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Automation Engineering

Wels

Sensor system for inspection and exploration with low visibility in a disaster environment

As **Bachelor 1 Thesis** submitted

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Bachelor of Science

of

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Wels, in January 2016

Advised from

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Clarification

Herewith I affirm that the present work is written independet and without help. I did not use other sources than the ones I used in the paper. I assure that this is the paper confirmed from my advisors.

Wels, on January 22nd 2016

Jürgen Buchner

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Preface

This Bachelor 1 Thesis is the result of my study in Automation Engineering at the University of Applied Sciences Upper Austria. Due to my semester abroad at Clarkson University in the Potsdam, NY(USA) in the 5th semester I did the research at this campus.

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Introduction

Disasters happen everywhere in the world in different forms and circumstances. Disaster response teams are called into action to assess the situation and determine the best plan of action for the rescue effort. However, harsh conditions make it difficult for rescue teams to get an overview of the area and to localize the victims. The focus of this and future projects is on the design of robots that support rescue and rescue organizations in post-disaster management operations. Typical disaster environments include fires, especially in closed areas such as tunnels, buildings, public transportation where the trapped smoke impedes visibility. Other domains with a restricted view can be from natural disasters, such as earthquakes, sandstorms, hurricanes or tornadoes. In these missions, rescue teams have to deal with harsh conditions such as smoke, dust or a lack of light. Existing sensor technology and the related cognitive approaches cannot cope with these demanding conditions. This paper proposes to create a concept of a sensor system, and in a further project to realize this concept. These projects have the potential to facilitate robotic systems that can perform under harsh conditions of smoke, dust or low light. In addition to the state of the art technologies, such as LIDAR and visible light cameras, which are affected by smoke or dust, this sensing unit includes sensors of different electromagnetic spectra as well as sound. To achieve this task, the first step is to analyze the root cause of why cameras operating in the visible light portion of the electromagnetic spectrum are incapable of imaging in adverse conditions. The next step was to evaluate sensors which operate in other portions of the electromagnetic spectrum. In addition, sound is a physical effect which is also used for remote sensing and can be used in adverse conditions. Evaluating the sensors in different spectra was performed by quantifying their ability to penetrate through matter. Real world testing was performed by simulating an environment with low visibility and testing the sensing ability of various sensors. The evaluation showed that thermal cameras, which operate in the infrared spectrum, are the most useful imaging sensors to create the 3D point cloud using the cameras stereo. They have the ability to penetrate through dust and smoke and work in environments with no light. To improve the data of the infrared cameras a 2D sonar(Sound Navigation And Ranging) system will be used. The sonar system will be used to provide generalized mapping and detect objects and can be seen as a backup for the stereo cameras. The third sensor is in the visible spectrum and located close to the ground. Due to the fact that warm smoke rises and air sinks, useful data can be captured with this sensor near the ground. After choosing and arranging the sensors, the last step was to determine future tasks and creating an awareness of useful technologies and papers which can be helpful such as "next best view" planning, the analysis of smoke or "see-through" technology.

Abstract

Disasters of all kinds such as fires, earthquakes or sandstorms happen frequently over the whole world and claim many victims. Disaster management organizations must respond quickly to bring aid and rescue to those affected. The faster the disaster response team responds, the higher the likelihood that more lives will be saved. Response teams arriving on a scene are faced with not only the challenges of executing an effective rescue, but also dealing with adverse conditions, such as smoke, dust, fire and lack of light. As a result, rescue teams face an uphill task in adequately assessing the situation and determining the correct course of action. To improve these operations, this paper proposes to create a novel sensor system that is able to localize and map an area in 3D in adverse conditions. Future projects will realize this goal and apply the proposed sensor system on an autonomous robot. In order to design an effective sensing system, the first necessary approach is to understand why traditional imaging systems are inadequate in adverse conditions. The next step was evaluating the entire electromagnetic spectrum and audio to determine how sensors are able to image in different conditions. The research results indicate that a combination of infrared, ultrasonic, and visible light sensors will lead to the best results as they are able to deal with the challenges presented by adverse conditions. Other technologies, which attempt to ”see through” matter works in the microwave end of the spectrum. However, these technologies are not mature enough to deploy on the proposed autonomous robot sensor system. By developing a multi-sensor system using infrared, ultrasonic, and visible light imaging, an improvement of the effectiveness of rescue teams in responding to a disaster can be achieved.

Chapter 1

Theory

1.1 Electromagnetic Waves

This theoretical background about Electromagnetic Waves and Optics are based on the book "Contemporary Optics for Scientists and Engineers" [16, Page 135 - 145], the "Tour of the The Electromagnetic Spectrum" [8], and the article "Why can radio waves pass through a wall but light cannot?" [2]

1.1.1 Definition of Light

Light is a form of energy with no mass which travels through space at about $299{,}8 \cdot 10^6 \frac{m}{s}$ if there is no interaction with matter. In geometrical optics light is described as beams with different behaviors like transmission, reflection, absorption, refraction, polarization, diffraction or scattering. For this application the focus is primary on transmission, absorption, reflection and scattering. To understand these behaviors light has to be seen from the physical optic's point of view. Light in this nature is an electromagnetic wave which is described by the Maxwell equations. Electromagnetic(EM) waves differ in length or frequency. The relationship between frequency and length is inversely proportional.

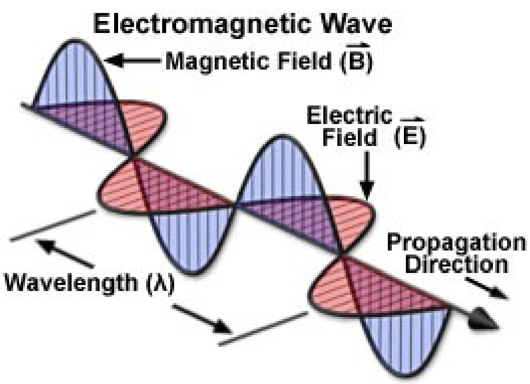

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Figure 1.1: electromagnetic wave

1.1.2 The Electromagnetic Spectrum

The EM Spectrum covers and categorizes the frequencies and lengths of electromagnetic waves. The most present part of the EM Spectrum is the visible region. This region includes wavelengths from $380nm$ to $760nm$ and is captured by human eyes and optical sensors like DSLRs(digital single-lens reflex). EM waves with a lower or a higher wave length than the visible spectrum, as in the Figure 1.2 is illustrated, cannot be seen with the human eye. Specific sensors are necessary to capture these waves.

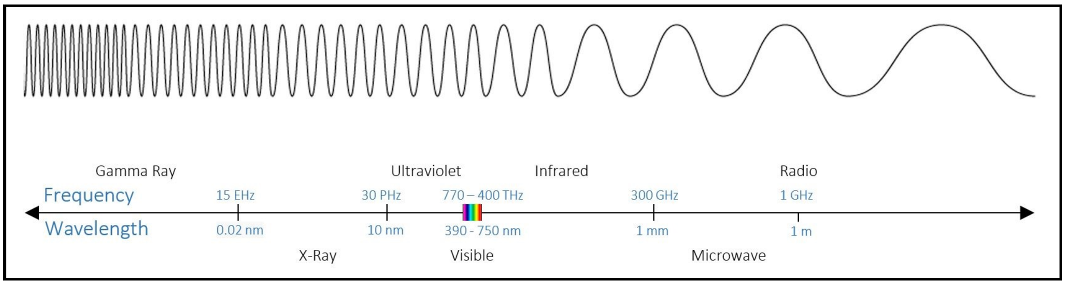


Figure 1.2: Electromagnetic Spectrum

1.2 Wave behavior

1.2.1 Transmission

Electromagnetic waves travel through space in vacuum and matter. The amount of intensity of the wave which is passing through matter or a certain object is dependent on the wavelength, the amount of energy, the structure of the material and the thickness of the object. Low frequency waves e.g. radio waves can penetrate through most materials. This is the reason why this frequency spectrum is used to fetch data from outer space because it penetrates through dust, gas or comets. Another application is radio stations. These also send data through dense objects, but as the thickness increases (e.g. in tunnels) the signal quality decreases. An example, which demonstrates that with a high amount of energy waves can be transmitted, even if the the transmitted waves normally are neglectable, can be shown with the following experiment. Visible light is mostly absorbed and reflected when it interacts with a dense object such as the human body which leads to a negligible intensity of transmitted waves. However, with enough energy it is possible with a torch to shine through a finger, which is shown in Figure 1.3.

[1] http://micro.magnet.fsu.edu/primer/lightandcolor/images/electromagneticfigure2.jpg

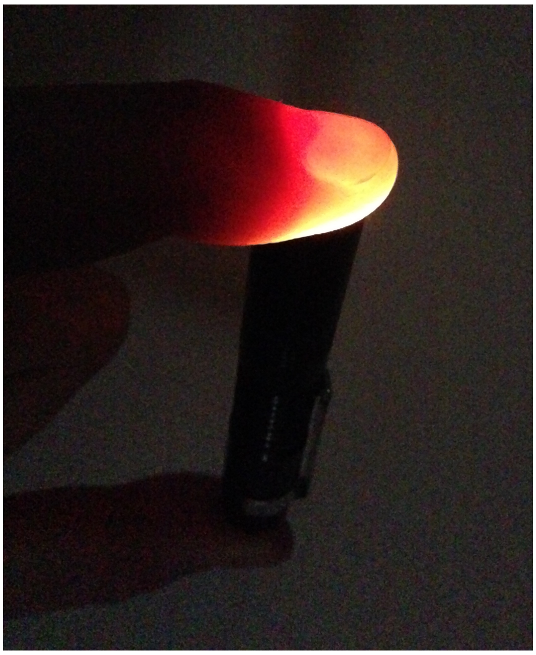


Figure 1.3: Example: Finger

1.2.2 Absorption

When light penetrates trough an object, a part of it will be absorbed which leads to a decrease of intensity I. The amount of absorption is dependent on the material (coefficient α) and the thickness l. The transmitted intensity is therefore geometrically described as:

$$I = I_0 \cdot e^{-\alpha l} \tag{1.1}$$

In addition, the absorption of materials is also dependent on the wavelength, which is neglected in the geometrical equation above.

1.2.3 Reflection

Reflection is the physical effect when light hits an object and bounces of the object. In the visible spectrum an objects color is defined as the wavelengths which are reflected by the object because the absorbed wavelengths cannot be detected. If an object seems darker to the human eye, it means that the object absorbs a high variety of the visible spectrum and a high percentage of the waves.

The electromagnetic effects transmission, absorption and reflection are shown in the Figure 1.4.

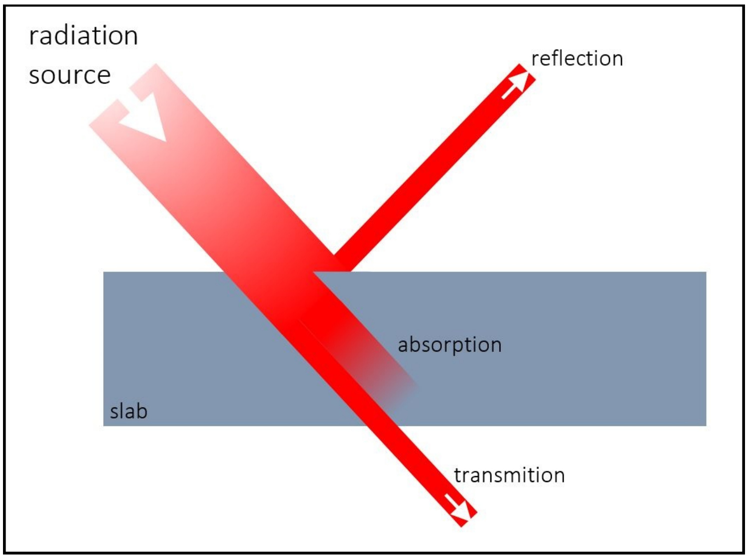


Figure 1.4: Effects of electromagnetic waves

1.2.4 Scattering

Scattering is the effect of waves bouncing off an object in different directions. The likelihood of scattering depends on the wavelength, size, and structure of the object. Backscattering is used in many sensing systems, for example in night time photography where a flash is used to illuminate the area, and the backscattered waves assist in capturing the image.

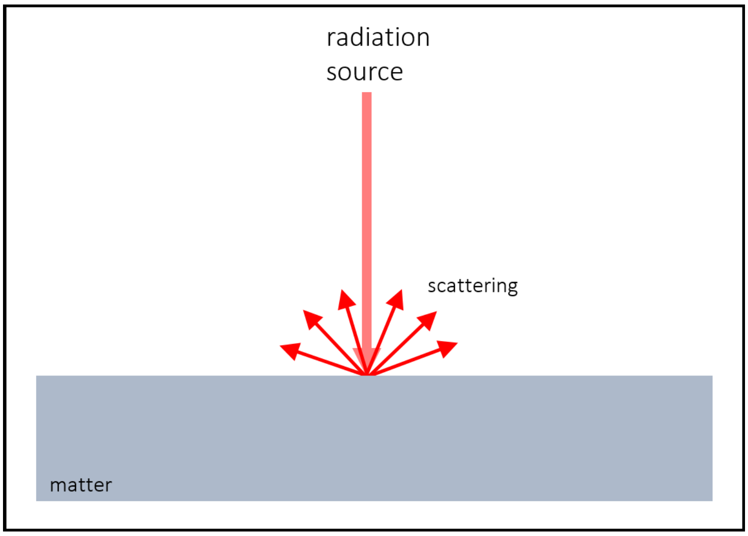
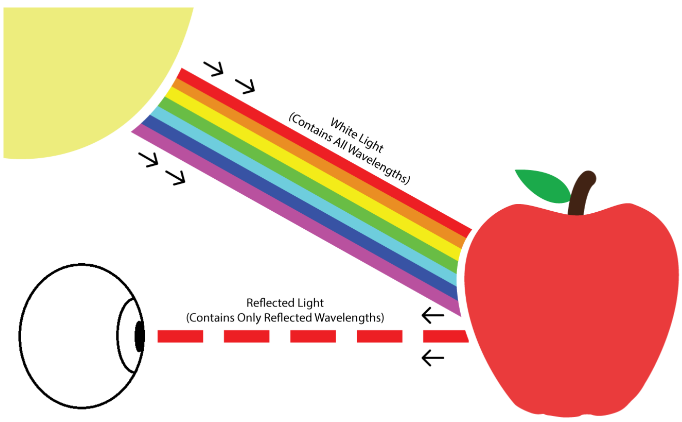


Figure 1.5: Scattering effect

1.3 How does optical cameras and the human eye work

To see the problem of state of the art camera systems an understanding of optical cameras is necessary.
As a base to capture electromagnetic waves in the visible spectrum a light source like the sun is necessary. The sun provides the whole spectrum of light. As the sun is spreading light to objects, waves are among others absorbed, transmitted or reflected. The waves are captured for example from the human eye or from an optical sensor. The variety of colors of an object who are recognized by a sensor or an eye, therefore, is built on the combined wavelengths who are reflected by the object and the brightness of the waves as in Figure 1.6 is shown.
For example an object reflects from the whole visible spectrum only the wavelength of $475nm$. People interpret this wavelength as blue.
Detecting frequencies is in optics not used because detectors are to slow (frequency in the visible region is $10^{15}Hz$). Therefore, the intensity of the wave is used and the interpretation is the brightness of a color.



[2]

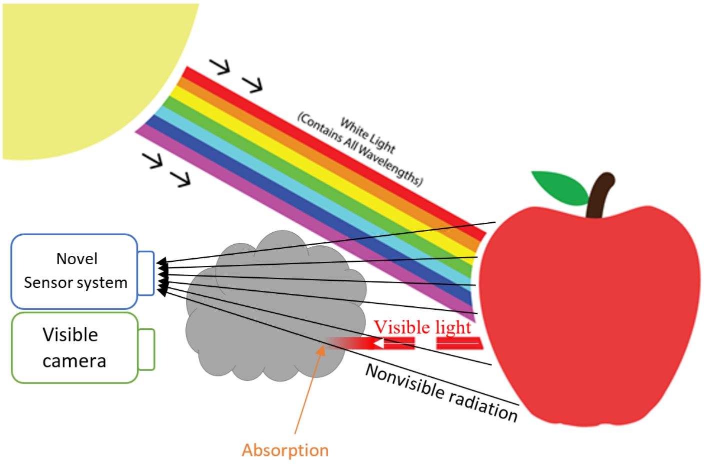
Figure 1.6: Reflection of waves

1.3.1 Restriction of optical cameras

Electromagnetic waves in the visible region are very likely to reflect. Particles or objects with a very low density such as smoke or dust already reflect visible waves. Therefore, in a disaster environment, important objects like human bodies or surfaces of surroundings cannot be detected because the reflected light of these objects do not reach the optical camera.
In addition, to capture useful data with a camera, the sensor needs the right amount of light. This is approached with the exposure time and the lens aperture of the camera. For environments with less light the lens aperture is completely open and a high exposure time is necessary. Using a long exposure time to capture more light

[2] https://illuminologybytisva.files.wordpress.com/2015/01/color-reflection-diagram1.png

is essential for night photography, but not possible for a moving robot. As this time increases the frames per second decreases which excludes the application of mapping an area.



[3]

Figure 1.7: Issue of visible cameras

1.4 Alternative spectra

Due to the disadvantage mentioned in the Section 1.3.1 other EM spectra needs to be chosen to fetch useful data for inspection of a disaster environment with low visibility. The applications of the different spectra mentioned in the Sections below are only examples related to observation and identification. Due to the high amount of applications of EM waves in all kind of areas applications which are unnecessary for this project are excluded.

1.4.1 Gamma Ray

Gamma Rays are the EM waves with the lowest length($10^{-12}m$) and with a high amount of energy. Sources for these type of waves are objects with the highest amount of energy or the hottest points like nuclear explosions, lightning or from radioactive decay which is produced by radionuclide like uranium or thorium.

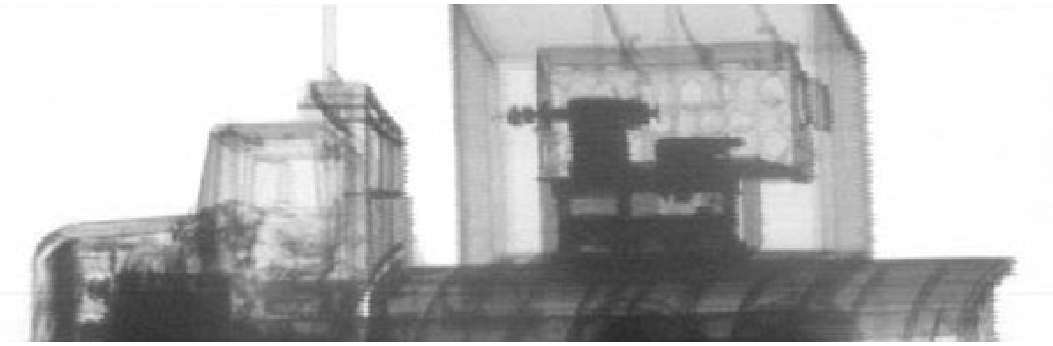
Advantage

The behavior of Gamma Rays are that they can pass through almost all materials because of the high amount of energy.

[3] https://illuminologybytisva.files.wordpress.com/2015/01/color-reflection-diagram1.png

Application

An application for inspection is from the Container Security Initiative(CSI) which is identifying container's objects before shipping to identify potential risk for terrorism. To examine the containers "large-scale X-ray and gamma ray machines and radiation detection devices" are in use. [1]



[4]

Figure 1.8: Container identification

Restrictions

Radiation received on the body can cause cancer. The consequences of radiation are not immediately but the chance of cancer increases as the dose increases. The reason why it can harm the body is because of ionization. gamma and x-rays have, due to their high amount of energy, the possibility to knock electrons out of atoms which leads to a change of the DNA. [19] An example for radiation doses is a "whole body CT". It delivers 14 to $32mSv$. The following list [6] shows the impact to the human body when radiation is received:

- 1,0 Sv: Causes slight blood changes
- 2,0 - 3,5 Sv: First lethal cases, nausea, hair loss
- 5,0 Sv: 50 % lethal cases

Gamma-ray detection to identify objects is used in closed environments, which means that on one side is the radiation source(transmitter) and on the other side is the sensor(receiver). State of the art technology which uses gamma-ray Backscattering is often used in material science and therefore, not for high ranges. [12] In addition, due to the increasing probability of cancer using gamma rays this spectrum is excluded from the sensor system.

[4] http://media.defenceindustrydaily.com/images/ELEC_Mobile_VACIS_Image_Truck_Container_lg.jpg

1.4.2 X-Ray

X-rays have a length between 0,03 and $3 \cdot 10^{-9}m$ and lower amount of energy than gamma-rays, but still ionizing. "X-rays can be produced naturally or artificially by machines using electricity." [19]

Advantage

Application

- CSI examining containers as described in the Section 1.4.1.
- Radiography: The technique radiography uses x-ray waves to examine objects for example bones of human bodies or to identify material defects. Machines for medical use usually detect the transmitted waves through the object and do not use the backscattering effect.
  Additionally, backscattering applications are used in security applications in the aircraft section which is similar to container inspection. [13]

Restrictions

This spectrum is less harmful then gamma-rays and therefore, it is used in medical applications, but also in a controlled environment and in low doses. Backscattering applications for inspections of airplanes inspection through dense objects can be achieved but the sensor system is to large to carry in a disaster environment and also the distance and the scanning time(4 minutes for about $4m^2$) is an issue. [13] Additionally, as in the gamma ray spectrum due to the fact that it is harmful to the human body it is not applicable for the sensor system.

1.4.3 Ultraviolet

The spectrum of ultraviolet (UV) light is between $400 \cdot 10^{-9}m$ and $10 \cdot 10^{-9}m$ and lower amount of energy than x-rays, but still the ability of ionizing. The spectrum is usually divided in UV-A, UV-B and UV-C. UV light is produced by the sun and for industrial and science applications it is also artificially created. [9]

Advantage

Application

UV sensors are used in different areas such as Bacterial Identification in biotechnology, clean room inspection in the field medicine or leak detection in automotive. [4] Other applications are in the industry for distance measurements.

Restrictions

UV is not of importance in this field of application because the range sensors are disturbed easily because UV "...is easily absorbed by most materials." [5] In addition, high frequency UV such as UV-B and UV-C also harms the human body in high doses because it is also ionizing. As known, the sun as a UV source causes sunburn due to UV-B radiation. [9]

1.4.4 Infrared

The spectrum of infrared light operates between $750 \cdot 10^{-9}m$ and $1 \cdot 10^{-3}m$ and it is not ionizing, which makes it harmless for human bodies. Heat radiates infrared energy. Therefore, infrared cameras alias thermal cameras capture temperatures. Due to temperature differences of objects and parts of objects sensing these and their structure is possible.

Advantage

The advantage of the infrared spectrum is that it penetrates through matter with low density such as smoke and dust. Due to the fact that it does not operates in the visible spectrum light does not influence the outcome which makes it applicable at night as well.

Application

The area of application of thermal imaging cameras is broad. Systems are used in UAVs(unmanned aerial vehicles), security, machine visions, firefighting, gas detection systems, security and many more.

Restrictions

In an environment with a heat source such as fire it can increase the temperature difference of objects which would lead to an improvement of data, but if the heat source is between the camera and the persons to be captured than the quality of the infrared camera data is decreasing.
To counteract against this issue is a new technology which is called "far-infrared digital holography". This technology makes it possible to see people behind fire. This can be achieved with lens less thermal camera. Without the lens saturation of the sensor is avoided as can be seen in Figure 1.9. After reconstruction of the holograph the human body can be seen. The author of the paper mentions that the reconstruction of the human hologram is quasi real time. [3]

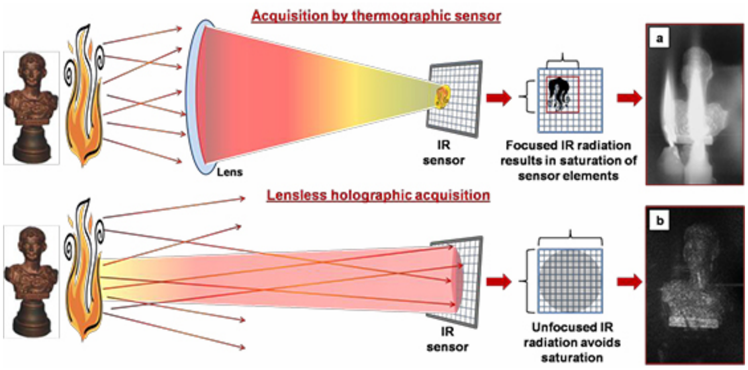


Figure 1.9: Object behind fire [3]

For disaster environments where high temperatures are common this factor needs to be considered by choosing the sensors. One of the leading companies in the area of thermal cameras is FLIR[5].Their electronics of their cameras do not have a high operation temperature. In the fire fighters section are only hand held cameras which have high operation temperatures which is because of the special case. In order to use a camera from FLIR with a high resolution and a sampling rate high enough to map the environment a fire resistant case needs to be created to apply it in the sensor system.

1.4.5 Microwave

Microwaves are between 0,001m and 1m long. These are classified in different, so called bands. Typical sources for microwaves are specialized vacuum tubes, FETs or tunnel diodes. In addition, warm objects in general create low level microwaves and due to penetration through clouds, they these waves are measured to analyze and forecast weather.

Advantage

Penetration through clouds, dust and smoke, which is the target for the sensor system.

Application

"Medium-length (C-band) microwaves penetrate through clouds, dust, smoke, snow, and rain to reveal the Earth's surface." [8]
Typical applications for microwaves are capturing the weather such as the temperature of the earth's surface or gathering hurricanes with a scatterometer.

Other applications, which are not directly used for mapping, but are still necessary for the application of the sensor system, are communication and navigation.

[5] http://www.flir.com/

Communication protocols such as IEEE 802.11(also called Wi-Fi) will be used to send data from the sensor to a stationary computer for data acquisition and to a control unit. Global navigation satellite systems(GNNS) such as Global Positioning System (GPS) work in the spectrum of microwaves. The data of the GNSS will be used to locate the captured observation data of the sensor system.
Another application is 2D mapping in an environment with vision and GPS denied environments. This project has a similar purpose, but is using 2D radar Simultaneous localization and mapping (SLAM). [15]

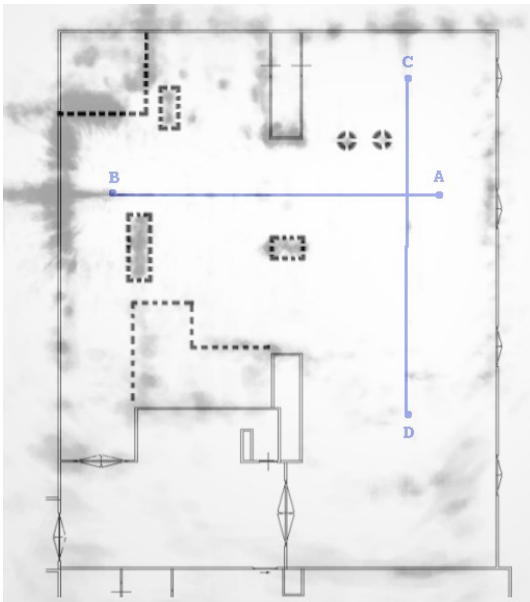


Figure 1.10: Constructed grid map with the actual map overlayed. 20 by 30 meters room. System movement: A to B and C to D. The map was created with no positioning data. [15]

Another application is see-through mapping via “wireless channel measurements” [14] This system is capturing obstacles which are in a closed environment with transmitting and receiving units as in Figure 1.11 shown. As the outcome shows it is not advanced enough that it could be a benefit for disaster environments where areas are larger and where more accurate data is necessary to get an overview of the situation. Another disadvantage is that it is not backscattering technology. The application of radar is described in the Section 1.4.6.

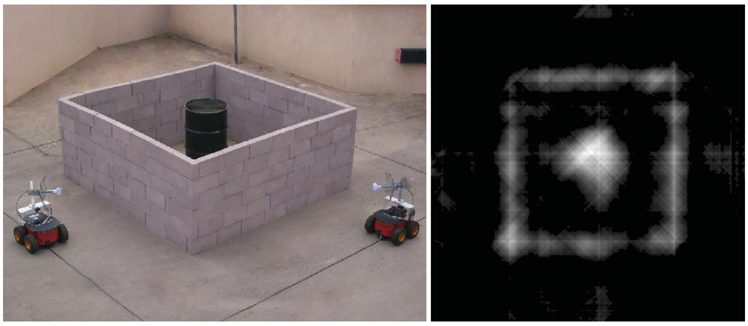


Figure 1.11: See-through via wireless channel measurements [14]

A more advanced see-through technology published in 2015 by MIT. This technology is sending and receiving the backscattered Wi-Fi signals to detect human bodies as can be seen in Figure 1.12. In addition, the data processing is nearly real-time. [7]

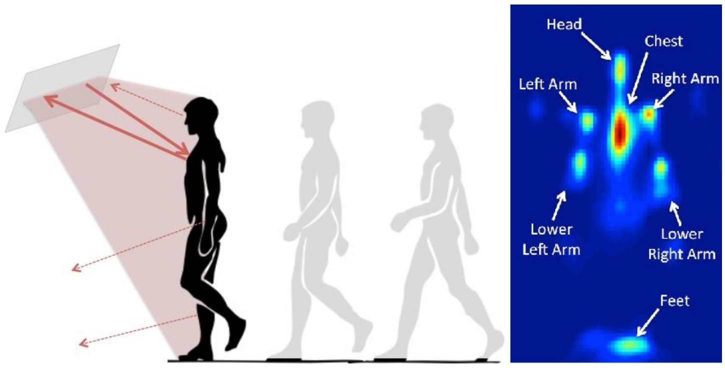


Figure 1.12: See-through technology to detect human bodies [7]

Restrictions

See-through technology can be very valuable for the sensor system in the future. The actual project which is published by MIT shows that a considerable approach was already achieved by detecting a human being. To consider this project in the sensor system the technology is not advanced enough and it would also go beyond the scope of this project because the main achievement is creating a concept for mapping and localizing human in an area without see-through technology.
Weather applications cannot be applied to the sensor system because it is not constructed for mobility and to expensive(satellites).

1.4.6 Radio

The spectrum of radar is between 1mm - 100,000km and is the spectrum with the highest wave lengths. Radio is produced by the sun and for industrial and science applications it is also artificially created.

Application

The radio frequency spectrum is used for communication and controlling such as broadcasting(AM, FM Radio) or radio control, but also radar technology. The application radar is an interesting field to get an overview of an environment due to the wide range. Radar systems operate in the spectrum of radio waves and microwaves. The main remote sensing applications of radar, which has a similar use as the purpose of this paper, are in the military and civilian field, such as aircrafts or ships. Also the automobile industry is interested is considering including radar systems. For both military and civilian use the purpose is to fetch data about objects in a certain area including warnings and behaviors due to unwanted circumstances. For civilian use such as boats and also automobiles clarifying if obstacles are in their path is common. [10]

Restrictions

The issue of the sensors for boats and surveillance cameras is that they do not have a high operation temperatures. Another disadvantage is that already the smallest radar sensors have a considerably high size for mobile robots. This is because military and civilian applications need high ranges because of the speed of the detecting objects and the speed of the vehicle where it is applied.

1.5 Beyond the EM spectrum

1.5.1 Sound

Another type of waves besides electromagnetic waves which are traveling through space with the speed of sound, specifically through a medium, are sound waves. The physical effect of these waves [...is a vibration that propagates as a typically audible mechanical wave of pressure and displacement...] [11].
Sound waves can be created artificially as it is in industrial applications.

Application

Ultrasound is used for distance measurements in the industry. A more specific application for distance measurements is sonar which is among others used for mapping. A project with a similar environment is creating a 2D map using sonar with the mobile robot “Pioneer 3-DX” . [18]

Restrictions

The speed of sound v_{sound} is 340,29m/s. For mapping application the range of the sensor and the response time of the sensor after sending a signal is among others important. As the range of the sensor is increased the frequency of pulses that can be sent decreases. For example, if the sensor is a distance s of $1m$ away from the object and is sending a pulse it takes the time t of 5,88mS to reach the receiver of the sensor, which would be a possible frequency f of $170Hz$. If the distance is increased to $5m$ the possible frequency would be $34Hz$. The equation to calculate these examples is the following:

$$f = \frac{1}{t} = \frac{2 \cdot s}{v_{sound}} \tag{1.2}$$

This calculation does not include processing of the sensor or other necessary delays.

1.6 Disaster environments with fire

In a disaster environment where objects burn, smoke develops. An understanding of how the smoke behaves can help fire fighters to estimate how dangerous the situation is and how smoke and fire will develop. Therefore, Shan Raffel distinguishes different indicators. He created a mnemonic which is called B-SAHF. The indicators are the following.

1.6.1 Indicators

- Building: Construction which is under fire. The fire can develop in different ways due to the material of the building
- Smoke: Characteristics such as the color, volume, pressure or the location.
- Air Track: Flow of the air and heated combustion products
- Heat: The impact of heat such as Blackening of Windows without flame showing, cracking glass, blistering or sudden heat build-up.
- Flame: Color and shape of the flame

Due to the fact that the main interfering factor for visibility in an environment with fire is smoke an analysis is necessary to understand the main issue.

1.6.2 Smoke

Additionally to the separation of the fire indicators, smoke is divided in four characteristics.

One important characteristic in order to arrange the sensor system is the Neutral Plane.

The Neutral Plane is the transition between heated smoke and cooler air as can be seen in Figure 1.13. When the Neutral Plane changes is height, it indicates a change of the fire as Raffel describes [17]. Describing the behavior more in detail would go beyond the scope of this project, but as it comes to data analysis referring the sensor system tracking the change of the Neutral Plane helps predicting smoke and fire behavior.

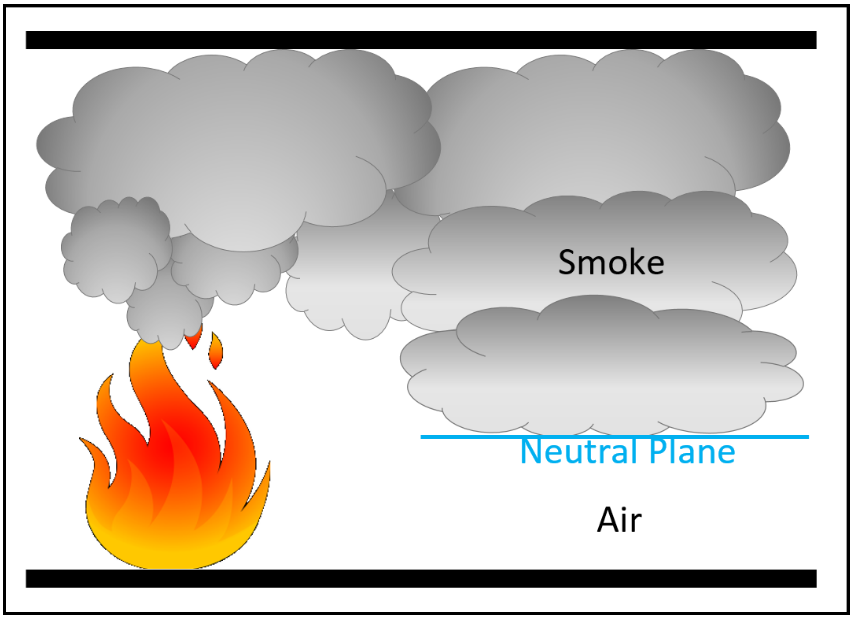


Figure 1.13: Neutral Plane

The three other characteristics are:

- Color and thickness (optical density)
- Volume and location
- Buoyancy and pressure

These and in general the other factors of B-SAHF will lead to a significant improvement for rescue operations as far as they are considered in data analysis in future projects.

1.7 Conclusion of theory

Gamma- and X-Rays have very good abilities to penetrate through dense objects, but do to the fact that the rays harm humans these spectra are excluded for this application. The ultraviolet spectrum is also not used because distance sensors are disturbed easily by noise. In Addition, rays are still harmful for human bodies. The infrared spectrum is not harmful for human bodies. Applications and chapter 2 shows that useful data can be fetched in environments with low visibility. Microwaves have the ability to penetrate through very dense objects such as walls as is achieved with See-through technology. This technology can be considered after achieving to create 3D models of environments where the robot is located, but for the first approach 3D

mapping it is beyond the scope. Common technology in the radio spectrum such as radar is used in applications such as military or boats. These sensors cannot applied for this sensor system because of the size of the sensors and the accuracy. Sound is already used in mapping applications with considerably achievements and therefore, it will also be considered in this sensor system. The behavior of smoke in disaster environments with fire shows that there is a possibility fo fetch useful data with visible sensors even in an environment with low visibility due to the buoyancy of warm smoke.
This leads to the concept of the three components:

- Infrared
- Visible
- Sound

Chapter 2

Simulation

A wind tunnel and a fog machine was used in to simulate the adverse conditions, such as dense smoke surrounding a burning house. To create a dense smoke filled environment, a portion of the wind tunnel was encased with cardboard, thus allowing the fog machine to generate dense smoke in a small, enclosed area. The wind tunnel also has another advantage as it allows quick dispersal of the smoke by using the auxiliary venting system. In this simulation, imaging was done using a portable mobile phone camera and a portable infrared imager that attaches to the mobile phone. These two are chosen as they represent low cost ubiquitous devices.

2.1 Used equipment and test scenario

- **Thermal imaging camera:** Seek Compact iPhone[1]
  - iOS Lightening Thermal Camera
  - Works on iPhone 5 or higher
  - 206 x 156 Thermal Sensor
  - 12μ Pixel Pitch
  - Vanadium Oxide Microbolometer
  - Chalcogenide Lens
  - 36° Field of View
  - Magnesium Housing
  - Long Wave Infrared 7.2 - 13 Microns
  - $-40°C$ to $330°C$ Detection($-40°F$ to $626°F$)
  - $< 9Hz$

[1] http://obtain.thermal.com/product-p/lw-aaa.htm

Figure 2.1: Seek Compact - iPhone

- **Visible spectrum camera:** iPhone 5 - iSight camera
  - 8 Megapixel
  - 3264 x 2448
- Smoke generator: O00QL-0041 from 1byone
  - 400 watt
  - Power Sources: input AC 120V 60Hz
  - Warm Up Time: 4-5 Minutes
  - Outline Size: 250 x 191.5 x 114 mm
- Fog: "Fog Juice Fluid" from 1byone
- Model car with metal body
- Concrete brick

2.2 Experimental results

In the testing the smoke was steadily increased to capture different densities. To analyze the camera performances four different scenarios were created. The photos were taken with the camera app from Seek "Seek Thermal" which saves both the visual and the infrared image. The cameras have a different view(distance of the cameras is about 130mm) and captures a different size because the of the angle of view. These offsets are not considered and therefore, for example, the temperature points are on different spots when you compare the iSight camera and the thermal camera as can be seen in Figures 2.2, 2.4 and 2.5.

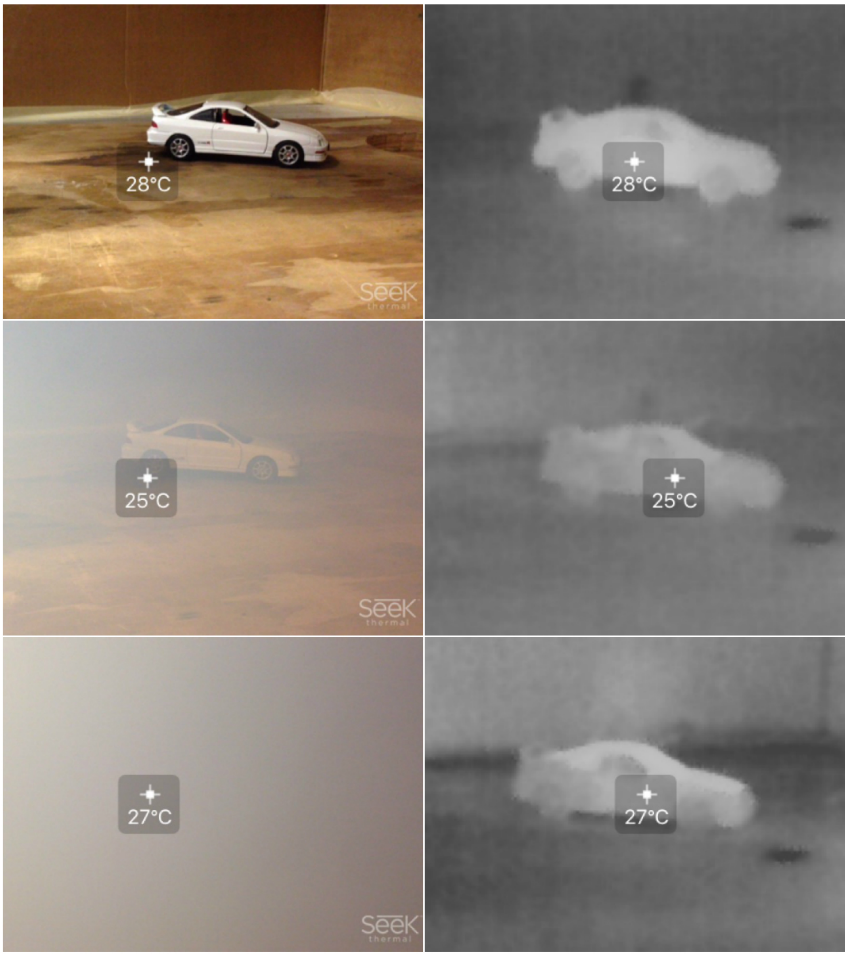


Figure 2.2: Test 1

In the first scenario, the car was preheated. As can be seen in Figure 2.2 with the thermal camera the car is captured with a level of detail that tires and the window can be seen. As the smoke increases it does not have a significant impact on the thermal camera, but the thermal camera captures that the car is cooling down to room temperature. As the smoke generator keeps creating smoke, the car increases the temperature because the ray of the smoke generator is coming from the direction in front of the car's point of view. The visible camera is highly affected as the smoke increases.

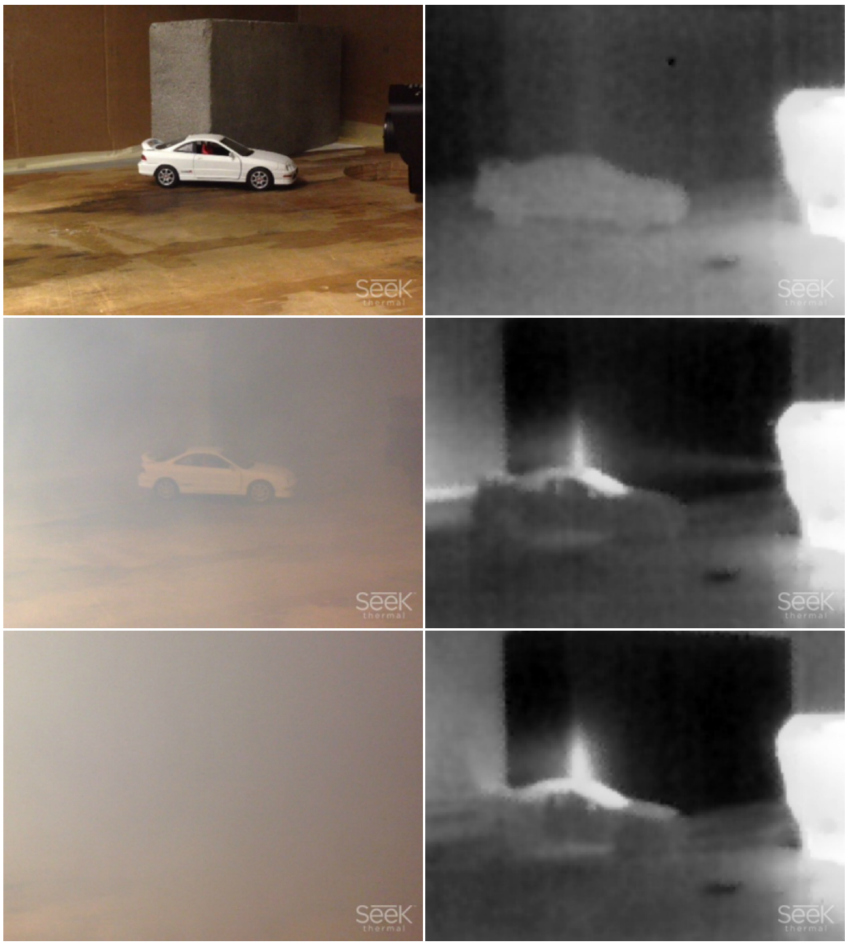


Figure 2.3: Test 2

In the second scenario, a concrete brick, to simulate a wall, and the smoke generator, as heat source such as fire, was included. In this test the car was not preheated. Without smoke only the shape of the car could be captured. The smoke generator was pointed at the car and the brick and as in Figure 2.3 can be seen the bricks corner and the car is increasing their temperature and the car is captured more detailed. The visible camera is affected the same in this test.

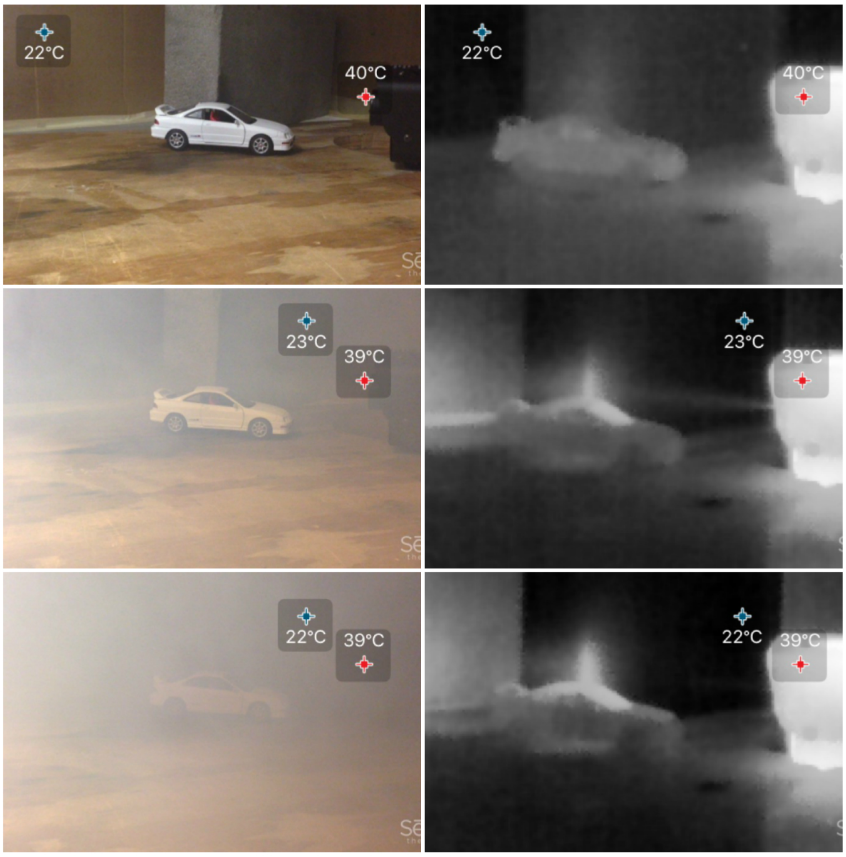


Figure 2.4: Test 3

The third test has the same circumstances, but the feature of the thermal camera in order to detect the lowest and the highest temperature was used. As can be seen, as the smoke and also the overall temperature increases the cardboard wall in the background and the wooden ground absorbs the heat faster than the brick and therefore, the shape of the brick gets colder compared to the other objects and can be seen clearly.

Figure 2.5: Test 4

In the fourth test the heat "source"(smoke generator) was removed that the car and the brick is not heated up by the smoke ray. The generator was placed that it does not increase the temperature with the direct ray. How this is solved is shown in the schematic drawing 2.6. Also a hand was added in this test to simulate a person.

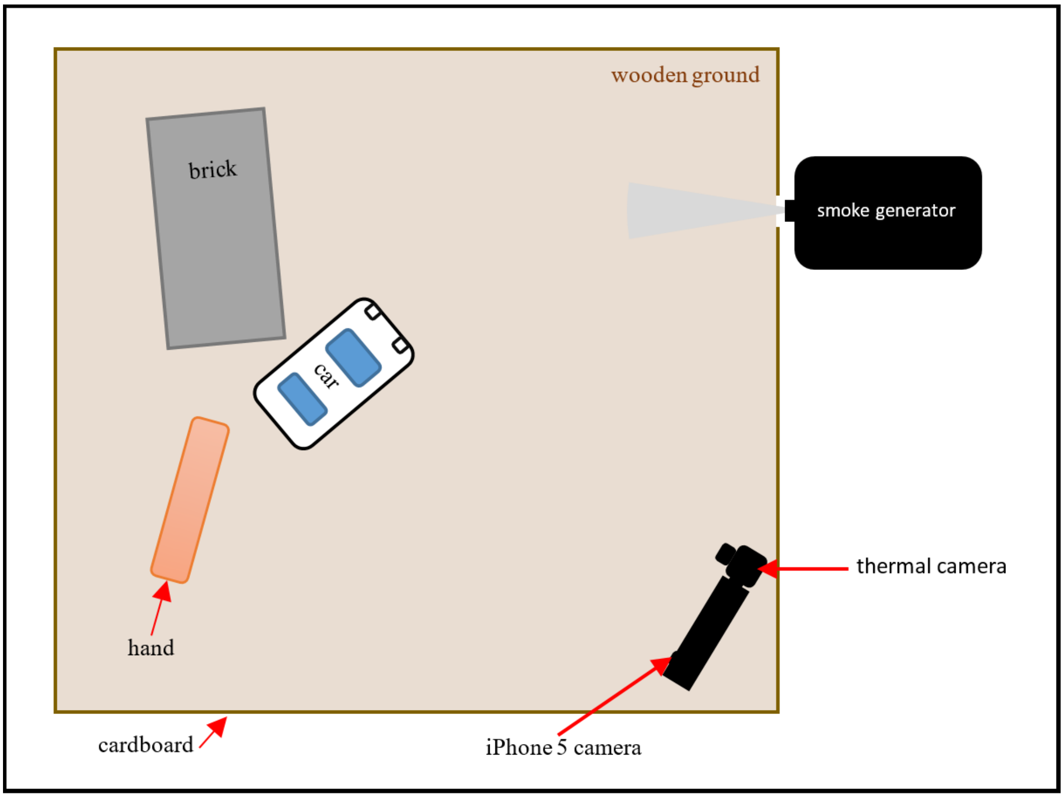


Figure 2.6: Test 4 schematic drawing

A considerable aspect in this test is that it seems that the car is radiating heat at the brick because the other corner which has a greater distance to the car is not heated up. In test two and three was the same situation but the corner could have been heated up from the smoke ray of the smoke generator. In addition, the wooden ground was this time even colder than the brick, but do to the color the difference is hardly noticeable. Another considerable fact is that the hand is $33°C$, but the average body temperature is $36°C$ - $37°C$. This leads to the fact that a calibration is necessary to improve the quality of the data.

Overall, the thermal camera is not influenced from the smoke as expected and therefore, the better choice in such a scenario. With a certain density of smoke the visual camera is not able to capture useful data to detect objects. Additionally, the thermal camera is influenced by heat sources such as the car was a heat source for the brick and as the smoke ray for the car. In addition the smoke was increasing the temperature overall, but depending on the material the rise was noticeable or not. Another considerable fact is that the Seek thermal camera for the iPhone has a resolution and sensitivity where it is possible to see structures of objects, but a calibration would be necessary in order capture a more accurate temperatures. The inaccuracy is detected by capturing the temperature of the hand.

Chapter 3

Comparison and Design of Sensors

Based on the research and the conclusion in chapter 1, the next step is to compare sensors in each field to find sensors to create a beneficial and cost effective sensor system. To accomplish this, criteria need to be defined. One important factor for rescue organizations is the cost factor. Therefore, sensor system concepts are created for different price sections from low cost to high end. These price categories are:

- Low cost: < \$1,000
- Middle: < \$5,000
- Mid-High end: < \$20,000
- High end: ∼ \$20,000

3.1 Theory

The comparison of the sensors was accomplished using a "Cost-utility analysis" method. The first step is to define criteria. These were compared pairwise and evaluated that the criteria have a certain weight in the comparison of the sensors. The next step was finding sensors from low cost to high end. After that, a desired value was set in each criterion and the senors were evaluated if they fulfill this value. The multiplication of the fulfillment and the weight of the criteria is the resulted value per criterion of a sensor.

$$\text{value} = \text{weight} \cdot \text{fulfillment} \tag{3.1}$$

The sum of all criterion's values is the value of the sensor.

3.2 Comparison

The detailed comparison of the sensors is shown in the tables and graphs which are attached A.

3.2.1 Sound

Common technology in the sound spectrum which are applied in SLAM are ultrasound distance sensors. In the common use sensors are arranged to create 2D maps. The following sensors are compared.

- Honeywell 946-A4V-2D-2C0-175E
- Senix TSPC-30S1-232 ToughSonic Waterproof
- Sick UM30-213111
- Maxbotix 4-20HR-MaxSonar-WRÂ
- SRF235
- HRXL-MaxSonar-WRS3
- SensComp 600 + Ranging Module
- SRF10
- SRF05

3.2.2 Infrared

In the infrared spectrum advanced camera technology exists. Using cameras stereo makes it possible to create 3D maps. This is the reason why the thermal cameras will be the main part to create the 3D point cloud. One of the leading companies in the field thermal cameras is FLIR. Therefore, mainly FLIR cameras where compared.

- Seek Compact - Android
- FLIR One - Android
- FLIR Vue
- FLIR Vue Pro
- FLIR K65
- FLIR FC-Series ID
- FLIR A310
- FLIR A320

- FLIR A615
- FLIR A655sc
- FLIR A6750sc SLS
- FLIR SC8300

3.2.3 Visible

To improve the data of the infrared camera unit in the visible spectrum is also used a stereo camera system. The following existing systems are compared.

- mvBlueSIRIUS
- ZED
- Bumblebee2 0.8 MP Color FireWire 1394a 2.5mm (Sony ICX204)
- Kinect 2
- PlayStation 4 Camera
- Scorpion 3D Stinger for Robot Vision
- Ensenso N35
- Ensenso N30
- Ensenso N20
- Ensenso N10

3.2.4 Sensor system packages

Regarding the different price categories the following sensor systems were created.

Actual pricelist of sensor systems				
	Low cost	Middle	Mid - High End	High End
Infrared	FLIR One	FLIR Vue (320x480)	A310	FLIR A615
Amount	2	2	2	2
Price apiece	$ 250,00	$ 1.500,00	$ 9.200,00	$ 18.300,00
Sum	$ 500,00	$ 3.000,00	$ 18.400,00	$ 36.600,00
Sonar	SRF05	SensComp Series 600	SensComp Series 600	SensComp Series 600
Amount	4	8	8	8
Price apiece	$ 16,50	$ 54,00	$ 54,00	$ 54,00
Sum	$ 66,00	$ 432,00	$ 432,00	$ 432,00
RGB	Kinect 2	ZED	ZED	ZED
Amount	1	1	1	1
Price apiece	$ 120,00	$ 450,00	$ 450,00	$ 6.000,00
Sum	$ 120,00	$ 450,00	$ 450,00	$ 6.000,00
~Additional Cost	100	200	300	400
ApproximateEnd Price	$ 786,00	$ 4.082,00	$ 19.582,00	$ 43.432,00

Figure 3.1: Sensor system packages

3.3 Design of sensors

The right design of the sensor system is important create good conditions in order to fetch useful data. As known from Section 1.6 and Figure 1.13 warm smoke is rising to the ceiling. Therefore, the probability to acquire useful data in the visible spectrum it at the bottom.
Regarding the infrared sensors and the ultrasonic sensors testing is necessary where the best height is. Figure 3.2 shows a schematic design of the sensor system applied in an environment with low visibility due to smoke.

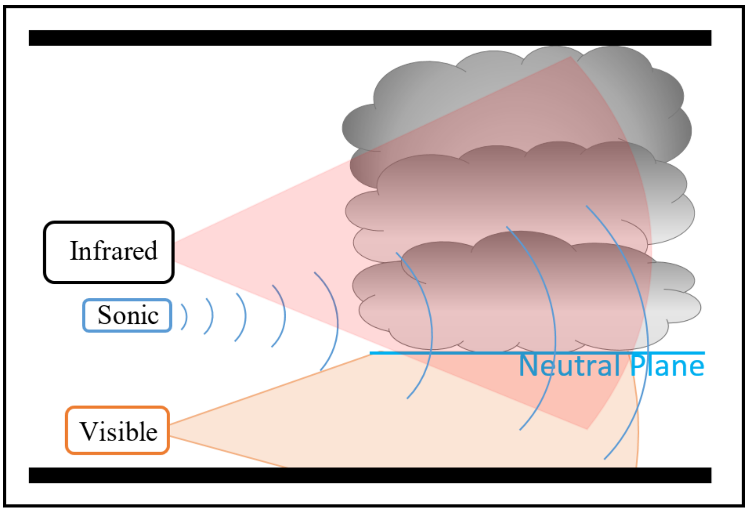


Figure 3.2: Sensor system sketch

Chapter 4

Conclusion

This paper presents a novel concept for 3D SLAM in low visibility environments such as fires, earthquakes, tornadoes or sandstorms. This work is a theoretical research to create a sensor system for harsh conditions in disaster environments such as smoke, dust or low visible light. To achieve this objective the problem of state of the art systems was analyzed. After that alternatives which does not operate in the visible spectrum and the general wave behavior were studied and a simulation was done in order to show the benefit of alternative spectra. The electromagnetic spectrum as well as sound were investigated to find the most useful sensors for low visibility disaster environments. The basis to create the 3D point cloud is a stereo camera unit which operates in the infrared spectrum. This will be supported by a stereo camera unit in the visible spectrum and a 2D sonar system. The design of the sensors is based of typical circumstances such as the smoke behavior in disaster environments. To make the sensor system more applicable, price categories from low cost to high-end were created. This makes it possible for organizations to decide a price section based on their needs. To realize these packages an evaluation of sensors due to important criteria for SLAM led to four categories of the sensor system. This work creates the basis for the realization of these novel systems. The application of the sensor systems in disaster environment operations will improve these significant. An overview of the area of application can be created by mapping the environment and localizing victims. To achieve this goal future work needs to be done which is described in Section 5.

Chapter 5

Future Work

The evaluation of the sensor cost forms the baseline for the future projects. The next steps in the process are:

- Research about if the created sensor set ups are still up to date or if there are new more accurate sensors available. In addition, lenses for the cameras need to be evaluated
- Purchase of the equipment
- Mechanics
  - Finding a design in order to fetch useful data
  - Constructing and building a mounting device
  - Assembly of the system
- Electronics
  - If necessary creating appropriate electronics for power supply and a data processing unit for data acquisition
- Software
  - Data acquisition: implementing software to fetch, manage and synchronize the data
  - Evaluation of SLAM algorithms and the implementation of a SLAM algorithm to create 3D maps
  - Implementing software for Navigation such as Next-Best-View
  - Designing the software modular in order to add other sensors such as a gas sensor (Adding the data on the point cloud)
- As the project progresses other sensors such as a gas sensor can be added. Knowing if harmful gases are in the disaster environment gives the fire fighter operator a better insight of the area.

- Another improvement for the system would be to make the visible camera movable. This could be either a rotational or translational movement upwards. In chase smoke or dust is decreasing in the disaster environment the movement of the visible camera increases the amount of useful data that can be captured.

- Other implementations which improve the system is software such as the "detection of human through fire", " see-through" technology or analysis algorithms for smoke.

Appendix A

Appendix

Sensor systems

Approximate Price weighting

Type of Sensor	**Weight of price [%]**	Low Cost	Mid	Mid-High End	High End
Stereocameras IR	70	$ 700,00	$ 3.500,00	$ 14.000,00	$ 70.000,00
Sonar System	10	$ 100,00	$ 500,00	$ 2.000,00	$ 10.000,00
Stereocameras Visible	15	$ 150,00	$ 750,00	$ 3.000,00	$ 15.000,00
Additional costs	5	$ 50,00	$ 250,00	$ 1.000,00	$ 5.000,00

Sensor System Packages	**Maximum price in categorie**
Low Cost	$ 1.000,00
Middle	$ 5.000,00
Mid-High End	$ 20.000,00
High End	$ 100.000,00

Thermal Imaging cameras	Seek Compact - Android	FLIR One	FLIR Vue™	FLIR Vue™ Pro	FLIR K65	FLIR FC-Series ID
						
Thermal Imager	Vanadium Oxide Microbolometer		Uncooled VOx Microbolometer	Uncooled VOx Microbolometer	Uncooled microbolometer	Uncooled VOx Microbolometer
Price	$250,00	$250,00	$1500, $3000	$ 1999+, $3700	$7.000,00	$7000
Resolution	206 x 156 (36°)	80 x 60 (tests shows it's clearly better than the Seek camera), VGA in visible spectrum	336x256 and 640x512	336x256 and 640x512	320 × 240 pixels	640 × 480
Temperature sensitivity / Accuracy	-	100mK	+/- 0.6C	+/- 0.6C	±4°C or ±4% of reading for ambient temperature, 10°C to 35°C	50 mK / ±2°C or ±2% of reading
Full Frame Rates	<9 Hz	<9 Hz	30 Hz (NTSC); 25 Hz (PAL)	30 Hz (NTSC); 25 Hz (PAL)	60 Hz	30 Hz (NTSC); 25 Hz (PAL)
Video output	USB	USB	Digital and Andalog Output	Digital and Andalog Output. SD slot to store data	In-camera video recording format: Non radiometric MPEG-4; Videos can be transfered via USB Mini-B	Video over ethernet: Two independent channels of H.264, MPEG-4 & M-JPEG ; Analog Video
Measurement Temperature Range	-40°C to +330°C	-20° to 120°C	-20°C to +50°C	-20°C to +50°C	–20 °C to +150 °C, 0 °C to +650 °C	-
Operating Temperature Range	-	0°C to 35°C	-20°C to +50°C	-20°C to +50°C	–20°C to +85°C/ +150°C : 15 min / +260°C	-50°C to 70°C
Non-Operating Temperature Range (Storage temperature)	-	-	-55°C to +95°C	-55°C to +95°C		-55°C to 85°C
Spectral Array	7.2 - 13 µm		7.5 - 13.5 µm	7.5 - 13.5 µm	7.5–13 µm	7.5 µm to 13.5 µm
Link	Link	Link	Link	Link	Link	Link
Comment	Smartphone camera, not proven if it works with linux or windows	Smartphone camera, visible camera already included, Lepton sensor, possibility not proven to use with Linux or Windows, http://hackaday.com/2014/09/07/building-the-worlds-smallest-thermal-camera/	Drone Camera with storaging directly on camera, US only, not for Export	Drone Camera with storaging directly on camera, US only, not for Export	Firefighter Camera, no Video out, storage on camera only	Security Cam without Pan/Tilt(rotating) with object(human, animal, vehicle) detection. Intelligent analytics

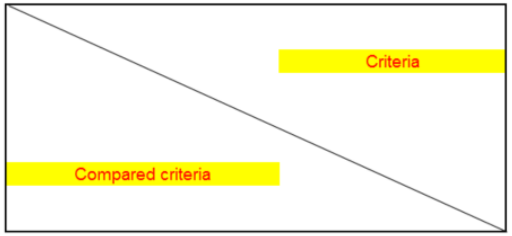
General Questions:

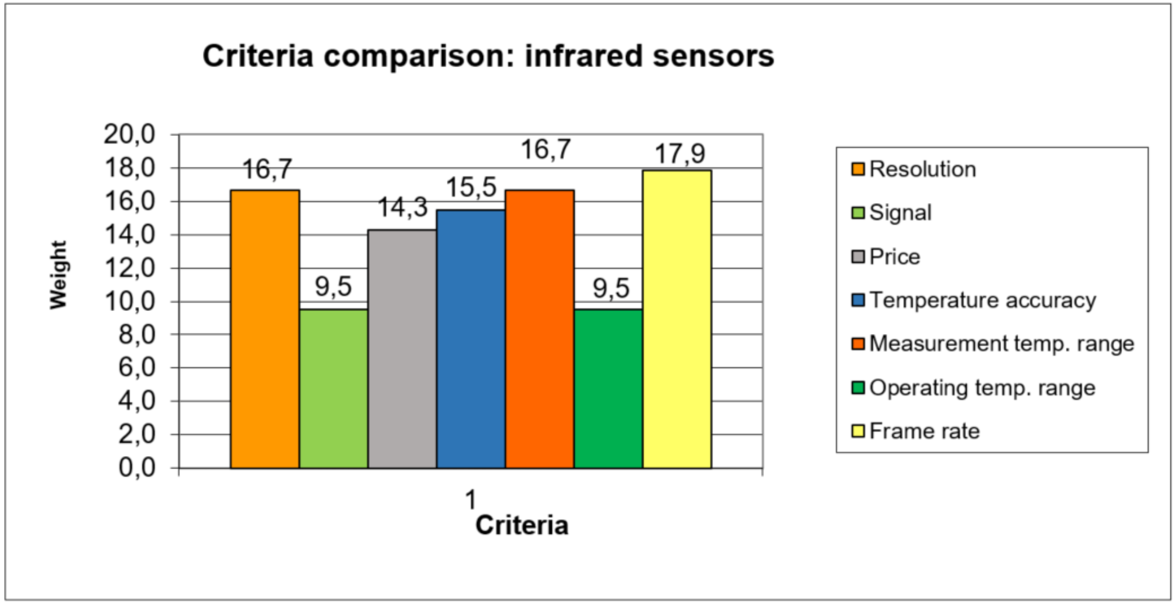
Why are some cameras "US Only, not for Export"?

Because of governmental regulations. It is still possible, if the potential owner registers the camera when he buys it and can give a plausible reason for it's use. The US government wants to keep under control who can own advanced technology like these cameras. There are also camera versions with low frame rates (<9Hz) which are possible to buy without a registration

Thermal Imaging cameras	FLIR A310	FLIR A320	FLIR A615	FLIR A655sc	FLIR A6750sc SLS	FLIR SC8300
						
Thermal Imager	Uncooled microbolometer	Uncooled microbolometer	Uncooled microbolometer	Uncooled microbolometer	Strained Layer Superlattice (SLS)	Indium Antimonide (InSb)
Price	$9200	$14.400,00	$18.300,00	$20.000,00	$100,000 - $150,000	$120,000 - $200,000
Resolution	320 × 240	320 × 240	640 × 480	640 × 480	640 × 512	1,344 x 784
Temperature sensitivity / Accuracy	50 mK / ±2°C or ±2% of reading	50 mK / ±2°C or ±2% of reading	50 mK / ±2°C or ±2% of reading	<30 mK / ±2°C or ±2% of Reading	<30 mK / ±2°C or ±2% of Reading	<25 mK / ±2°C or ±2% of Reading
Full Frame Rates	30 Hz	30 Hz	50 Hz (100/200 Hz with windowing)	51 Hz (100/200 Hz with windowing)	0.0015Hz to 125Hz	132 Hz
Video output	Digital(Ethernet) and analog(PAL,NTSC) output	Digital(Ethernet) and analog(PAL,NTSC) output	Digital(Ethernet) and analog(PAL,NTSC) output	Digital(Ethernet, USB, I/O Connector) out	Digital Data Streaming: Gigabit Ethernet; Analog Video	Simultaneous Gigabit Ethernet and Camera Link Full
Measurement Temperature Range	–20 to +120°C, 0 to +350°C	–20 to +120°C, 0 to +350°C	-20 to +150°C +100 to +650°C +300 to +2000°C	-20 to +150°C +100 to +650°C +300 to +2000°C	-20°C to 650°C	-20°C to 500°C (Up to 2,000°C)
Operating Temperature Range	–15 to +50°C	–15 to +50°C	–15 to +50°C	-15°C to +50°C	-40°C to 50°C	-40°C to 50°C
Non-Operating Temperature Range (Storage temperature)	–40°C to +70°C	–40°C to +70°C	–40°C to +70°C	-40°C to 70°C	-55°C to 80°C	-55°C to 80°C
Spectral Array	7.5–13 µm	7.5–13 µm	7.5–14 µm	7.5–14 µm	7.5 - 9.5 µm	1.5 - 5.0 µm
Link	Link	Link	Link	Link	Link	Link
Comment	Field of view (FOV) / Minimum focus distance 25° × 18.8° / 0.4 m	Field of view (FOV) / Minimum focus distance 25° × 18.8° / 0.4 m	Field of view (FOV) / Minimum focus distance...15°: 15° × 11° (19° diagonal) / 0.50 m (1.64 ft.) 25°: 25° × 19° (31° diagonal) / 0.25 m (0.82 ft.) 45°: 45° × 34° (55° diagonal) / 0.15 m (0.49 ft.) 7°: 7° × 5.3° (8.7° diagonally) / 2.0 m (6.6 ft.) 80°: 80° × 64.4° (92.8° diagonal) / 65 mm (2.6 in.)		Standard camera case (R&D) "affordable" 2000°C and 4k Hz possible	R&D camera: Probably the best they have

Method to compare criterias of ultrasonic sensors pairwise												
	K1	K2	K3	K4	K5	K6	K7			Sum	Projection [%]	-> Criteria
K1	-	1	2	2	2	1	2				16,7	
K2	3	-	2	3	3	2	3				9,5	
K3	2	2	-	2	2	2	2				14,3	
K4	2	1	2	-	2	1	3				15,5	
K5	2	1	2	2	-	1	2				16,7	
K6	3	2	2	3	3	-	3				9,5	
K7	2	1	2	1	2	1	-				17,9	
											0,0	
											0,0	
Digit sum	14	8	12	13	14	8	15	0	0	84,00	100,0	
Compared criteria												





LEGEND	
K1	Resolution
K2	Signal
K3	Price
K4	Temperature accuracy
K5	Measurement temp. range
K6	Operating temp. range
K7	Frame rate

Information

Operating Temperature is not so important because this factor needs to be increased with a sensor case anyway.

Used criteria for infrared cameras			Sensors						
			Seek Compact	FLIR One	FLIR Vue (336x256)	FLIR Vue Pro (336x256)	FLIR Vue (640x512)	FLIR Vue Pro (640x512)	FLIR K65
Position	Criteria	Optimum	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]
1	Resolution	640 x 480	2,0	4,0	6,0	6,0	10,0	10,0	8,0
2	Signal	analog/digital/I²C	4	4	10	10	10	10	1
3	Price	$ 650,00	10	10	0	0	0	0	0
4	Temperature accuracy	<50mK / +- 2C°	5	6	10	10	10	10	6
5	Measurement temp. range	-20°C to 300°C	10	8	6	6	6	6	10
6	Operating temp. range	-15°C to >90°C	5	5	7	7	7	7	10
7	Frame rate	50 Hz	3	3	7	7	7	7	7

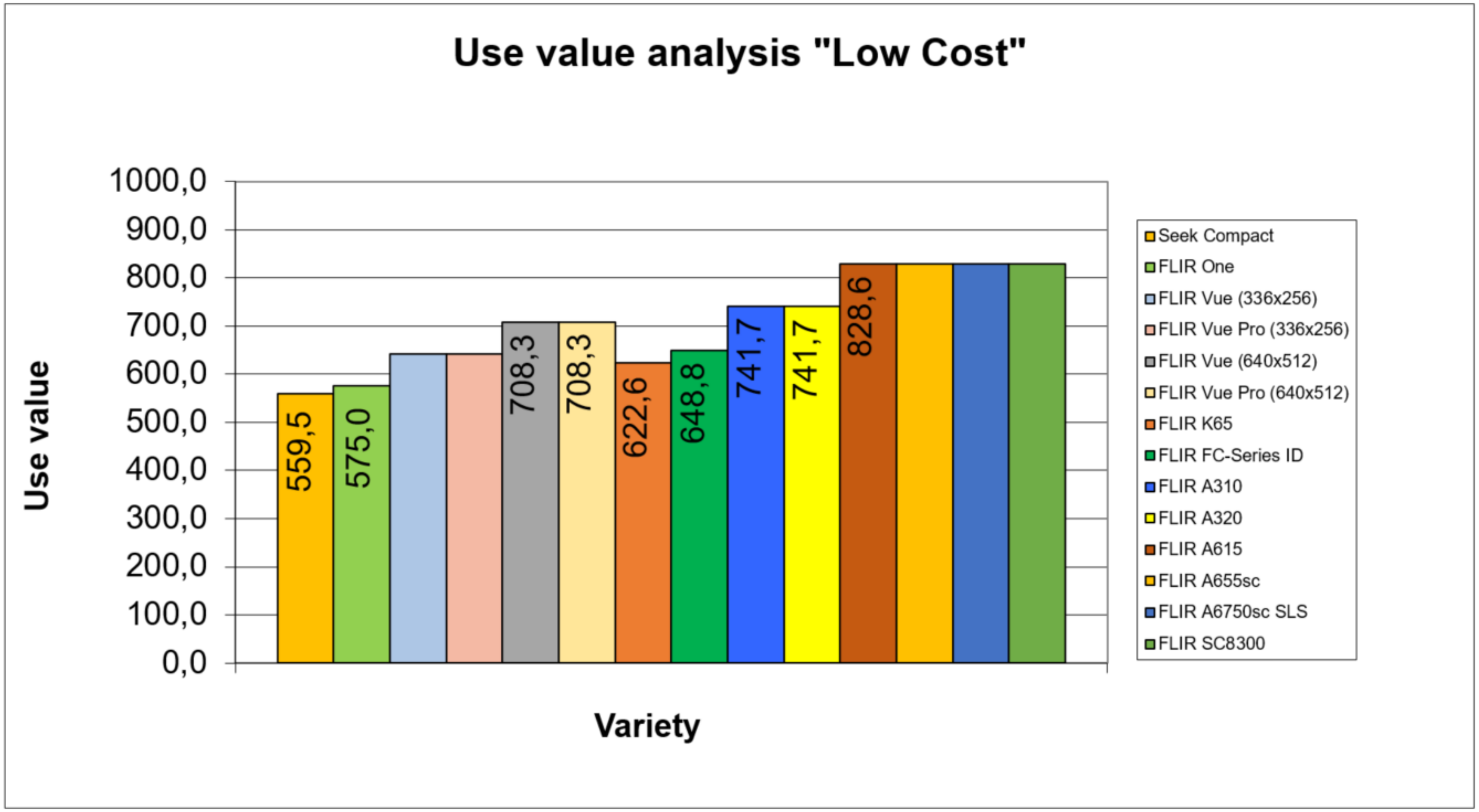
Due to the lack of information 5 was taken

Used criteria for ultrasonic sensors									
			FLIR FC-Series ID	FLIR A310	FLIR A320	FLIR A615	FLIR A655sc	FLIR A6750sc SLS	FLIR SC8300
Position	Criteria	Optimum	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]
1	Resolution	640 x 480	10,0	8,0	8,0	10,0	10,0	10,0	10,0
2	Signal	analog/digital/I²C	10	10	10	10	10	10	10
3	Price	$ 650,00	0	0	0	0	0	0	0
4	Temperature accuracy	<50mK / +- 2C°	6	10	10	10	10	10	10
5	Measurement temp. range	-20°C to 300°C	5	10	10	10	10	10	10
6	Operating temp. range	-15°C to >90°C	9	7	7	7	7	7	7
7	Frame rate	50 Hz	7	7	7	10	10	10	10

Sensors

Criteria	Weight [%] W	Seek Compact		FLIR One		FLIR Vue (336x256)		FLIR Vue Pro (336x256)		FLIR Vue (640x512)		FLIR Vue Pro (640x512)		FLIR K65	
		Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F					Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	16,7	2	33,3	4	66,7	6	100,0	6	100,0	10	166,7	10	166,7	8	133,3
K2	9,5	4	38,1	4	38,1	10	95,2	10	95,2	10	95,2	10	95,2	1	9,5
K3	14,3	10	142,9	10	142,9	0	0,0	0	0,0	0	0,0	0	0,0	0	0,0
K4	15,5	5	77,4	6	92,9	10	154,8	10	154,8	10	154,8	10	154,8	6	92,9
K5	16,7	10	166,7	8	133,3	6	100,0	6	100,0	6	100,0	6	100,0	10	166,7
K6	9,5	5	47,6	5	47,6	7	66,7	7	66,7	7	66,7	7	66,7	10	95,2
K7	17,9	3	53,6	3	53,6	7	125,0	7	125,0	7	125,0	7	125,0	7	125,0
Total	100%		559,5		575,0		641,7		641,7		708,3		708,3		622,6

Criteria	Weight [%] W	FLIR FC-Series ID		FLIR A310		FLIR A320		FLIR A615		FLIR A655sc		FLIR A6750sc SLS		FLIR SC8300	
		Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	16,7	10	166,7	8	133,3	8	133,3	10	166,7	10	166,7	10	166,7	10	166,7
K2	9,5	10	95,2	10	95,2	10	95,2	10	95,2	10	95,2	10	95,2	10	95,2
K3	14,3	0	0,0	0	0,0	0	0,0	0	0,0	0	0,0	0	0,0	0	0,0
K4	15,5	6	92,9	10	154,8	10	154,8	10	154,8	10	154,8	10	154,8	10	154,8
K5	16,7	5	83,3	10	166,7	10	166,7	10	166,7	10	166,7	10	166,7	10	166,7
K6	9,5	9	85,7	7	66,7	7	66,7	7	66,7	7	66,7	7	66,7	7	66,7
K7	17,9	7	125,0	7	125,0	7	125,0	10	178,6	10	178,6	10	178,6	10	178,6
Total	100%		648,8		741,7		741,7		828,6		828,6		828,6		828,6



Conclusion Due to the fact the price limits are set the only two cameras which can be choosen are the Seek thermal or the FLIR One. As can be seen in the graph the Flir One has a better Use value and therefore, this sensor will be in the low cost package.

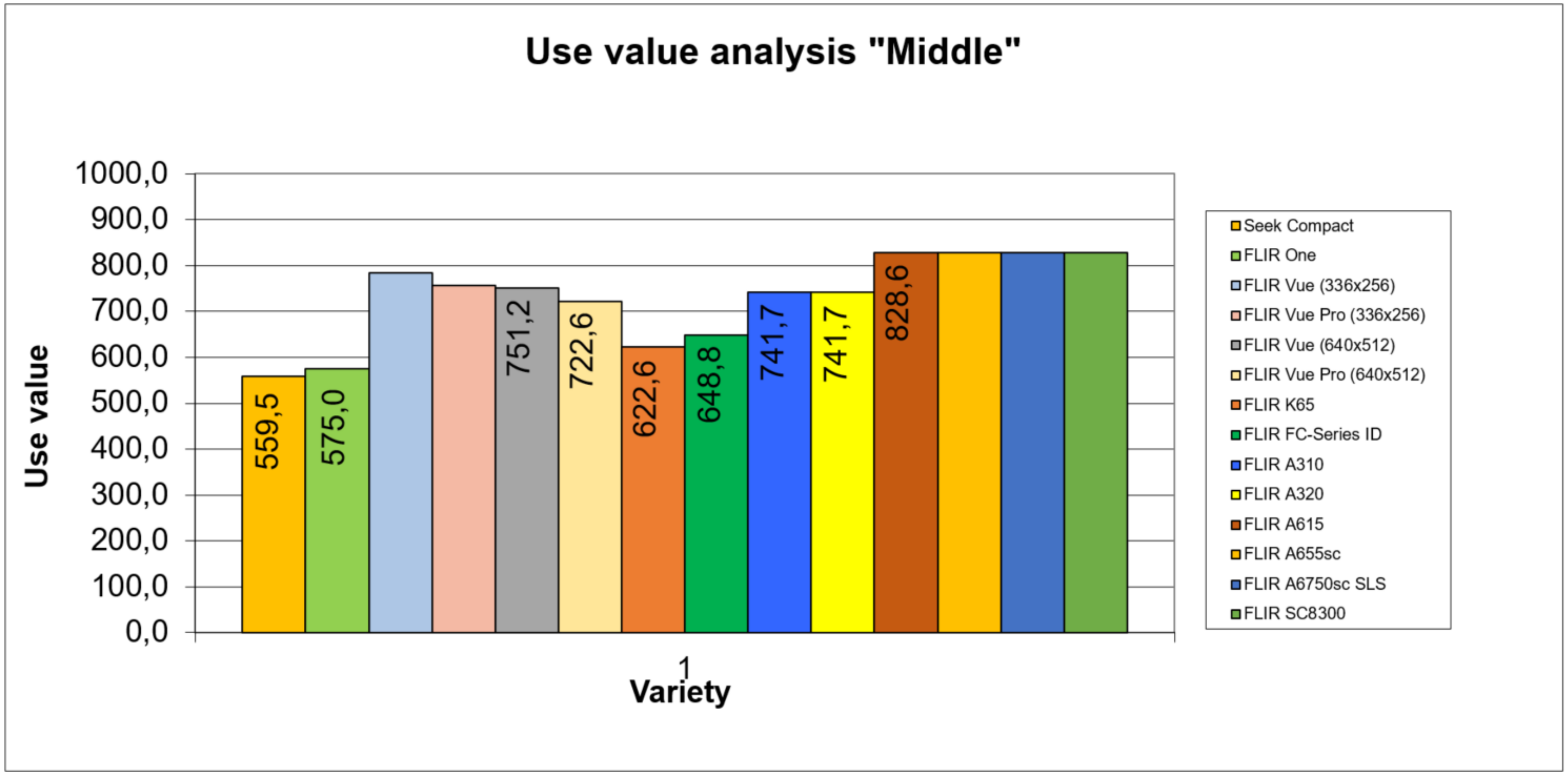
Used criteria for infrared cameras			Sensors						
			Seek Compact	FLIR One	FLIR Vue (336x256)	FLIR Vue Pro (336x256)	FLIR Vue (640x512)	FLIR Vue Pro (640x512)	FLIR K65
Position	Criteria	Optimum	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]
1	Resolution	640 x 480	2,0	4,0	6,0	6,0	10,0	10,0	8,0
2	Signal	analog/digital/I²C	4	4	10	10	10	10	1
3	Price (2 x camera)	$ 3.900,00	10	10	10	8	3	1	0
4	Temperature accuracy	<50mK / +- 2C°	5	6	10	10	10	10	6
5	Measurement temp. range	-20°C to 300°C	10	8	6	6	6	6	10
6	Operating temp. range	-15°C to >90°C	5	5	7	7	7	7	10
7	Frame rate	50 Hz	3	3	7	7	7	7	7

Due to the lack of information 5 was taken

Used criteria for ultrasonic sensors									
			FLIR FC-Series ID	FLIR A310	FLIR A320	FLIR A615	FLIR A655sc	FLIR A6750sc SLS	FLIR SC8300
Position	Criteria	Optimum	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]
1	Resolution	640 x 480	10,0	8,0	8,0	10,0	10,0	10,0	10,0
2	Signal	analog/digital/I²C	10	10	10	10	10	10	10
3	Price (2 x camera)	$ 3.900,00	0	0	0	0	0	0	0
4	Temperature accuracy	<50mK / +- 2C°	6	10	10	10	10	10	10
5	Measurement temp. range	-20°C to 300°C	5	10	10	10	10	10	10
6	Operating temp. range	-15°C to >90°C	9	7	7	7	7	7	7
7	Frame rate	50 Hz	7	7	7	10	10	10	10

Criteria	Weight [%] W	mpact	FLIR One		FLIR Vue (336x256)		FLIR Vue Pro (336x256)		FLIR Vue (640x512)		FLIR Vue Pro (640x512)		FLIR K65	
		Use Value U=W*F	Fulfillment F	Use Value U=W*F					Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	16,7	33,3	4	66,7	6	100,0	6	100,0	10	166,7	10	166,7	8	133,3
K2	9,5	38,1	4	38,1	10	95,2	10	95,2	10	95,2	10	95,2	1	9,5
K3	14,3	142,9	10	142,9	10	142,9	8	114,3	3	42,9	1	14,3	0	0,0
K4	15,5	77,4	6	92,9	10	154,8	10	154,8	10	154,8	10	154,8	6	92,9
K5	16,7	166,7	8	133,3	6	100,0	6	100,0	6	100,0	6	100,0	10	166,7
K6	9,5	47,6	5	47,6	7	66,7	7	66,7	7	66,7	7	66,7	10	95,2
K7	17,9	53,6	3	53,6	7	125,0	7	125,0	7	125,0	7	125,0	7	125,0
Total	**100%**	**559,5**		**575,0**		**784,5**		**756,0**		**751,2**		**722,6**		**622,6**

Criteria	Weight [%] W	FLIR FC-Series ID		FLIR A310		FLIR A320		FLIR A615		FLIR A655sc		FLIR A6750sc SLS		FLIR SC8300	
		Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	16,7	10	166,7	8	133,3	8	133,3	10	166,7	10	166,7	10	166,7	10	166,7
K2	9,5	10	95,2	10	95,2	10	95,2	10	95,2	10	95,2	10	95,2	10	95,2
K3	14,3	0	0,0	0	0,0	0	0,0	0	0,0	0	0,0	0	0,0	0	0,0
K4	15,5	6	92,9	10	154,8	10	154,8	10	154,8	10	154,8	10	154,8	10	154,8
K5	16,7	5	83,3	10	166,7	10	166,7	10	166,7	10	166,7	10	166,7	10	166,7
K6	9,5	9	85,7	7	66,7	7	66,7	7	66,7	7	66,7	7	66,7	7	66,7
K7	17,9	7	125,0	7	125,0	7	125,0	10	178,6	10	178,6	10	178,6	10	178,6
Total	**100%**		**648,8**		**741,7**		**741,7**		**828,6**		**828,6**		**828,6**		**828,6**



Conclusion: As can be seen in the graph the Flir Vue (336x256) has the best use value in the price category < 3900$ (for two cameras).

Used criteria for infrared cameras — **Sensors**

Position	Criteria	Optimum	Seek Compact Fulfillment [0-10]	FLIR One Fulfillment [0-10]	FLIR Vue (336x256) Fulfillment [0-10]	FLIR Vue Pro (336x256) Fulfillment [0-10]	FLIR Vue (640x512) Fulfillment [0-10]	FLIR Vue Pro (640x512) Fulfillment [0-10]	FLIR K65 Fulfillment [0-10]
1	Resolution	640 x 480	2,0	4,0	6,0	6,0	10,0	10,0	8,0
2	Signal	analog/digital/I²C	4	4	10	10	10	10	1
3	Price	$ 18.600,00	10	10	10	10	10	10	10
4	Temperature accuracy	<50mK / +- 2C°	5	6	10	10	10	10	6
5	Measurement temp. range	-20°C to 300°C	10	8	6	6	6	6	10
6	Operating temp. range	-15°C to >90°C	5	5	7	7	7	7	10
7	Frame rate	50 Hz	3	3	7	7	7	7	7

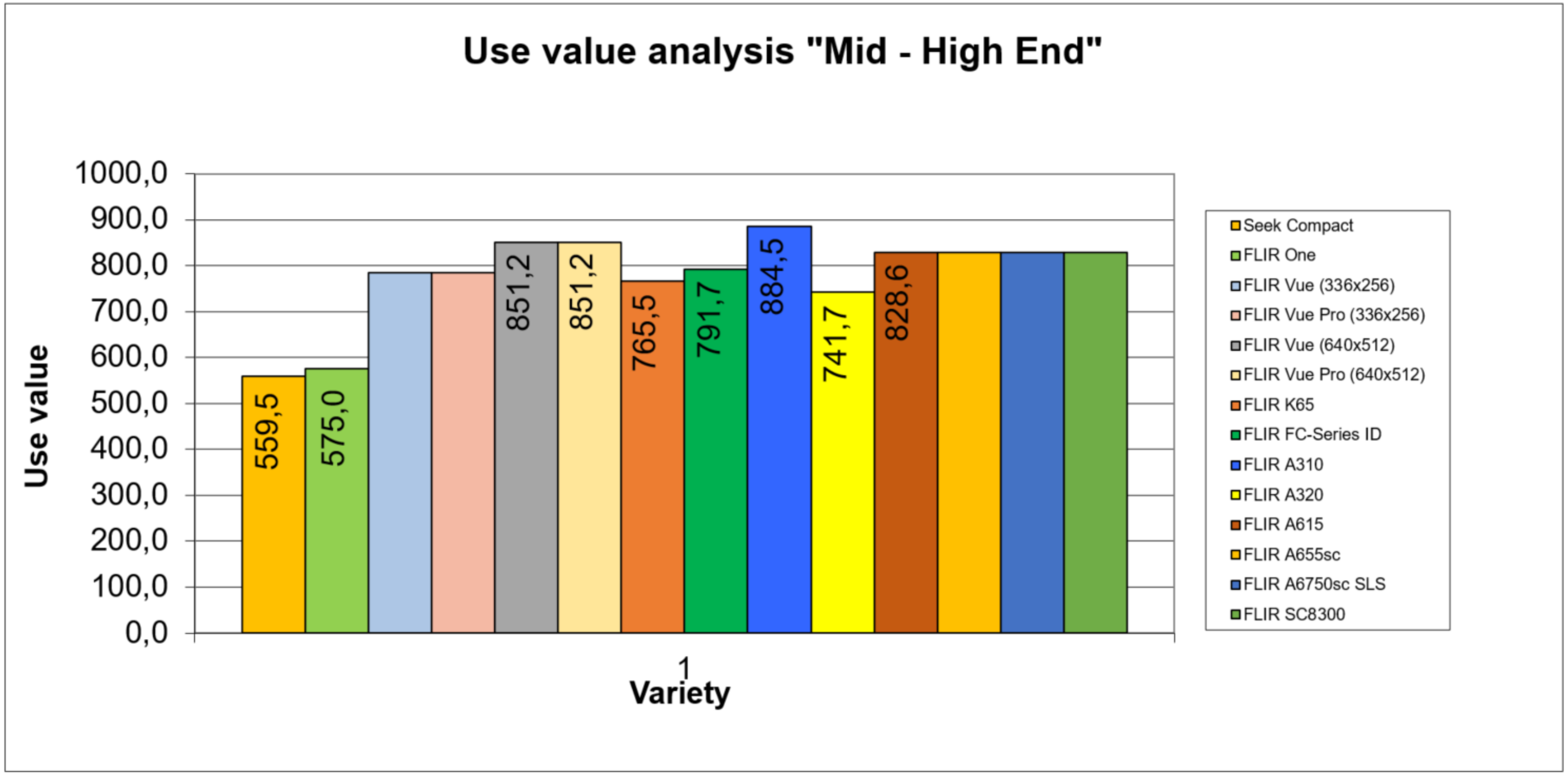
Due to the lack of information 5 was taken

Used criteria for ultrasonic sensors

Position	Criteria	Optimum	FLIR FC-Series ID Fulfillment [0-10]	FLIR A310 Fulfillment [0-10]	FLIR A320 Fulfillment [0-10]	FLIR A615 Fulfillment [0-10]	FLIR A655sc Fulfillment [0-10]	FLIR A6750sc SLS Fulfillment [0-10]	FLIR SC8300 Fulfillment [0-10]
1	Resolution	640 x 480	10,0	8,0	8,0	10,0	10,0	10,0	10,0
2	Signal	analog/digital/I²C	10	10	10	10	10	10	10
3	Price	$ 18.600,00	10	10	0	0	0	0	0
4	Temperature accuracy	<50mK / +- 2C°	6	10	10	10	10	10	10
5	Measurement temp. range	-20°C to 300°C	5	10	10	10	10	10	10
6	Operating temp. range	-15°C to >90°C	9	7	7	7	7	7	7
7	Frame rate	50 Hz	7	7	7	10	10	10	10

Criteria	Weight [%] W	Sensors													
		Seek Compact		FLIR One		FLIR Vue (336x256)		FLIR Vue Pro (336x256)		FLIR Vue (640x512)		FLIR Vue Pro (640x512)		FLIR K65	
		Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F					Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	16,7	2	33,3	4	66,7	6	100,0	6	100,0	10	166,7	10	166,7	8	133,3
K2	9,5	4	38,1	4	38,1	10	95,2	10	95,2	10	95,2	10	95,2	1	9,5
K3	14,3	10	142,9	10	142,9	10	142,9	10	142,9	10	142,9	10	142,9	10	142,9
K4	15,5	5	77,4	6	92,9	10	154,8	10	154,8	10	154,8	10	154,8	6	92,9
K5	16,7	10	166,7	8	133,3	6	100,0	6	100,0	6	100,0	6	100,0	10	166,7
K6	9,5	5	47,6	5	47,6	7	66,7	7	66,7	7	66,7	7	66,7	10	95,2
K7	17,9	3	53,6	3	53,6	7	125,0	7	125,0	7	125,0	7	125,0	7	125,0
Total	100%		559,5		575,0		784,5		784,5		851,2		851,2		765,5

Criteria	Weight [%] W														
		FLIR FC-Series ID		FLIR A310		FLIR A320		FLIR A615		FLIR A655sc		FLIR A6750sc SLS		FLIR SC8300	
		Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	16,7	10	166,7	8	133,3	8	133,3	10	166,7	10	166,7	10	166,7	10	166,7
K2	9,5	10	95,2	10	95,2	10	95,2	10	95,2	10	95,2	10	95,2	10	95,2
K3	14,3	10	142,9	10	142,9	0	0,0	0	0,0	0	0,0	0	0,0	0	0,0
K4	15,5	6	92,9	10	154,8	10	154,8	10	154,8	10	154,8	10	154,8	10	154,8
K5	16,7	5	83,3	10	166,7	10	166,7	10	166,7	10	166,7	10	166,7	10	166,7
K6	9,5	9	85,7	7	66,7	7	66,7	7	66,7	7	66,7	7	66,7	7	66,7
K7	17,9	7	125,0	7	125,0	7	125,0	10	178,6	10	178,6	10	178,6	10	178,6
Total	100%		791,7		884,5		741,7		828,6		828,6		828,6		828,6



Conclusion: As can be seen in the graph the Flir A310 has the best use value in the Mid-High End category. Therefore, it is chosen for this category

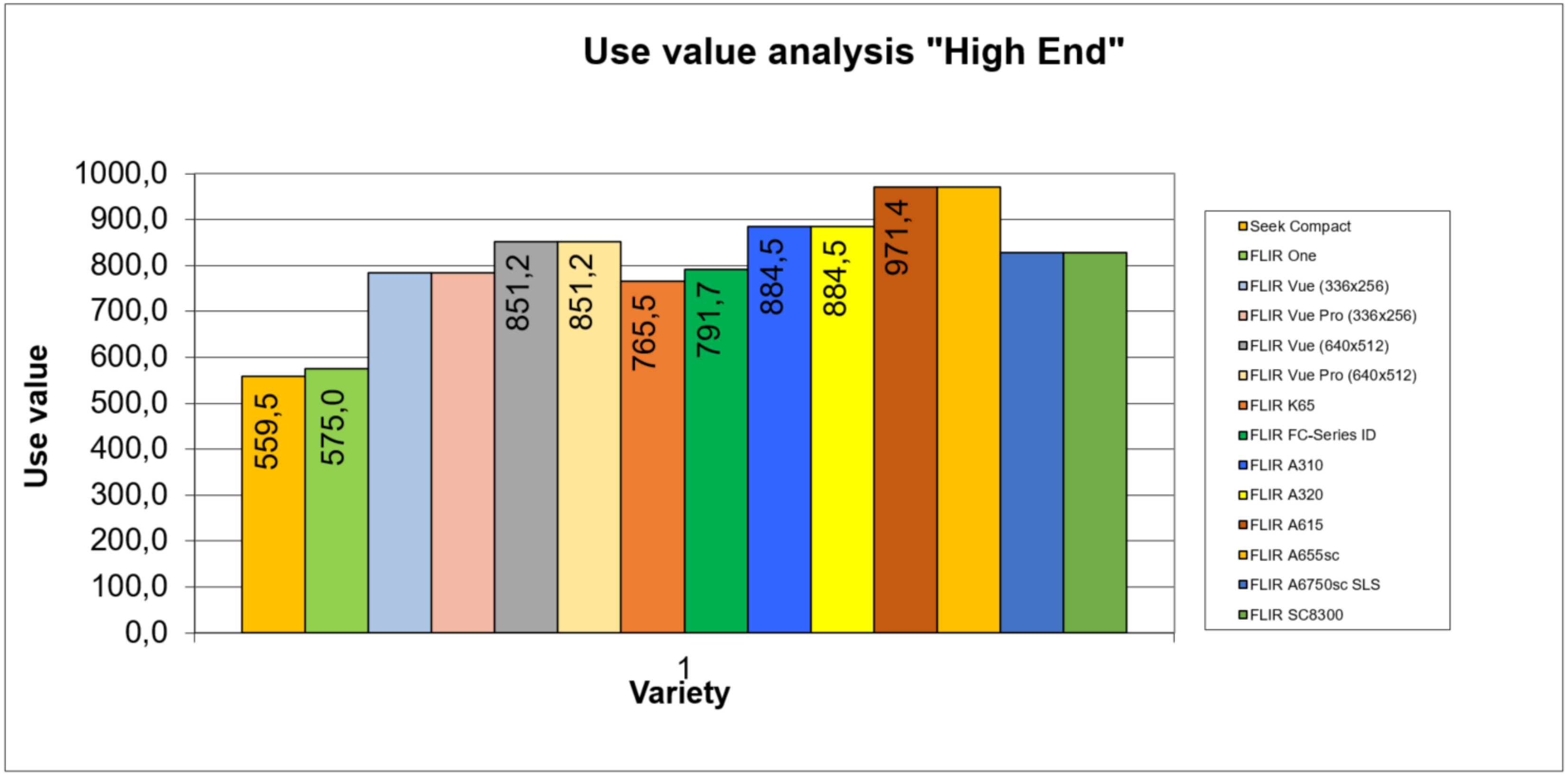
Used criteria for infrared cameras			Sensors						
			Seek Compact	FLIR One	FLIR Vue (336x256)	FLIR Vue Pro (336x256)	FLIR Vue (640x512)	FLIR Vue Pro (640x512)	FLIR K65
Position	Criteria	Optimum	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]
1	Resolution	640 x 480	2,0	4,0	6,0	6,0	10,0	10,0	8,0
2	Signal	analog/digital/I²C	4	4	10	10	10	10	1
3	Price	$ 93.000,00	10	10	10	10	10	10	10
4	Temperature accuracy	<50mK / +- 2C°	5	6	10	10	10	10	6
5	Measurement temp. range	-20°C to 300°C	10	8	6	6	6	6	10
6	Operating temp. range	-15°C to >90°C	5	5	7	7	7	7	10
7	Frame rate	50 Hz	3	3	7	7	7	7	7

			FLIR FC-Series ID	FLIR A310	FLIR A320	FLIR A615	FLIR A655sc	FLIR A6750sc SLS	FLIR SC8300
Position	Criteria	Optimum	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]
1	Resolution	640 x 480	10,0	8,0	8,0	10,0	10,0	10,0	10,0
2	Signal	analog/digital/I²C	10	10	10	10	10	10	10
3	Price	$ 93.000,00	10	10	10	10	10	0	0
4	Temperature accuracy	<50mK / +- 2C°	6	10	10	10	10	10	10
5	Measurement temp. range	-20°C to 300°C	5	10	10	10	10	10	10
6	Operating temp. range	-15°C to >90°C	9	7	7	7	7	7	7
7	Frame rate	50 Hz	7	7	7	10	10	10	10

Sensors

Criteria	Weight [%] W	Seek Compact		FLIR One		FLIR Vue (336x256)		FLIR Vue Pro (336x256)		FLIR Vue (640x512)		FLIR Vue Pro (640x512)		FLIR K65	
		Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F					Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	16,7	2	33,3	4	66,7	6	100,0	6	100,0	10	166,7	10	166,7	8	133,3
K2	9,5	4	38,1	4	38,1	10	95,2	10	95,2	10	95,2	10	95,2	1	9,5
K3	14,3	10	142,9	10	142,9	10	142,9	10	142,9	10	142,9	10	142,9	10	142,9
K4	15,5	5	77,4	6	92,9	10	154,8	10	154,8	10	154,8	10	154,8	6	92,9
K5	16,7	10	166,7	8	133,3	6	100,0	6	100,0	6	100,0	6	100,0	10	166,7
K6	9,5	5	47,6	5	47,6	7	66,7	7	66,7	7	66,7	7	66,7	10	95,2
K7	17,9	3	53,6	3	53,6	7	125,0	7	125,0	7	125,0	7	125,0	7	125,0
Total	100%		559,5		575,0		784,5		784,5		851,2		851,2		765,5

Criteria	Weight [%] W	FLIR FC-Series ID		FLIR A310		FLIR A320		FLIR A615		FLIR A655sc		FLIR A6750sc SLS		FLIR SC8300	
		Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	16,7	10	166,7	8	133,3	8	133,3	10	166,7	10	166,7	10	166,7	10	166,7
K2	9,5	10	95,2	10	95,2	10	95,2	10	95,2	10	95,2	10	95,2	10	95,2
K3	14,3	10	142,9	10	142,9	10	142,9	10	142,9	10	142,9	0	0,0	0	0,0
K4	15,5	6	92,9	10	154,8	10	154,8	10	154,8	10	154,8	10	154,8	10	154,8
K5	16,7	5	83,3	10	166,7	10	166,7	10	166,7	10	166,7	10	166,7	10	166,7
K6	9,5	9	85,7	7	66,7	7	66,7	7	66,7	7	66,7	7	66,7	7	66,7
K7	17,9	7	125,0	7	125,0	7	125,0	10	178,6	10	178,6	10	178,6	10	178,6
Total	100%		791,7		884,5		884,5		971,4		971,4		828,6		828,6



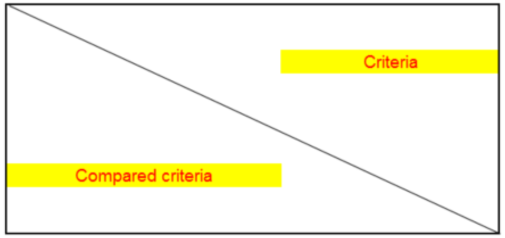
Conclusion: The use value graph shows that the FLIR A615 and the A655sc have the same value, but the A615 is less expensive. Therefore, the A615 is in the High End sensor system package.

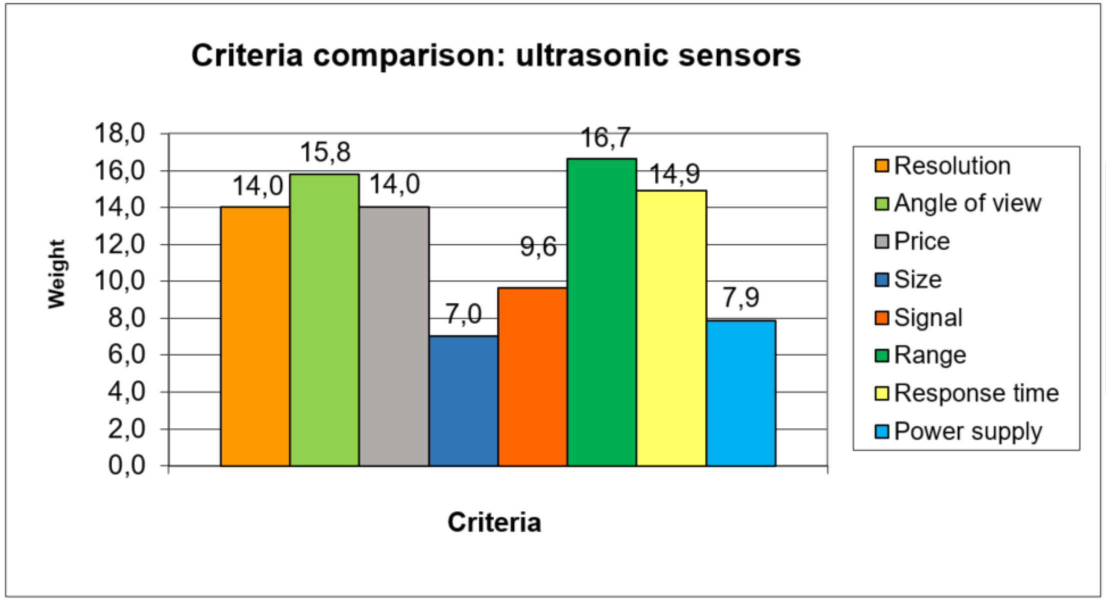
Ultrasonic sensors - Sonar					
Name	Honeywell 946-A4V-2D-2C0-175E	Senix TSPC-30S1-232 ToughSonic Waterproof	Sick UM30-213111	Maxbotix 4-20HR-MaxSonar-WR	SRF235
Image					
Price	1100	550	262	200	110
Angle of View	10°	narrow	32°	<5	15°
Resolution	-	0,086 mm	4 - 36	1,6mm	30 - 40mm
Range	80 mm to 2000 mm	102 - 4300mm	200 - 1300 mm	500 - 5000mm	100 - 1200mm
Response time	<65 ms	nominal 50 ms (5ms- 2,7h)	110 ms	133 ms	10ms
Size	d30 x ~150	d30mm x 103mm	M30 x 84mm	3/4-inch PVC pipe fitting (d19mm x 38mm)	34mm x 20mm x 19mm
Signal	alog 0 Vdc to 10 Vdc|Analog 4 mA to 20 r	analog voltage, current, NPN/PNP and RS-232 serial	PNP: 0 - <2V	Analog current output of 4-20mA	I2C bus interface
Operating Temperature Range	-25 °C to 70 °C	-40 to +70 C	-25 to +70C	-40°C to +65°C	-
Power Input	10 Vdc to 30 Vdc	10-30 VDC (15 VDC min. required for some outputs)	9-30Vdc	10V-32VDC	5V
Link	Link	Link	Link	Link	Link

Ultrasonic sensors - Sonar				
Name	HRXL-MaxSonar-WRS3	SensComp 600 + Ranging Module	SRF10	SRF05
Image				
Price	105	54	38,5	16,5
Angle of View	<5	15°	72°	55°
Resolution	10mm	6mm	30 - 40mm	30 - 40mm
Range	200 - 10680mm	25 - 15200 mm	40 - 6000 mm	30 - 4000 mm
Response time	100 ms	-	65 ms	65 ms
Size	3/4-inch PVC pipe fitting (d19mm x 38mm)	d50 x 30mm	32mm x 15mm x 10mm.	43mm x 20mm x 17mm
Signal	Analog Voltage, Serial, Analog Envelope	TTL	I2C	Pulse Width
Operating Temperature Range	-40ºC to +70ºC	-	-	-
Power Input	3.0 - 5.5V	5V	5V	5V
Link	Link	Link	Link	Link
Link	Link	Link	Link	Link

Method to compare criterias of ultrasonic sensors pairwise

	K1	K2	K3	K4	K5	K6	K7	K8		Sum	Projection [%]	-> Criteria
K1	-	2	3	1	1	2	2	1			14,0	
K2	2	-	1	1	1	2	2	1			15,8	
K3	1	3	-	1	2	2	2	1			14,0	
K4	3	3	3	-	3	4	3	2			7,0	
K5	3	3	2	1	-	4	3	2			9,6	
K6	2	2	2	1	1	-	2	1			16,7	
K7	2	2	2	1	1	2	-	1			14,9	
K8	3	3	3	2	2	3	3	-			7,9	
											0,0	
Digit sum	16	18	16	8	11	19	17	9	0	**114,00**	**100,0**	
Compared criteria												





LEGEND	
K1	Resolution
K2	Angle of view
K3	Price
K4	Size
K5	Signal
K6	Range
K7	Response time
K8	Power supply

Used criteria for ultrasonic sensors			Sensors				
			SRF05	SRF10	SensComp 600	HRXL - MS - WRS3	SRF235
Position	Criteria	Optimum	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]
1	Resolution	10	0,0	0,0	0,0	0,0	0,0
2	Angle of View	10°-20°	5	2	10	1	10
3	Price (per sonar system)	$ 750,00	10	10	10	0	8
4	Size	35³ mm³	8	10	7	10	9
5	Signal	analog/digital/I²C	10	10	10	10	10
6	Range	0-4000mm	10	10	10	10	3
7	Response time	<50ms (20 Hz)	8	8	5	4	10
8	Power Supply	0 - 12V	10	10	10	10	10
9							
	Min. Recommended amount for the sonar system refering to angle:		3	3	8	>20	8

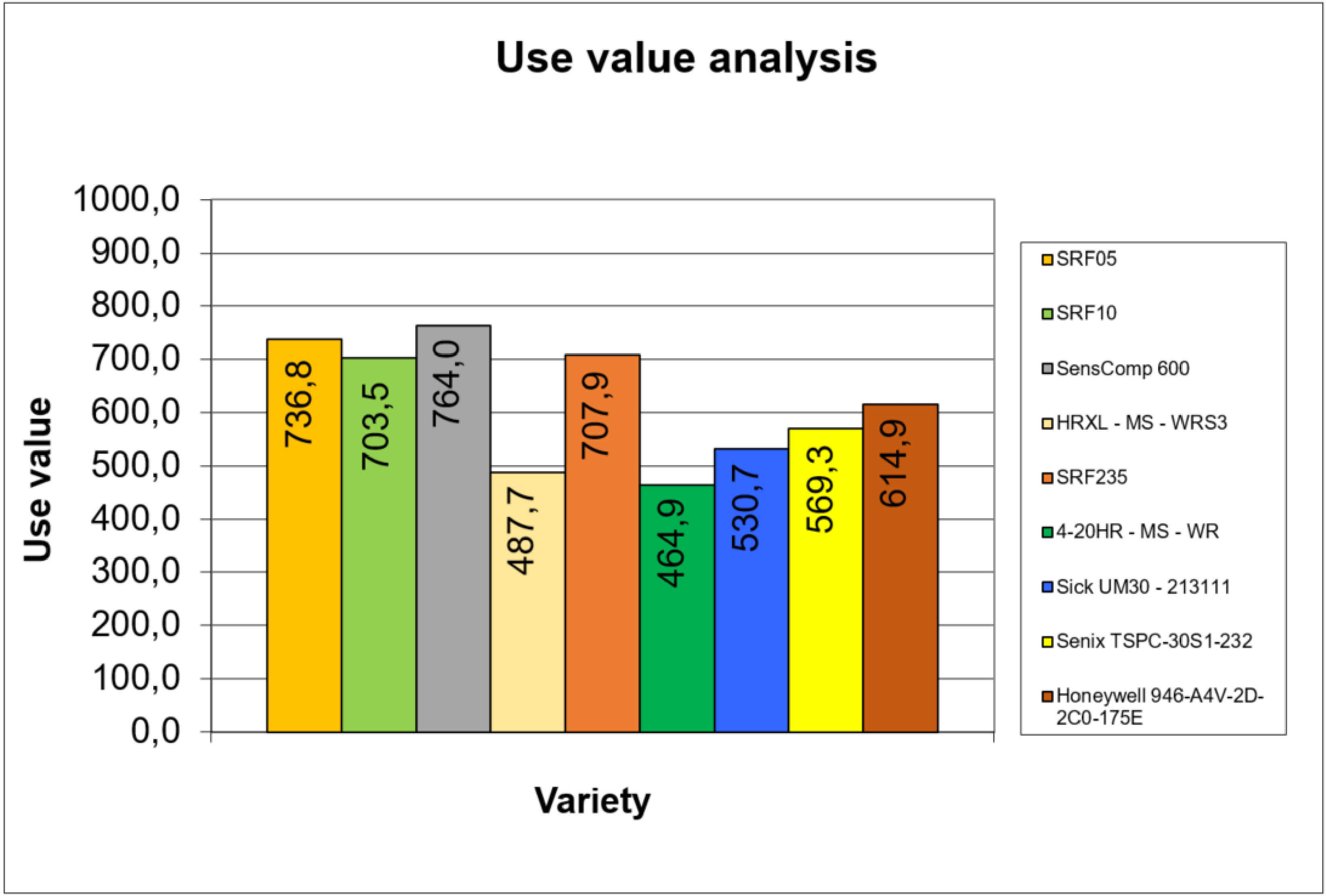
This is based on the Pioneer PX3 sonar robot with 8x15° with 10° distance each sensor

Due to the lack of information 5 was taken

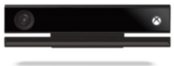
Used criteria for ultrasonic sensors						
			4-20HR - MS - WR	Sick UM30 - 213111	Senix TSPC-30S1-232	Honeywell 946-A4V-2D-2C0-175E
Position	Criteria	Optimum	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]
1	Resolution	10	0,0	0,0	0,0	0,0
2	Angle of View	10°-20°	1	7	1	10
3	Price (per sonar system)	$ 750,00	0	4	0	0
4	Size	35³ mm³	10	10	10	10
5	Signal	analog/digital/I²C	10	10	10	10
6	Range	0-4000mm	10	4	10	6
7	Response time	<50ms (20 Hz)	3	4	10	8
8	Power Supply	0 - 12V	9	9	9	9
9						
	Min. Recommended amount for the sonar system refering to angle:		>20	5	>20	10

Criteria	Weight [%] W	*Sensors*									
		SRF05		SRF10		SensComp 600		HRXL - MS - WRS3		SRF235	
		Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	14,0	0	0,0	0	0,0	0	0,0	0	0,0	0	0,0
K2	15,8	5	78,9	2	31,6	10	157,9	1	15,8	10	157,9
K3	14,0	10	140,4	10	140,4	10	140,4	0	0,0	8	112,3
K4	7,0	8	56,1	10	70,2	7	49,1	10	70,2	9	63,2
K5	9,6	10	96,5	10	96,5	10	96,5	10	96,5	10	96,5
K6	16,7	10	166,7	10	166,7	10	166,7	10	166,7	3	50,0
K7	14,9	8	119,3	8	119,3	5	74,6	4	59,6	10	149,1
K8	7,9	10	78,9	10	78,9	10	78,9	10	78,9	10	78,9
K9	0,0	0	0,0	0	0,0	0	0,0	0	0,0	0	0,0
Total	**100%**		**736,8**		**703,5**		**764,0**		**487,7**		**707,9**

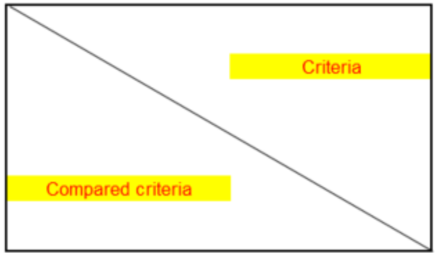
Criteria	Weight [%] W	4-20HR - MS - WR		Sick UM30 - 213111		Senix TSPC-30S1-232		Honeywell 946-A4V-2D-2C0-175E	
		Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	14,0	0	0,0	0	0,0	0	0,0	0	0,0
K2	15,8	1	15,8	7	110,5	1	15,8	10	157,9
K3	14,0	0	0,0	4	56,1	0	0,0	0	0,0
K4	7,0	10	70,2	10	70,2	10	70,2	10	70,2
K5	9,6	10	96,5	10	96,5	10	96,5	10	96,5
K6	16,7	10	166,7	4	66,7	10	166,7	6	100,0
K7	14,9	3	44,7	4	59,6	10	149,1	8	119,3
K8	7,9	9	71,1	9	71,1	9	71,1	9	71,1
K9	0,0	0	0,0	0	0,0	0	0,0	0	0,0
Total	**100%**		**464,9**		**530,7**		**569,3**		**614,9**

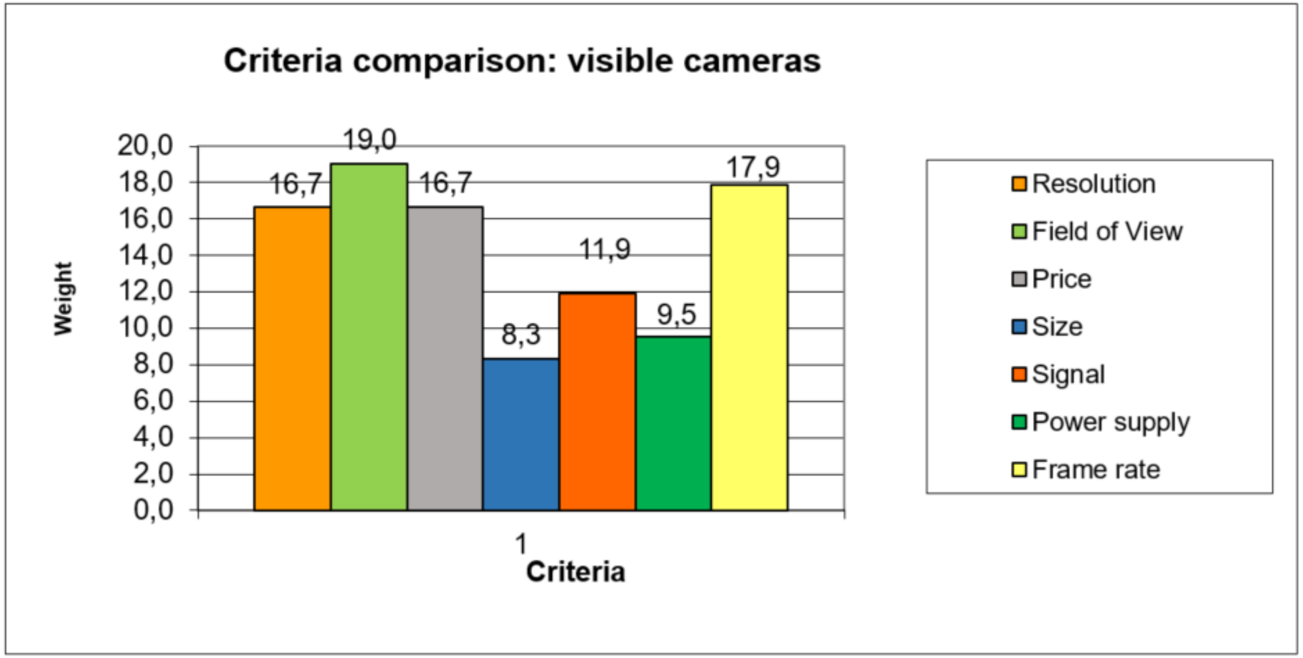


Conclusion: As can be seen in the use value figure, the SensComp 600 is the most useful sensor in comparison to the other sensors. Therefore, it is applied to Middle, Mid-High End and in the High End sensor system package. The SRF05 is choosen for the Low Cost package due to the second highest rating and the low cost

Visible cameras	mvBlueSIRIUS	ZED	Bumblebee2 0.8 MP Color FireWire 1394a 2.5mm (Sony ICX204)	Kinect 2	PlayStation 4 Camera	Ensenso N10
						
Price	$6.000,00	$450,00	-	$120,00	$50,00	$3.900,00
Resolution	1.3MP (overlap area 1024 x 1024)	2.2k - VGA (depending on Mode)	1032 x 776	1080p	720p	752 x 480
Frame Rate	25 FPS	15 - 120 FPS (depending on Mode)	20 FPS	30 FPS	60 FPS (120 Hz)	30 FPS
Field of View	53° Detection Range	110°	100°	70° x 60°	85°	50 - 300° (depending on cameras)
Video output	GBit Ethernet LAN, 4x Digital In, 4x Digital Out	digital (USB)	analog (3.3V), Interface: FireWire 1394a, Serial Port	digital (USB)	digital (USB)	digital (USB)
Recommended distance	270 mm up to 2500 mm	1.5 - 20 m	-	500 - 4500mm	-	2000 mm
Operating Temperature Range	0 .. 40 °C	-	0° to 40°C	5° to 35°	5° to 50°	0° to 40°C
Power supply	24V	5V	12V	12V	110 - 230V	5V
Size	61 x 56 x 234 mm	175 x 30 x 33 mm	157 mm x 36 mm x 47.4 mm	24.9cm x 6.6cm x 6.7cm	186 x 27 x 27mm	150 x 45 x 45mm
Link	Link	Link	Link	Link	Link	Link
Comment				In tests the Kinect is better than the PS4 Camera		cameras can be choosen

Method to compare criterias of ultrasonic sensors pairwise												
	K1	K2	K3	K4	K5	K6	K7			Sum	Projection [%]	-> Criteria
K1	-	2	3	1	1	1	2				16,7	
K2	2	-	1	1	1	1	2				19,0	
K3	1	3	-	1	2	1	2				16,7	
K4	3	3	3	-	3	2	3				8,3	
K5	3	3	2	1	-	2	3				11,9	
K6	3	3	3	2	2	-	3				9,5	
K7	2	2	2	1	1	1	-				17,9	
											0,0	
											0,0	
Digit sum	14	16	14	7	10	8	15	0	0	84,00	100,0	
Compared criteria												



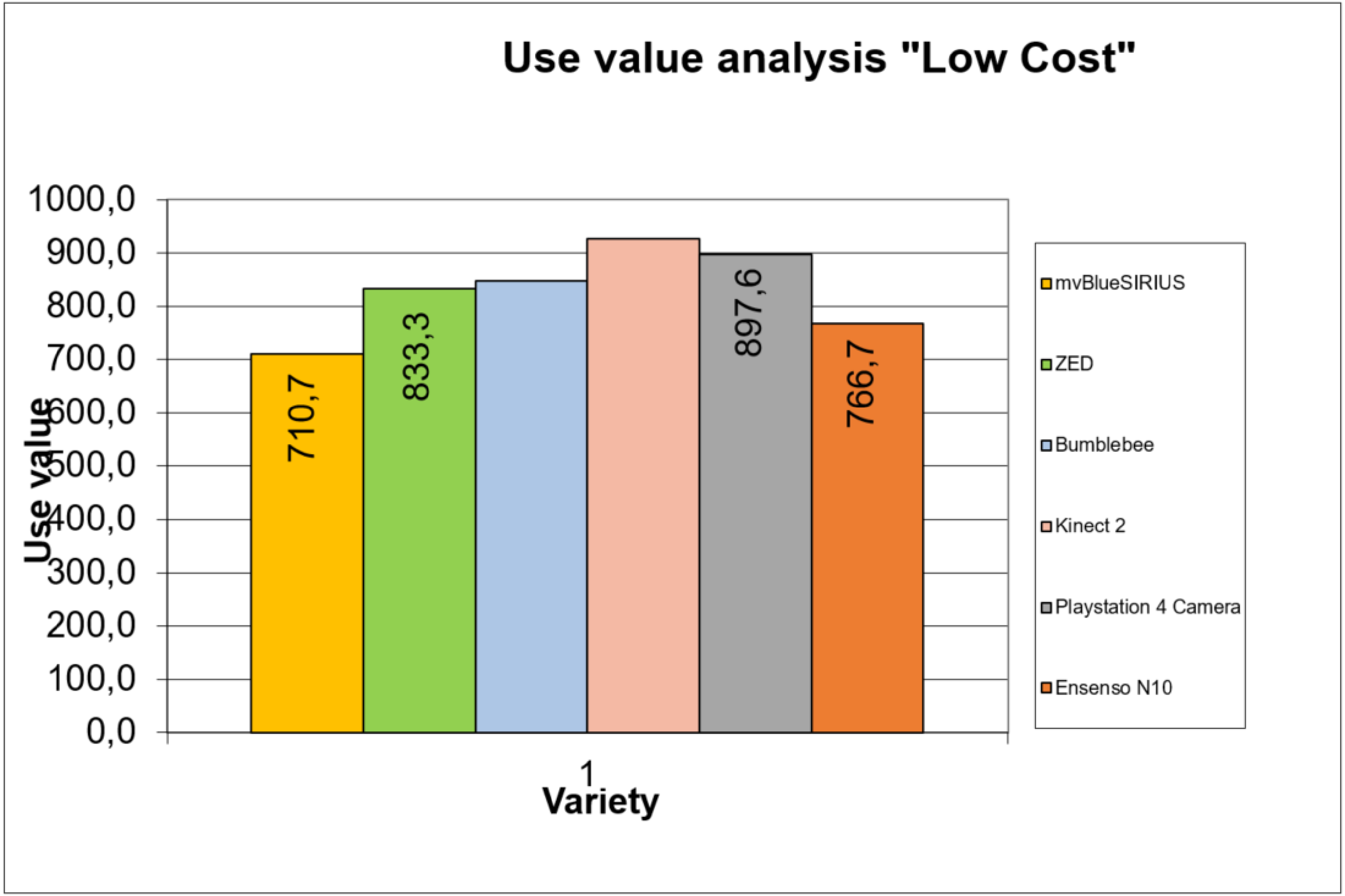


LEGEND	
K1	Resolution
K2	Field of View
K3	Price
K4	Size
K5	Signal
K6	Power supply
K7	Frame rate

Used criteria for visible cameras			Sensors					
			mvBlueSIRIUS	ZED	Bumblebee	Kinect 2	Playstation 4 Camera	Ensenso N10
Position	Criteria	Optimum	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]
1	Resolution	1280 x 1024 (1.3MP)	10,0	10,0	8,0	10,0	9,0	6,0
2	Field of View	100°	6	10	10	7	8	10
3	Price	$ 150,00	0	0	5	10	10	0
4	Size	220 x 210 x 220	9	10	10	8	10	10
5	Signal	analog/digital/I²C	10	10	10	10	10	10
6	Power supply	0 - 12V	6	10	10	10	5	10
7	Frame rate	25 FPS / 50 Hz	10	10	8	10	10	10

Due to the lack of information 5 was taken

Criteria	Weight [%] W	Sensors											
		mvBlueSIRIUS		ZED		Bumblebee		Kinect 2		Playstation 4 Camera		Ensenso N10	
		Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F					Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	16,7	10	166,7	10	166,7	8	133,3	10	166,7	9	150,0	6	100,0
K2	19,0	6	114,3	10	190,5	10	190,5	7	133,3	8	152,4	10	190,5
K3	16,7	0	0,0	0	0,0	5	83,3	10	166,7	10	166,7	0	0,0
K4	8,3	9	75,0	10	83,3	10	83,3	8	66,7	10	83,3	10	83,3
K5	11,9	10	119,0	10	119,0	10	119,0	10	119,0	10	119,0	10	119,0
K6	9,5	6	57,1	10	95,2	10	95,2	10	95,2	5	47,6	10	95,2
K7	17,9	10	178,6	10	178,6	8	142,9	10	178,6	10	178,6	10	178,6
Total	**100%**		**710,7**		**833,3**		**847,6**		**926,2**		**897,6**		**766,7**

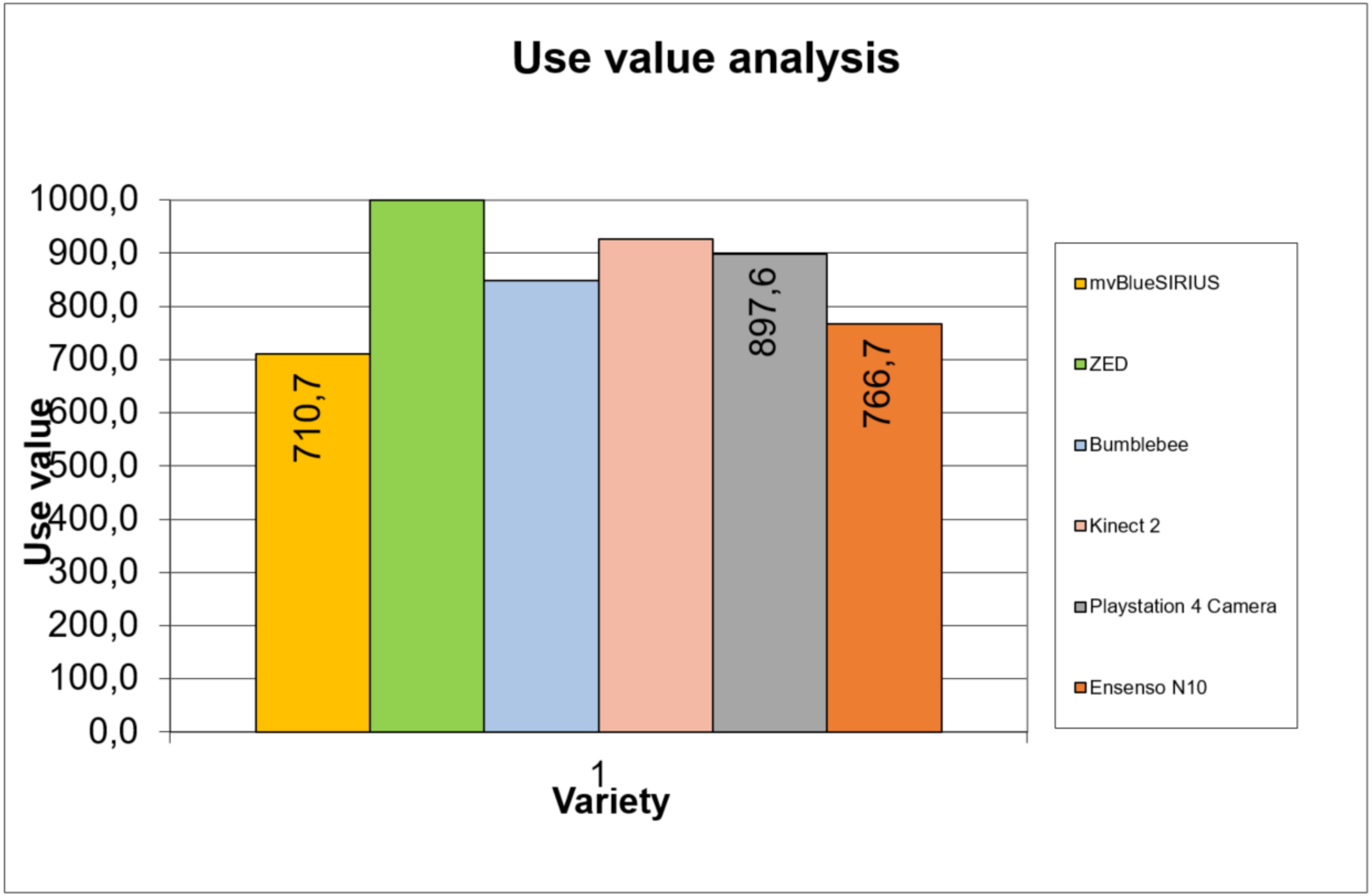


Conclusion: As can be seen in figure "use value analysis" the kinect 2 has the best use for the Low cost price category.

Used criteria for visible cameras			Sensors					
			mvBlueSIRIUS	ZED	Bumblebee	Kinect 2	Playstation 4 Camera	Ensenso N10
Position	Criteria	Optimum	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]
1	Resolution	1280 x 1024 (1.3MP)	10,0	10,0	8,0	10,0	9,0	6,0
2	Field of View	100°	6	10	10	7	8	10
3	Price	$ 750,00	0	10	5	10	10	0
4	Size	220 x 210 x 220	9	10	10	8	10	10
5	Signal	analog/digital/I²C	10	10	10	10	10	10
6	Power supply	0 - 12V	6	10	10	10	5	10
7	Frame rate	25 FPS / 50 Hz	10	10	8	10	10	10

Due to the lack of information 5 was taken

Criteria	Weight [%] W	Sensors											
		mvBlueSIRIUS		ZED		Bumblebee		Kinect 2		Playstation 4 Camera		Ensenso N10	
		Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F					Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	16,7	10	166,7	10	166,7	8	133,3	10	166,7	9	150,0	6	100,0
K2	19,0	6	114,3	10	190,5	10	190,5	7	133,3	8	152,4	10	190,5
K3	16,7	0	0,0	10	166,7	5	83,3	10	166,7	10	166,7	0	0,0
K4	8,3	9	75,0	10	83,3	10	83,3	8	66,7	10	83,3	10	83,3
K5	11,9	10	119,0	10	119,0	10	119,0	10	119,0	10	119,0	10	119,0
K6	9,5	6	57,1	10	95,2	10	95,2	10	95,2	5	47,6	10	95,2
K7	17,9	10	178,6	10	178,6	8	142,9	10	178,6	10	178,6	10	178,6
Total	**100%**		**710,7**		**1000,0**		**847,6**		**926,2**		**897,6**		**766,7**

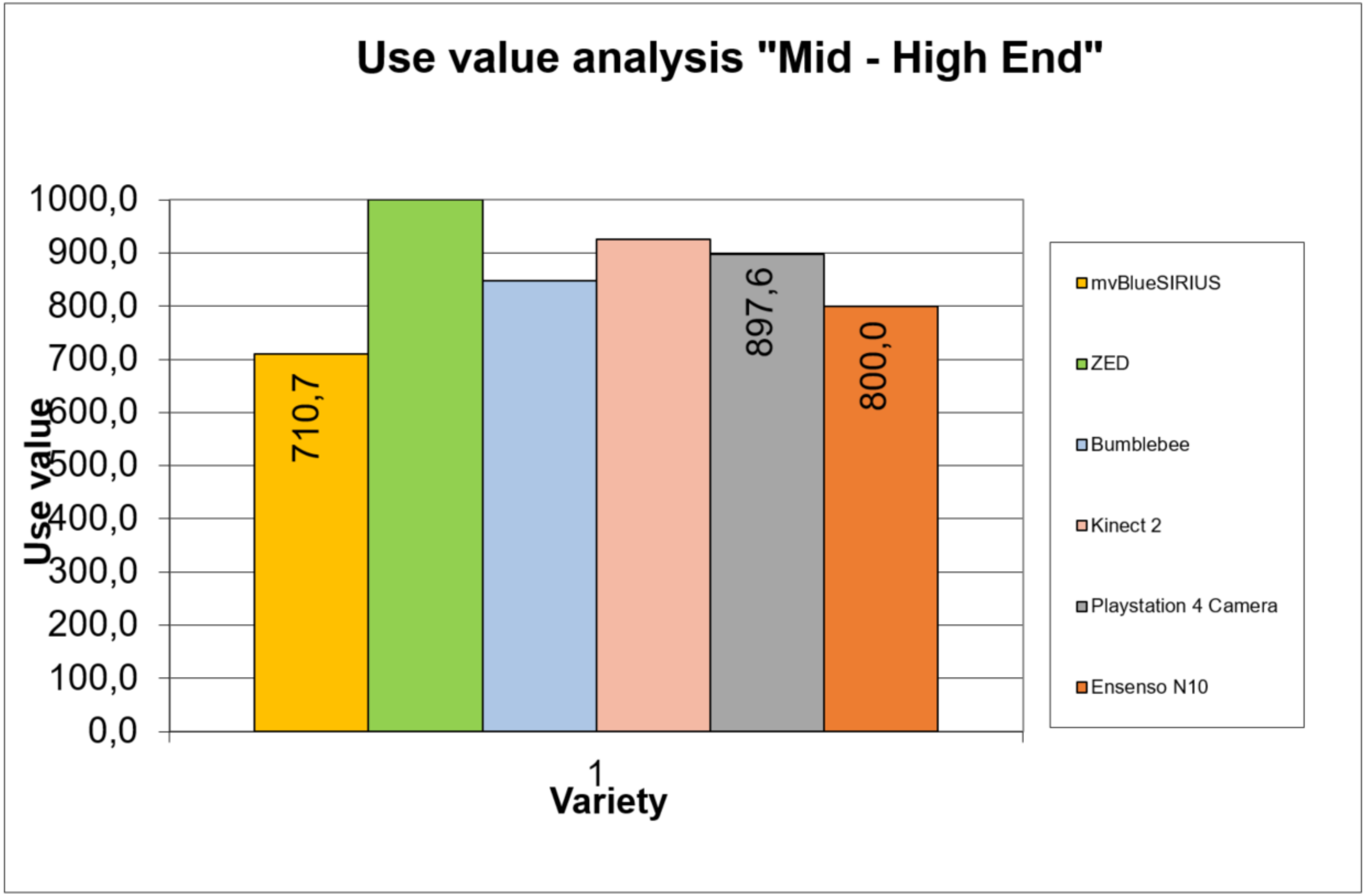


Conclusion: As can be seen in figure "use value analysis" the ZED has the best use for the Middle price category.

Used criteria for visible cameras			Sensors					
			mvBlueSIRIUS	ZED	Bumblebee	Kinect 2	Playstation 4 Camera	Ensenso N10
Position	Criteria	Optimum	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]
1	Resolution	1280 x 1024 (1.3MP)	10,0	10,0	8,0	10,0	9,0	6,0
2	Field of View	100°	6	10	10	7	8	10
3	Price	$ 3.000,00	0	10	5	10	10	2
4	Size	220 x 210 x 220	9	10	10	8	10	10
5	Signal	analog/digital/I²C	10	10	10	10	10	10
6	Power supply	0 - 12V	6	10	10	10	5	10
7	Frame rate	25 FPS / 50 Hz	10	10	8	10	10	10

Due to the lack of information 5 was taken

Criteria	Weight [%] W	Sensors											
		mvBlueSIRIUS		ZED		Bumblebee		Kinect 2		Playstation 4 Camera		Ensenso N10	
		Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F					Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	16,7	10	166,7	10	166,7	8	133,3	10	166,7	9	150,0	6	100,0
K2	19,0	6	114,3	10	190,5	10	190,5	7	133,3	8	152,4	10	190,5
K3	16,7	0	0,0	10	166,7	5	83,3	10	166,7	10	166,7	2	33,3
K4	8,3	9	75,0	10	83,3	10	83,3	8	66,7	10	83,3	10	83,3
K5	11,9	10	119,0	10	119,0	10	119,0	10	119,0	10	119,0	10	119,0
K6	9,5	6	57,1	10	95,2	10	95,2	10	95,2	5	47,6	10	95,2
K7	17,9	10	178,6	10	178,6	8	142,9	10	178,6	10	178,6	10	178,6
Total	**100%**		**710,7**		**1000,0**		**847,6**		**926,2**		**897,6**		**800,0**



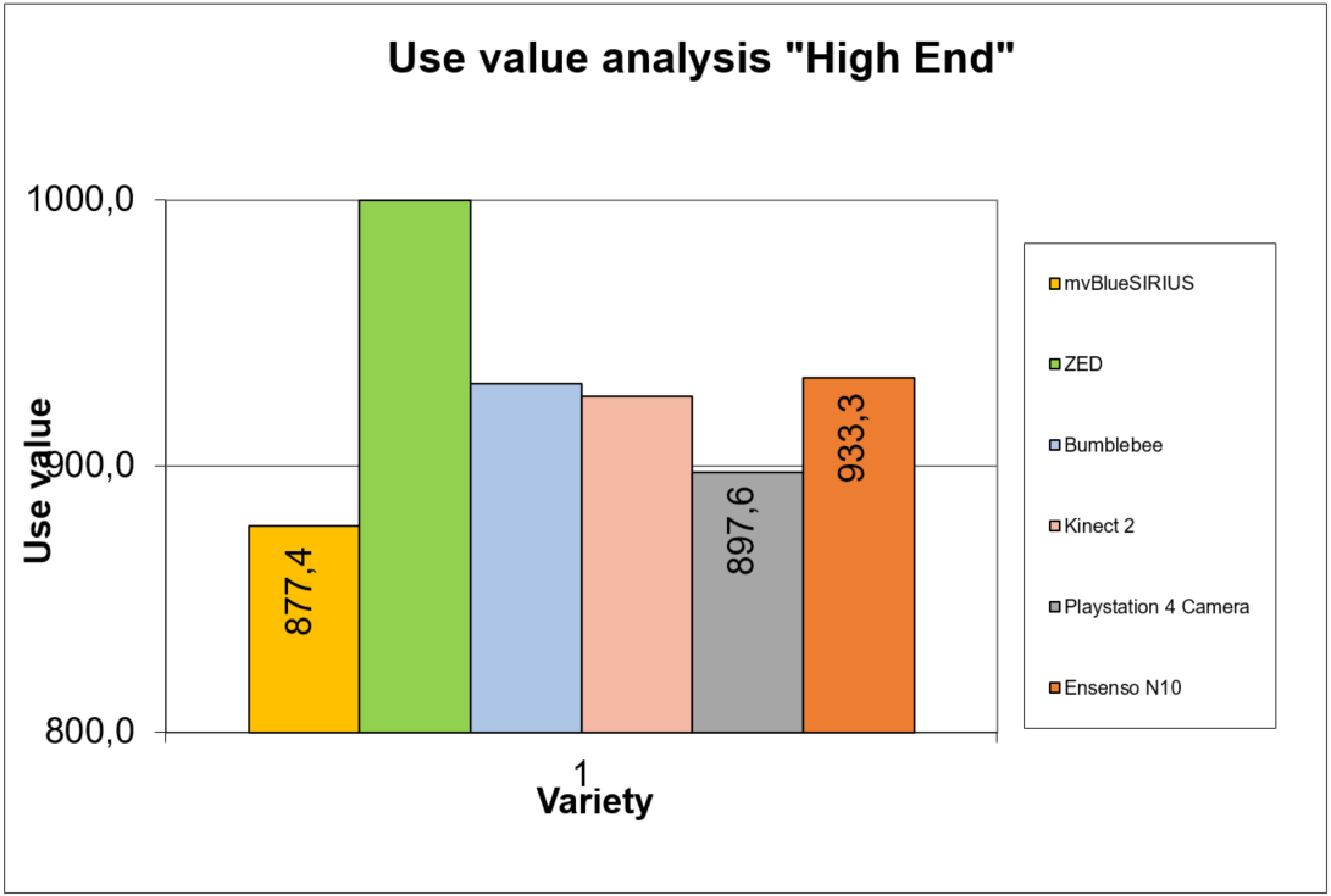
Conclusion: As can be seen in figure "use value analysis" the ZED has the best use for the Mid-High End price category.

Used criteria for visible cameras			Sensors					
			mvBlueSIRIUS	ZED	Bumblebee	Kinect 2	Playstation 4 Camera	Ensenso N10
Position	Criteria	Optimum	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]	Fulfillment [0-10]
1	Resolution	1280 x 1024 (1.3MP)	10,0	10,0	8,0	10,0	9,0	6,0
2	Field of View	100°	6	10	10	7	8	10
3	Price	$ 15.000,00	10	10	10	10	10	10
4	Size	220 x 210 x 220	9	10	10	8	10	10
5	Signal	analog/digital/I²C	10	10	10	10	10	10
6	Power supply	0 - 12V	6	10	10	10	5	10
7	Frame rate	25 FPS / 50 Hz	10	10	8	10	10	10

Due to the lack of information 5 was taken

In this price category it is assumed that the Bumblebee is less expensive, therefore it gets 10 points

Criteria	Weight [%] W	Sensors											
		mvBlueSIRIUS		ZED		Bumblebee		Kinect 2		Playstation 4 Camera		Ensenso N10	
		Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F					Fulfillment F	Use Value U=W*F	Fulfillment F	Use Value U=W*F
K1	16,7	10	166,7	10	166,7	8	133,3	10	166,7	9	150,0	6	100,0
K2	19,0	6	114,3	10	190,5	10	190,5	7	133,3	8	152,4	10	190,5
K3	16,7	10	166,7	10	166,7	10	166,7	10	166,7	10	166,7	10	166,7
K4	8,3	9	75,0	10	83,3	10	83,3	8	66,7	10	83,3	10	83,3
K5	11,9	10	119,0	10	119,0	10	119,0	10	119,0	10	119,0	10	119,0
K6	9,5	6	57,1	10	95,2	10	95,2	10	95,2	5	47,6	10	95,2
K7	17,9	10	178,6	10	178,6	8	142,9	10	178,6	10	178,6	10	178,6
Total	**100%**		**877,4**		**1000,0**		**931,0**		**926,2**		**897,6**		**933,3**



Conclusion: As can be seen in figure "use value analysis" the ZED has the best use for the High End price category.

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