TRANSPORT AND SAFETY

A summary of the SIGHT project - Evaluation of sensors for obstacle detection

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- Evaluation of sensors

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Abstract

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Atlas Copco Rock Drills, Komatsu Forest and Volvo Construction Equipment have together with Örebro University, Luleå Technical University, RISE Research institutes of Sweden (former SP), Robotdalen and The Association of Heavy Vehicles, cooperate in this project to evaluate sensors. The aim is to develop the machine capability of "obstacle detection".

A single sensor alone is not expected to fulfil the safety requirements. Research is needed to develop sensor systems - combinations of two or more sensor technologies.

Key words: mobile machinery, sensors, obstacle detection, safety

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Innehåll

Preface

The Association of Heavy Vehicles (Swe. “Tunga fordon”) has initiated a research project to evaluate sensors intended for obstacle detection. The overall objective of the project is to develop cost efficient and robust sensor systems for obstacle detection. The sensor systems must fulfil the needs of heavy vehicles. This report summarizes results from evaluations in the laboratory and from theoretical studies.

Some of the illustrations in this report are based on standards. Standards are protected by copyright. For full understanding, the complete standard must be purchased. Standards are available from national standardization organizations, e.g. www.sis.se.

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PROCESS INDUSTRIAL IT AND AUTOMATION

Summary

Mobile machinery in forestry, mining and construction work must be able to detect obstacles in their surroundings. The safety of the operator of the machine and of the individuals in the risk area will be increased by obstacle detection and avoidance capability. Obstacle detection and avoidance will also enable autonomous vehicles to interact in an unpredictable environment. A high degree of automation will mean a more efficient production, reduced wear of the vehicles and reduced fuel consumption.

Atlas Copco Rock Drills, Komatsu Forest and Volvo Construction Equipment have together with Örebro University, Luleå University of Technology, RISE Research institutes of Sweden (former SP), Robotdalen and The Association of Heavy Vehicles, cooperate in this project to evaluate sensors. The aim is to develop the machine capability of “obstacle detection”.

A single sensor is not expected to fulfil the safety requirements. Research is needed to develop sensor systems, i.e. a combination of two or more sensor technologies. This report summarizes the results of theoretical studies and of laboratory testing.

1 Sensor technologies

The goal of the evaluation is to test a variety of different sensor modalities. This section describes the sensing principle of the set of sensors evaluated on a higher level. The intension is to give a short and description of each modality, its sensing principle along with pros and cons.

1.1 Sonars

Sonars returns distance estimates using “sound”. It operates by measuring the time between a signal (pressure peak) is emitted until it returns. Depending on the medium used, the speed of the pressure wave will be different. In this context of SIGHT the medium used is air (as oppose to underwater applications). The speed of sound in air is also mainly dependent on the temperature (and also the humidity), for example, a change from 0 to 20 degrees Celsius will increase the speed of sound with approx. 4%.

Sonars that operate in air have a set of different properties. The pressure wave (sound) that is emitted could be of different frequency ranging from very low to high (ultra-sonic). The width of the emitted signal or cone can be varied. In order to have multiple readings at different direction multiple sonar devices needs to be configured in an array. In principle, the “Doppler effect” could be used to also estimate the relative speed between the sonar and the detected object although this seems not to be used.

To detect the time of traversal for a signal is commonly done in other sensor modalities, such as laser range scanners, radars, for example. The main difference here is the use of the medium (air). Due to the propagation of pressure waves in air it is much more difficult to control the width of the sensor cone. The speed of sound is also relatively slow meaning that the amount of data received is much more limited. The envision application for sonars is shorter range and where the larger cone could be used to detect obstacles, but without the capabilities to recognize what type of object it is. It is also relatively insensitive to various weather conditions such as fog, rain and snow.

1.2 Time of flight Cameras

As the name indicates, the output of these family of sensors are readings in a 2D grid, similar to the pixels in a camera. For ToF cameras, the output (similar to a laser scanner) is depth estimates and re-emission (reflectance) values. Oppose to laser scanners, which shoots a thin laser beam and measure its time of return, the ToF cameras needs to illuminate the whole scene. The drawback of illuminating a whole scene is that it requires a relatively strong lamp to do so. The required power needed is proportional to the square of the distance. To illuminate at 10 meters, you need 100 times as strong light source as for 1 meter. Due to the illumination, the field of view and max range of a ToF camera goes hand in hand meaning that is difficult to see far with a wide FOV.

There exist a variety of different techniques how to emit and measure the light. One of the most common one is to continuously pulse the light with a specific frequency (instead of sending a single pulse and measure the time of flight). This “simplifies” the problem to detect the phase shift between the submitted light and the returned light. This comes with another problem to determine the distance can only be determined relative to the modulus operator of the max range. That is if the max range is 5 meters, you cannot tell if the distance is 1, 6 or 11 meters and so on. Nowadays, there are multiple solution how to encode multiple frequencies in the illumination to cancel this out.

Time of flight cameras is currently commonly used in indoor short range applications, up to 10 meters. As mentioned, one crucial part is the required illumination. With limited FOV coverage multiple sensors needs to be used. The spatial resolution is good with a high frame rate, furthermore there is no dependencies on textures (nor good illumination conditions) as in stereo vision based systems.

1.3 Stereo cameras

This technique relies on triangulation. Given two images and the projection function to map pixels to 3D rays we can take two points on for each image that observes the same part of an, compute the rays’ intersection and we have a 3D estimate of this part of the object. The core requirement is to be able find corresponding areas in both images, which makes these types of systems dependent on the appearance and structure of the environment. To find correspondences on a plain white wall is very difficult and therefore the performance in non-textured areas will be poor. The correspondence search is speeded up by rectifying the images which allows the search to be done along a line.

To determine correspondences are costly in terms of computational resources to obtain a dense set of measurements. Stereo cameras therefore commonly come with additional hardware such as FPGA to lower the burden on the host machine. The accuracy of the system decreases with the depth to be measured (proportional to the inverse of the depth). It is also essential to have a rigid frame between the cameras, making stereo camera systems with a large base line to be bulky and most camera systems today have a baseline from 10-30 cm. Related to the correspondence search the FOV is typically relatively small in stereo cameras < 70 degrees. As mentioned above the accuracy is dependent on the texture but also how the cameras are mounted. In most cases the cameras is mounted with a horizontal displacement. These cameras have difficulties in detecting the depth in areas with only minor changes along the horizontal direction, for example, a cylinder lying horizontally on the ground.

Shortly, stereo cameras produce lots of information which is costly to process. It is passive and therefore requires good illumination conditions and is dependent on the texture of the environment. The spatial information is large also giving the possibility to do detection in the camera images directly and to not only rely on range data.

1.4 Lidar

A lidar use laser light (typically using infra-red light) to measure the distance and reflective properties of the environment. The benefits here are that the beam width could be made very thin which allows to measure objects far away. The typical lidar scanners that are used for autonomous vehicles provide ranges up to 130 meters.

One limiting factor with lidar is that it only gets one range measurement per diode. To acquire more data in parallel several diodes needs to be used. Lidars are often mounted on a rotating device (or to utilize a rotating mirror) to point the diode(s) into different direction and continuously measure while the device is rotating. There exist systems that have from one up to 64 diodes. Single diode scanners are commonly configured to see in a single plane, although full 3D surveying scanners also exist, however, these takes order of minutes to complete a full scan. Due to the single point measuring principle, you need either many diodes or to wait longer to get the same point density.

The benefit is that there is no limitation on the FOV per say, one can point the laser diode in any direction. The movement of the diode is constrained from the mechanical design, typically the rotation is around a single axis and therefore the resolution for 3D scanners will be highly dependent on the number of diodes used. These single axis scanner produces range data in form of rings, one per diode where the amount of data in the horizontal view is in the order of 0.1 degrees or even higher whereas the vertical resolution is from 0.5 up to as low as 10 degrees.

Laser scanners produces highly accurate range estimate and are relatively insensitive to ambient light conditions. The drawback is the cost and that goes hand in hand with a higher vertical resolution. For all continuous sensors that measure continuously over time, like a roller shutter camera, it is of importance to correct the data using ego motion estimates. The FOV is typically very large, often 360 degrees, however, it is often non-trivial to place a device anyway without having parts of the vehicle occluding the sensor.

The laser will be affected by dust, smoke, fog and snow although sensors which report multiple echoes back are nowadays more common which could be used to improve the robustness.

1.5 Radar

Similar to lidars, radars emit an electromagnetic wave, although at a much longer wavelength. The frequency that Radars operates for tracking and detection from ground vehicles spans from 20-110 GHz.

The main difference compared to a lidar it the possibility to have by far a more narrower detection cone in a laser system, however, in radars there is the possibility to use the change of frequency of the returned signal to compute the relative motion between the object and the radar sensor, a.k.a. the Doppler effect. The Doppler effect is one of the main reason that radars is commonly used nowadays in cars, where the focus is to detect motion towards other cars. Note that the relative speed detection is only done along the radar beams, essentially an object moving from right to left keeping the same distance to the radar will not be seen as a moving target.

As mentioned, the drawback of the radar is the angular resolution is lower than a lidar and a ToF camera. One key benefit is in its robustness towards ambient conditions such as snow, smoke, rain, dust etc. which makes this sensory highly useful in real world conditions. The technology for using radars as a range device is rapidly developing and devices exist today that can generate radar data in a 2D grid, that is to produce depth image based on radar echoes which targets moving vehicles.

Radar is also commonly utilized in sensor fusion systems, where relatively cheap and low resolution radars are used to detect possible object and where vision systems are utilized to classify what object the radar detected, for example, pedestrian detection systems.

2 Obstacle detection

2.1 Background

Heavy vehicles must be able to detect obstacles automatically. The sensor technology development is progressing rapidly. It may be hard and expensive to evaluate several types of sensors. Manufacturers of mobile machinery have identified sensor technology as a necessary innovation area, and have decided to cooperate on this. “Obstacle detection” means the ability to detect obstacles you do not want to collide with in the vicinity of the machine. Examples of such objects are persons, other machines, rocks, ditches, trees and horizontal tree trunks.

Mobile machinery in forestry, mining and construction work must be able to detect obstacles in their surroundings. The research focus on obstacle detection is motivated by the participating industries in the previous research project SIAA have identified this machine ability as on of the most important functions for both autonomous and manually controlled mobile machinery. The safety of the operator of the machine and of the individuals in the risk area will be increased by obstacle detection and avoidance capability. Obstacle detection and avoidance will also enable autonomous vehicles to interact in an unpredictable environment. A high degree of automation will mean a more efficient production, reduced wear of the vehicles and reduced fuel consumption.

The research on the machine ability “obstacle detection” and its enabling technology will build competence to identify and evaluate obstacles around a mobile machine. The project anticipates that a single sensor alone cannot fulfil the requirements. Research Is needed to develop sensor systems, i.e. a combination of two or more sensor technologies.

The sensor information can be used in different ways. Information may be used as driver support for decisions how to maneuver the vehicle. Information may also be used as input to automated driving without the intervention by the driver. The research of the project is for obstacle detection, not how the information is used in the mobile machine.

It must however be realized that obstacle detection at automated driving will put much higher safety requirements than obstacle detection used as driver support. In the latter case, the driver is always in control and may compensate for sensor errors. In the former case, the sensor information will directly control the automated driving.

2.2 Safety-related sensors

It must be possible to describe the safety aspects of sensors to be used for detection of persons in the risk area around a mobile machine. There are standards for sensors in special applications (e.g. safety light beams and safety light grids), and standards for safety-related control systems. None of the existing standards give covering support for how safety shall be described for a sensor detecting persons in the surroundings of a mobile machine.

The sensor functionality is important to describe. Which obstacles are intended to be detected? But also the dependability of the sensing function must be described. Can the safety and the reliability be impaired? What will the effects of the surrounding environment be on the sensing function? Does it matter if the sensor is used indoors or outdoors? Can faults in software or in electronics affect the safety functions?

The standardization organization IEC (The International Electrotechnical Commission) is working to develop a technical specification to support the development of safety-related sensors for the protection of persons. A conceptual model of a safety-related sensor (Figure 1) must consider both the physical properties of the object, and how the surrounding environment may interfere with the sensor. The interface between the sensor and the machine control system will probably comprise both safety-related information and other information of the machine control. Those aspects must be covered by the model.

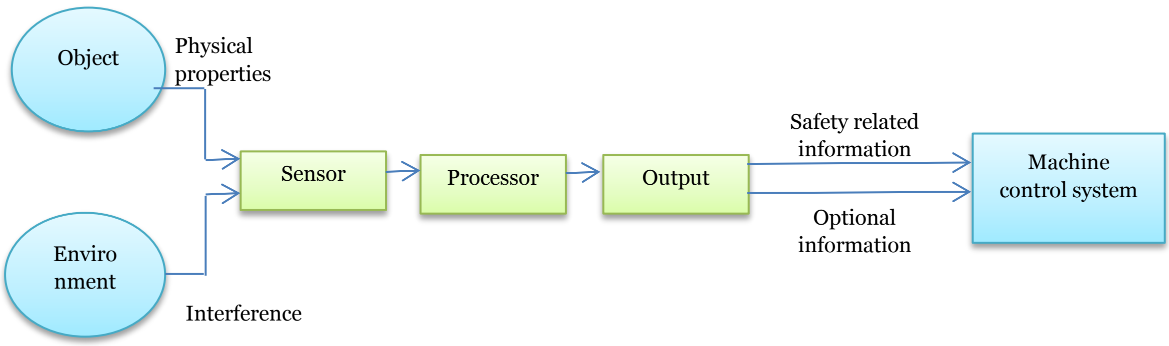


Figure 1. Example of architecture for Safety Related Sensor (SRS)

A safety-related sensor may comprise more than one sensing element. By the application of sensors of complementary sensing principles (e.g. radar and vision/camera), it can sometimes be expected to have a more reliable sensing function. All sensor data is transmitted from the sensing elements for processing and fusioning ("sensor fusion"). A model showing how two sensors produce information to be processed within the sensor unit can be presented. (Figure 2.)

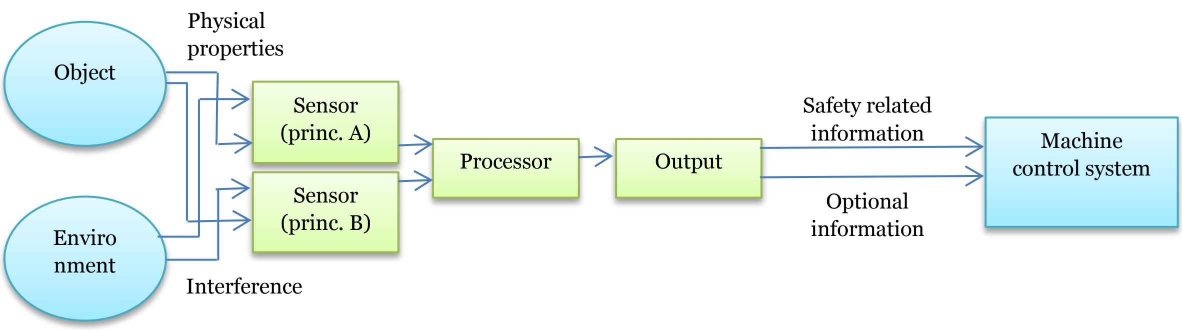


Figure 2. Example of architecture for Safety Related Sensor (SRS) with two sensors

A machine builder sometimes wants to by commercial off-the-shelf sensors for a safety-related sensor system (SRSS) without developing the algorithm to process the raw data of the sensors. (Figure 3.) One example of such an application may be a laser scanner combined with a mechanical obstacle sensor (a "bumper"). The sensor themselves are independent units, but are integrated into a sensor system where a processing unit controls the outputs according to the safety-related information from the sensors.

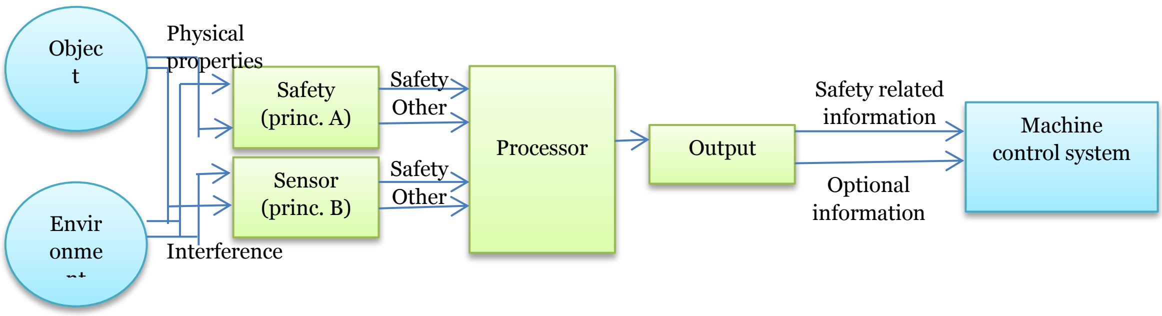


Figure 3. Example of architecture for Safety Related Sensor System (SRSS) with two sensor units

2.3 Operation scenarios

There are different operation scenarios for the mobile machine. The different scenarios will put different technical requirements on the performance of the sensing system:

a) To detect obstacles in the working area of the machine (stationary vehicle). E.g. loading/unloading of timber. The information from this kind of sensor systems must be possible to combine with the information from other on-board sensors already existing on the machine. This will be necessary to know the position of the tools of the mobile machine. The need to combine information from already existing sensors can make it difficult to assemble safety-related sensor systems on an existing machine.

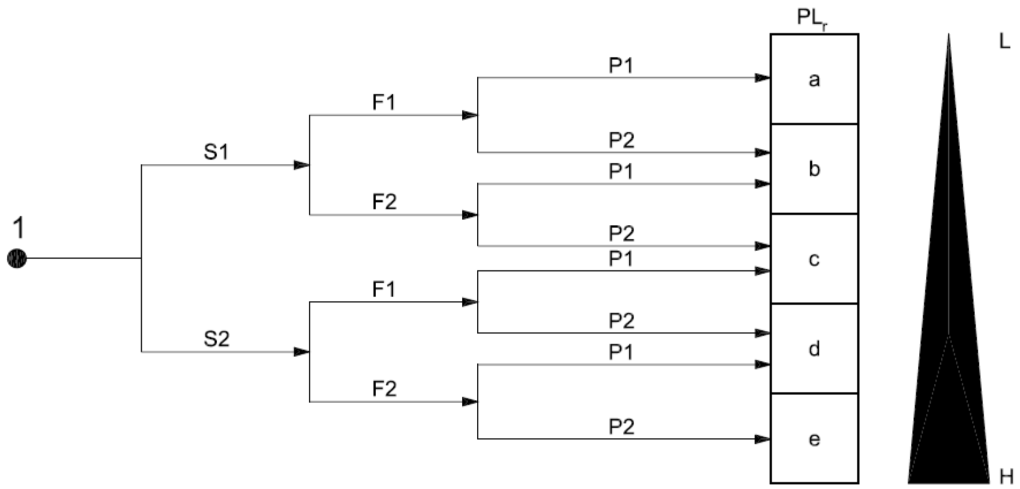
b) To detect obstacles at positioning/parking of the machine. (Similar to the driver assistance system in a car for detection of obstacles when parking.) The speed of the machine will be very low in this application. The requirements on the reaction time of the sensor system will be reduced. But a fairly wide detection zone will be required.

c) Transport/driving
The requirements will be for a short reaction time (compared to b)), but the detection zone can be made narrow and focused in the direction of travelling. The safety-related sensor for detection of persons will be a key part of the safety function of the machine to inform the driver or even to brake/maneuver the vehicle when the driver does not observe obstacles in the risk area.

2.4 Standards for machine control

The standard EN ISO 13849-1 "Safety of machinery - Safety-related parts of control systems - Part 1: General design principles" provides safety requirements and guidance on design principles and integration of safety-related parts in machine control systems. The standard specifies characteristics of the safety-related parts of the control system, including the required performance level for performing the safety features. Performance levels are divided into five levels by the likelihood of dangerous failure per hour.

The need for risk reduction can be difficult to assess. By combining the severity of the injury with the exposure rate, an assessment can be made. (See example in Figure 4.) The risk assessment is based on a situation before the intended safety function is applied.



Key

1 starting point for evaluation of safety function's contribution to risk reduction
L low contribution to risk reduction
H high contribution to risk reduction
PL_r required performance level

Risk parameters:

S severity of injury
S1 slight (normally reversible injury)
S2 serious (normally irreversible injury or death)
F frequency and/or exposure to hazard
F1 seldom-to-less-often and/or exposure time is short
F2 frequent-to-continuous and/or exposure time is long
P possibility of avoiding hazard or limiting harm
P1 possible under specific conditions
P2 scarcely possible

Figure 4. Example of a graph to determine the required performance level according to EN ISO 13849-1

The standard IEC 61508 "Functional safety of electrical / electronic / programmable electronic safety-related systems" is an internationally established standard consisting of seven parts. The requirements for integrity (risk reduction) of the safety functions are assessed according to SIL 1-4 (Safety Integrity Level 1-4), where SIL 4 sets the highest requirements. The standard is often used to describe safety in components with embedded electronics, such as programmable control systems (PLC). The standard is extensive. Full compliance means activities for functional safety throughout the life cycle ("Safety life cycle").

The standard EN 62061 "Safety of machinery - Functional safety of electrical, electronic and programmable electronic safety-critical control systems" provides safety requirements and guidance on design principles and integration of safety-related parts in machine control systems. The standard is based on IEC 61508 and is a sector-specific application for the machinery industry. Depending on the risk analysis, a safety-related function is formed with different SILs; SIL1, SIL2 or SIL3. In standard IEC 61508, SIL4 is also defined, but this high degree of risk reduction is not considered necessary for machines.

It is difficult to compare different measurements of risk reduction from different standards. The parameters to determine levels like PL and SIL differ. Often, an estimate is needed in order to compare different safety features or different components. (Figure 5.)

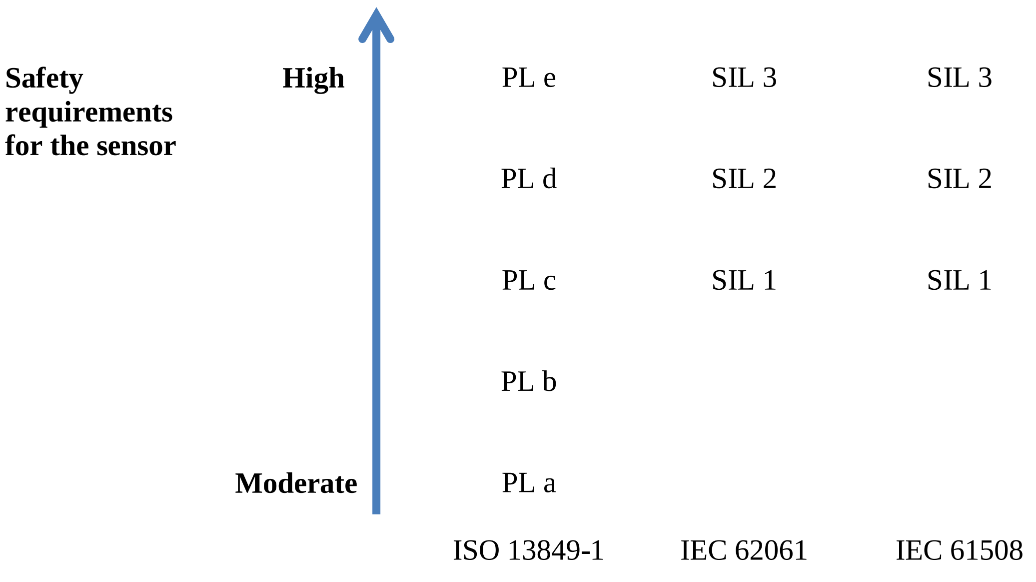


Figure 5. Comparison between safety levels of different standards

2.5 Describing the level of safety

A safety function can be described as three blocks; Input signal, logic and output signal. (Figure 6.) By analyzing the risks, one can determine "how reliable" the safety function needs to be. Often, the safety function is assigned a performance level (PL) according to standard EN 13849-1 or a Safety Integrity Level (SIL) according to standard IEC 61508.

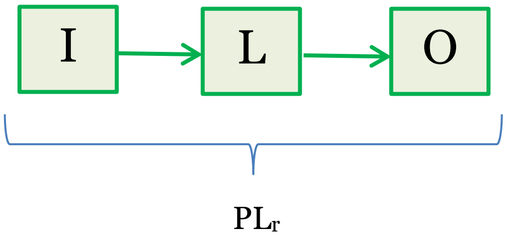


Figure 6. Simplified block diagram for the safety function ”detect obstacle and brake”

If the transducer is available on the market as a safety component, it will be easy to describe the first block "I" of the safety function. The manufacturer of the sensor has specified the detection capability, the conditions under which the sensor can be used and for which PL (or SIL) the sensor can be used.

It is fully possible to develop a sensor system that works both for protection of persons and for protection of equipment at the same time. The safety function will detect a defined obstacle and this property must be PL / SIL-rated. One can then imagine that one of the sensors in the sensor system has higher / better resolution and on its own it can also detect smaller obstacles (equipment protection) but that this property itself is not PL / SIL-rated.

For sensor systems intended for personal protection, there are three possible technology choices for achieving safety:

2.6 Off-the-shelf safety component

The manufacturer of the sensor has specified the detection capability, the conditions under which the sensor can be used and which PL (or SIL) the sensor can be used.

Example: Automatic trucks in the indoor environment

Risk analysis for a particular type of automatic truck shows that the truck needs to be able to detect obstacles and stop its motion in order not to hit the obstacle. Required safety level PLr = d. A manufacturer sells a scanner designed to detect people in front of a truck. This safety component is EC type-approved for applications up to and including PL = d (Category 3), and declared with the probability of hardware failure (PFH_d) = 8 * 10-8. The scanner is installed according to the installation manual of the manufacturer. Together with logic and actuator, the truck manufacturer calculates whether the safety function achieves PL = d.

2.7 Sensor system

The machine manufacturer may not find an appropriate security component to buy. On the other hand, the manufacturer estimates that a combination of sensors constitutes a sensor system which can meet his requirements specification. It is possible to show that a combination can meet the safety requirements.

A sensor system must at least meet requirements

- Functionality (detection capability, resolution, response time, etc.)
- Safety Level (Performance Level PL or Safety Integrity Level SIL)

In addition, environmental conditions (temperature, sunlight, precipitation, vibration etc.) must be taken into account. Unless a sensor meets the environmental requirements, the machine may need to be adapted, for example, with an additional headlight.

If a sensor system consists of two sensors connected in parallel, these should be independent and not depend on how the other sensor detects obstacles. In addition, the same errors should not occur in both sensors. Common Cause Failure must be avoided. This can be achieved, for example, by combining two sensors with different sensor principles. Each sensor must independently be able to dtect all obstacles.

When then know the probability of errors in each sensor is known, you can calculate the total probability of hardware failure, and which PL or SIL that is met. The safety function can be divided into different blocks; Input signal, logic and actuator. (Figure 7.)

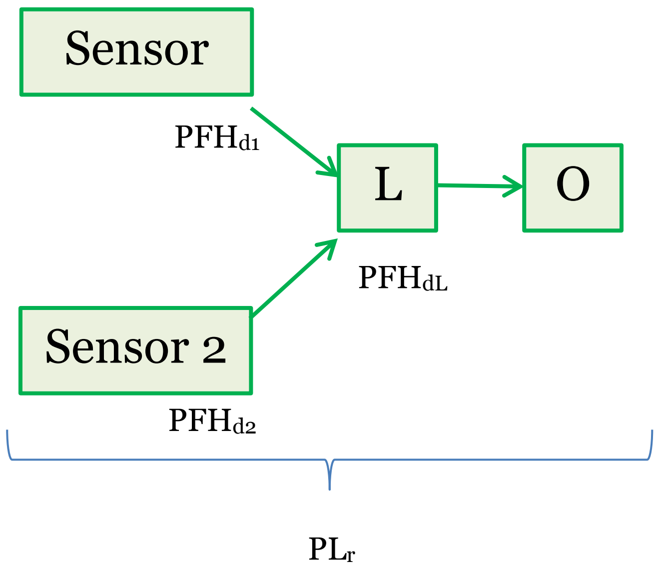


Figure 7. Simplified block diagram for the safety function ”detect obstacle and brake”

The logic to compare the output of both sensors is important. Among other things, the logic must take into account hysteresis of the sensors and their possible differences in response time.

The ability to detect errors in the sensor system is important for achieving a good level of safety. The commercially available sensors claiming to fulfil category 3 must continue to work with the specified performance of the safety function in the presence of a single fault. At the same time, most errors will be detected. When building sensor systems, it is important to be able to argue for the detection of fault. If a fault can disable one of the sensors without being discovered, building a sensor system with a good level of safety will be difficult.

There are also possible configurations to build sensor systems with three or more sensors.

2.8 Rugged standard sensor

It may also be possible to find a standard sensor and modify the design for a higher level of safety. The sensor is not originally intended for safety applications. By strengthening the enclosure and increasing the resistance to environmental stress, you can have a sensor that meets low safety levels. It is hardly possible to claim fault tolerance at the sensor. Probably you do not reach a higher performance level than PL = a or PL = b.

2.9 Safety of machinery

The European Machinery Directive provides the basic health and safety requirements for all machines to be placed on the market within the EU (and EEA). The Directive stipulates that the manufacturer manages risks identified, but does not provide detailed design requirements. It is the manufacturer's responsibility to declare conformity with the directive as well as to CE-mark the machine.

The vehicle itself ("truck" or "tractor") is not covered by the Machinery Directive. On the other hand, machinery mounted on vehicle is covered by the Machinery Directive (e.g. waste trucks and construction machinery).

The working methodology required for machines is to reduce risks by design, protect against residual risks, and in cases where this is not possible, warn of remaining risks.

A control system sold separately to be mounted on a vehicle to allow remote control of vehicles, and machinery mounted on the vehicle, can be considered a safety component under the Machinery Directive as it meets the four conditions of the Machinery Directive:

> *'safety component' means a component:*
> *— which serves to fulfil a safety function,*
> *— which is independently placed on the market,*
> *— the failure and/or malfunction of which endangers the safety of persons, and*
> *— which is not necessary in order for the machinery to function, or for which normal components may be substituted in order for the machinery to function.*

Logic units for safety functions are listed in annex IV of the Machinery Directive for safety components.

2.10 Standards for mobile machinery

The technical committee ISO/TC 127 ”Earth-moving machinery” is a part of the International Standardisation Organisation (ISO). National committees exist among in the members of ISO. The Swedish national committee for earth-moving machinery is handled by SIS (Standardiseringen i Sverige) TK 225. There is also a working group within ISO, ISO/TC 127/SC 2, for safety, ergonomics and general requirements.

A draft standard ISO 17757 ”Earth-moving machinery and mining — Autonomous and semi-autonomous machine system safety” is under development. Four failure types are mentioned in the section “Perception”:

- Failure to detect or late detection of an object
- False detection of non-existent object
- Erroneous location of a detected object
- Misclassification of an object

The standard ISO 19014 "Earth-moving machinery - Safety" is available for construction machinery. The first part of the standard is about how the safety-related parts of the control system and how performance requirements are determined. The standard uses the term Machine Performance Level (MPL). The second part deals with the control system architecture. The third part concerns control systems and environmental problems. The fourth part is about software and safety-related data communication.

An international standard exists for machines in forestry: “ISO 6814:2009 Machinery for forestry - Mobile and self-propelled machinery - Terms, definitions and classification”.

Terms are defined, and guidance for the classification of mobile and self-propelled machinery used in forestry and related operations is given.

3 Sensors tested

The SIGHT project has evaluated a number of different sensors and sensor systems. Evaluation have been made in laboratories and in field trials. The detailed results of the tests are handled by the project partners.

The tested sensor have been working according to following principles:

- Ultrasonic sensor
- Time-of-flight 3D camera
- Lidar
- Lidar without moving parts
- Stereo camera
- Radar

Among the observations made were comments on

- Resolution
- Field of view (FOV)
- Easy installation
- Linear measuring of the distance to target
- Sensitivity to different surface materials of the target
- Use of Linux and ROS (Robot Operating System)
- Sensitivity to ambient conditions

4 Conclusions

All sensors possess strengths and weaknesses. Targets which may be easy to find using one sensing principle, may be hard to find using another sensing principle. Certain environmental influences will affect a sensor operating according to a certain sensing principle, while the sensor may be immune to other environmental influence. Some applications require combinations of sensors to increase the probability of target detection in different environments.

Initially this project aimed to evaluate the capability of different off-the-shelf sensors with specific respect to obstacle detection. However, most of the sensors included in the evaluation was not advanced enough to identify obstacles (i.e. being able to distinguish between objects that are obstacles and those that are not). Instead the sensors delivered "raw-data" as response (e.g. measures of the estimated distance to any detected object within the sensor detection range). Thus, to reach any conclusion regarding obstacle detection capability of a sensor, the specific algorithms for obstacle classification also has to be regarded and evaluated. Analysis and evaluation of algorithms for obstacle classification has not been part of this project.

ROS (Robot Operating System) and its provided feature RViz has been used as a common platform for the project participants for gathering, presenting and sharing the results from the experiments made with great success. It has proven to be a powerful platform and highly suitable for use in future projects that involves these types of sensors.

The precise data format of the output from the sensors is very important for the evaluation of the sensor (this includes both the point-cloud and metadata if provided) and thus should be studied in detail with respect to the intended application of the sensor before use.

Furthermore, an adequate specification of the safety function is essential. The functionality has to be specified; what objects have to be detected and at which distance? Also other parameters such as response time must be specified. But also the requirements for the integrity of the safety function are essential; with what reliability must the safety function be performed?

A combination of two or more safety related sensors providing the safety function can be called a Safety Related Sensor System. Some sensor manufacturers call their products 'Sensor System' when they comprise a sensing unit and an evaluation unit. As long as the parts are combined into one system by the sensor manufacturer to provide the sensing function, the word 'Sensor' should be used.

Most sensors manufacturers do not provide any statement on the safety of a sensor. The conclusion on which Performance Level (PL) or Safety Integrity Level (SIL) can be reached is left to the machine builder. This may be a difficult task for the machine builder, especially if the manufacturer does not have detailed sensor competence in their development organization. The situation is different from automation of workshop machinery. Safety light grids, light beams and scanners are declared with a PL or SIL and can be fairly easily applied to a machine e.g. in an automated production line. Detailed competence in sensor technology is not required from the machine builder.

The task of detecting obstacles around a mobile machine is of course more difficult than detecting persons in a controlled indoor environment of the workshop. International standards for the application of safety-related sensors are under development. There is a great market potential for the first sensor supplier able to provide a sensor with specified safety performance for use on mobile machinery.

The user-friendliness of the sensor systems differ. Some sensors are developed for easy application. They are intended to be integrated by a machine builder without extensive sensor knowledge. Other sensor systems may require expert knowledge and application development work to as intended. Such sensors may be most suitable for machines produced in large series.

A single sensor alone is not expected to fulfil the safety requirements. For the present time, there is no Safety Related Sensor available which covers all needs of the manufacturers of mobile machinery. The machine builder has to combine at least two sensors into a Safety Related Sensor System to reach the performance required.

Appendix A. Standards

Construction equipment

There is an international standard for control systems for earth-moving machinery:

ISO 15998:2008, Earth-moving machinery — Machine-control systems (MCS) using electronic components — Performance criteria and tests for functional safety

ISO/TS 15998-2:2012

Earth-moving machinery -- Machine control systems (MCS) using electronic components -- Part 2: Use and application of ISO 15998

There is a draft for a new standard

ISO 17757 ”Earth-moving machinery and mining — Autonomous and semi-autonomous machine system safety” (Committee Draft, CD 29 september 2015)

The standard ISO 19014 for earth-moving machinery is under development

ISO 19014-1, Earth-moving machinery — Safety — Part 1: Methodology to determine safety-related parts of the control system and performance requirements

ISO 19014-2, Earth-moving machinery — Safety — Part 2: Control system performance level architecture and requirements

ISO 19014-3, Earth-moving machinery — Safety — Part 3: Control system performance level environmental requirements

ISO 19014-4, Earth-moving machinery — Safety — Part 4: Design and evaluation of software and data transmission for safety related parts of the control system

Forestry

An international standard exists for machines in forestry:

ISO 6814:2009 Machinery for forestry - Mobile and self-propelled machinery - Terms, definitions and classification

Terms are defined, and guidance for the classification of mobile and self-propelled machinery used in forestry and related operations is given.

Control systems

Standard EN ISO 13849-1 Safety of machinery – Safety-related parts of control systems

Standard IEC 61508 (seven parts), Functional safety of electrical/electronic/ programmable electronic safety-related systems

Standard EN 62061, Safety of machinery – Functional safety of safety-related electrical, electronic and programmable electronic control systems

Sensors

Standard IEC 61496 “Safety of machinery - Electro-sensitive protective equipment” addresses sensors for automation, e.g. safety light beams and safety light curtains. It consists of several parts:

Part IEC 61496-1 describes general requirements and tests. Contains information on basic concepts and environmental stress which may be applicable for many safety-related sensors.

Part IEC 61496-2 describes active opto-electronic protective devices (AOPDs), (Swe. ljusbommar och ljusridåer).

Part IEC 61496-3 describes Active Opto-electronic Protective Devices responsive to Diffuse Reflection (AOPDDR), (Swe. scanners).

The technical specification IEC TS 61496-4-2 describes vision based protective devices (VBPD), especially reference pattern techniques (VBPDPP). This part of the standard is for camera-based technology.

The technical specification IEC TS 61496-4-3 describes vision based protective devices (VBPD), especially stereo vision techniques (VBPDST). This part of the standard is for stereo camera-based technology.

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