | TRUE |
| 06.png | Pass | 0 | 0 | 0 | TRUE | TRUE | TRUE | 0.692 | 0.0101 | 0 | TRUE | TRUE | TRUE |
| 07.png | Pass | 0 | 4.578 | 0 | TRUE | TRUE | TRUE | 0.037 | 0 | 0.0024 | TRUE | TRUE | TRUE |
| 08.png | Pass | 0 | 3.685 | 0 | TRUE | TRUE | TRUE | 0.153 | 0.5441 | 0 | TRUE | TRUE | TRUE |
| 09.png | Pass | 1.385 | 2.066 | 0 | TRUE | TRUE | TRUE | 0.007 | 0.5003 | 0.03275 | TRUE | TRUE | TRUE |
| 10.png | Fail | 13.46 | 0 | 11.25 | FALSE | TRUE | FALSE | 0.191 | 0 | 0.26998 | TRUE | TRUE | TRUE |
| 11.png | Fail | 27.45 | 2.401 | 0 | FALSE | TRUE | TRUE | 0.079 | 0.7098 | 0 | TRUE | TRUE | TRUE |
| 12.png | Fail | 13.42 | 1.843 | 25.54 | FALSE | TRUE | FALSE | 0.023 | 1.0851 | 0.5783 | TRUE | TRUE | TRUE |
| 13.png | Fail | 18 | 1.843 | 16.96 | FALSE | TRUE | FALSE | 0.059 | 0.8855 | 0.30912 | TRUE | TRUE | TRUE |
| 14.png | Fail | 5.895 | 0 | 0 | FALSE | TRUE | TRUE | 0.18 | 0 | 0.01118 | TRUE | TRUE | TRUE |
| 15.png | Fail | 48.3 | 0 | 0 | FALSE | TRUE | TRUE | 5.221 | 0 | 0 | FALSE | TRUE | TRUE |
| 16.png | Pass | 0 | 0 | 0 | TRUE | TRUE | TRUE | 0.637 | 0.2719 | 0 | TRUE | TRUE | TRUE |
| 17.png | Fail | 0 | 0 | 0 | TRUE | TRUE | TRUE | 0 | 0.0295 | 0 | TRUE | TRUE | TRUE |
| 18.png | Pass | 0 | 0 | 0 | TRUE | TRUE | TRUE | 1.601 | 0 | 0.18819 | TRUE | TRUE | TRUE |
| 19.png | Fail | 10.27 | 28.47 | 12.42 | FALSE | FALSE | FALSE | 0.125 | 0.9723 | 0.4479 | TRUE | TRUE | TRUE |
| 20.png | Fail | 10.4 | 18.19 | 0 | FALSE | FALSE | TRUE | 2.351 | 0.6198 | 0.18541 | TRUE | TRUE | TRUE |
| 21.png | Fail | 15.74 | 0 | 0 | FALSE | TRUE | TRUE | 0.901 | 0 | 0 | TRUE | TRUE | TRUE |
| 22.png | Pass | 0 | 0 | 0 | TRUE | TRUE | TRUE | 0.002 | 0.2847 | 0.00479 | TRUE | TRUE | TRUE |
| 23.png | Fail | 12.68 | 14.74 | 0 | FALSE | FALSE | TRUE | 0.048 | 0.4814 | 0.00559 | TRUE | TRUE | TRUE |
| 24.png | Fail | 9.966 | 18.34 | 12.77 | FALSE | FALSE | FALSE | 0.014 | 1.3924 | 0.02476 | TRUE | TRUE | TRUE |
| 25.png | Pass | 0 | 0 | 0 | TRUE | TRUE | TRUE | 0.087 | 0 | 0.00879 | TRUE | TRUE | TRUE |
| 26.png | Fail | 6.463 | 0 | 12.05 | FALSE | TRUE | FALSE | 0.176 | 0.0067 | 0.22525 | TRUE | TRUE | TRUE |
| 27.png | Fail | 14.7 | 12.41 | 0 | FALSE | FALSE | TRUE | 0.278 | 0.6915 | 0.01118 | TRUE | TRUE | TRUE |
| 28.png | Fail | 0 | 0 | 10.27 | TRUE | TRUE | FALSE | 0 | 0 | 0.0671 | TRUE | TRUE | TRUE |
| 29.bmp | Fail | 0 | 0 | 0 | TRUE | TRUE | TRUE | 0 | 0 | 0 | TRUE | TRUE | TRUE |