SAFECOBOT PROJECT TECHNICAL REPORT

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1. INTRODUCTION

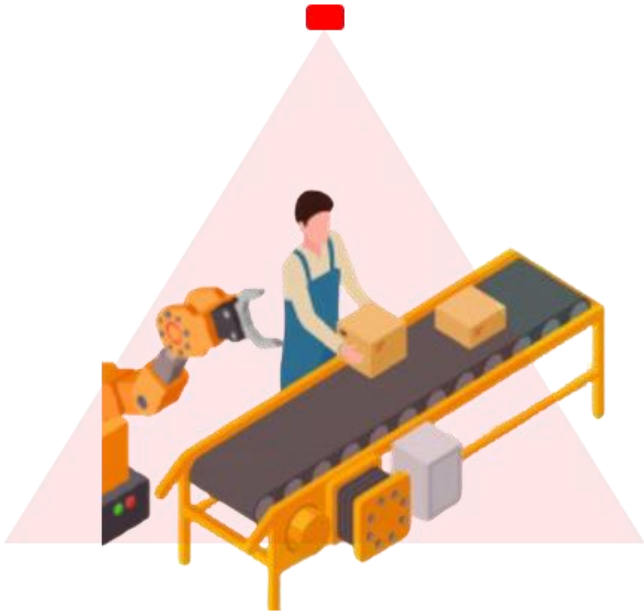


Figure 1 Collaborative Workplace

The SAFECOBOT project was about the design, integration and validation of a safety related sensors system to be used in manufacturing plants where robots usually share working area with humans. A place is called collaborative workplace when both humans and robots share the same workplace, an example is shown in the Figure 1. In the last decades robotic solutions called COBOTs are gaining market shares thanks to their design targeted to safety. COBOTs are usually manipulator certified for operations in a collaborative workplace without any other safety system. They implement an impact detection system stopping the movement in hazardous situation, but they are also designed with a form without edges and in general they have a tolerable risk of injury in the case of a collision with a human operator. Two main standards deal with robotics' safety, the ISO 10218-2 and ISO/TS 15066 (especially dedicated to collaborative robots), all integrators must refer to those standards before designing a manufacturing process involving robots and before planning the risk analysis document.

In many cases COBOTs are used in not-collaborative scenarios, in fact the impact force of the COBOT in a potential collision with a human must be less than a value expressed in Newton as reported in the ISO/TS 15066 technical specification, so if the COBOT's arm speed and load weight combination is excessive the risk of injury is not acceptable. Also load with edges or heat sources such as welder or laser introduce risks that cannot be eliminated respecting the collision force limit.

Manufacturing processes with safety risks that cannot be eliminated only by the use of a COBOT, but also not using COBOTs at all, must equip the collaborative workplace with safety-related sensors. They are applied to machinery presenting a risk of personal injury, they provide protection by causing the machine to revert to a safe condition before a person can be placed in a hazardous situation.

They can be divided in two main categories:

- Perimetric barriers
- Distance monitoring

In the first category we can find classic and widely used sensors such as infra-red barriers monitoring the perimeter of an area. These sensors close a safety relay as soon as someone cross the perimeter. The manufacturing process collaboration between the robot and the human operator implies that when the human operator is inside in the collaborative workplace the robot is stopped. The productivity is reduced and processes requiring constant proximity between robots and humans cannot be implemented.

In the second category more modern and complex sensors evaluate the distance between the human and the robot actuating the safety stop as soon as the distance is below a limit. These sensors are usually based on LiDAR or Radar technologies.

Safety-related sensors design shall follow four main standards dealing with safety:

- IEC 61508
- IEC 62061
- IEC 61496
- IEC/TS 62998-1

The first one is about the functional safety of electrical/electronic/programmable electronic safety-related systems. The second one is the application of the first to the machinery. The third one is about the requirements and performance of electro-sensitive sensors. The fourth one deals with the Safety of machinery- Safety-related sensors used for the protection of persons. While the first two standards shall be used for the architectural design of the sensors system and it can be applied without accounting the characteristics and the technology of a sensor, the last one deals with the systematic capabilities of a sensor system, environmental influences and technological limits.

The aim of this project is the design, integration and validation of a safety-related sensors system for a generic manufacturing process involving robots and collaborative workplaces. In the project recent sensing technologies have been exploited in order to build a flexible and high-performance sensors system. This means the design have these goals:

- Real-time monitoring of the distance between a human operator and the robot, avoiding the robot stopping during the presence of the human for a true collaborative process;
- Exploit different technologies advantages in order to fill known gaps;
- Apply the protective separation distance described in the ISO/TS 15066 measuring all possible variables with sensors, without some conservative approximation and enabling the process to reach the performance limit;

- Minimize the sensors system response time;
- Maximize the sensors system accuracy;
- Implement a main safety function stopping the robot as the human operator is nearby;
- Implement a secondary process optimization function, slowing the robot or changing its program as the human operator approaches or move in a specific area.

The IEC 61508/IEC 62061 standards have not been applied, since the aim has been a mere technological comparison and analysis.

In this project a Han's Robot model Elfin E05-L has been used. It can manipulate loads up to 3.5Kg, with a maximum extension of 95cm. The maximum tool speed is 2m/s. It is a professional COBOT with a repeatability of +-0.02mm, some input/output ports and two safety inputs. It communicates with external software with a Modbus TCP interface and a custom TCP/IP text protocol. In the experiments both interfaces have been used. The COBOT has been equipped with a DH-Robotics collaborative PGC-140-50 electric gripper.

Also, an Autonomous Mobile Robot has been used. The chosen model is TurtleBot 4, a robot especially designed for developers and experiments, since it is fully programmable with open-source software and tools.
The manipulator has been used in a manufacturing scenario of the company, while the AMR has been introduced for the experimentation purpose.

2. REFERENCE DOCUMENTS

Reference Documents		
[RD1]	ISO/TS 15066	
[RD2]	CEI EN IEC 62061:2022	
[RD3]	ISO 13855	
[RD4]	ISO 10218-2	
[RD5]		

3. SAFETY RELATED SENSORS SYSTEM DESCRIPTION

3.1 Architecture

The sensors system is composed by three sensing devices, one telecommunication gateway and the COBOT besides a networking router.

Three sensors have been integrated in the system:

- EnviSense, developed by Cognimade Srl, supporting the Infra-red Array technology;
- EnviRadar, developed by Cognimade Srl, supporting 60 GHz FMCW Radar technology and ultra-sonic "ToF" technology;
- RP-LiDAR A2.

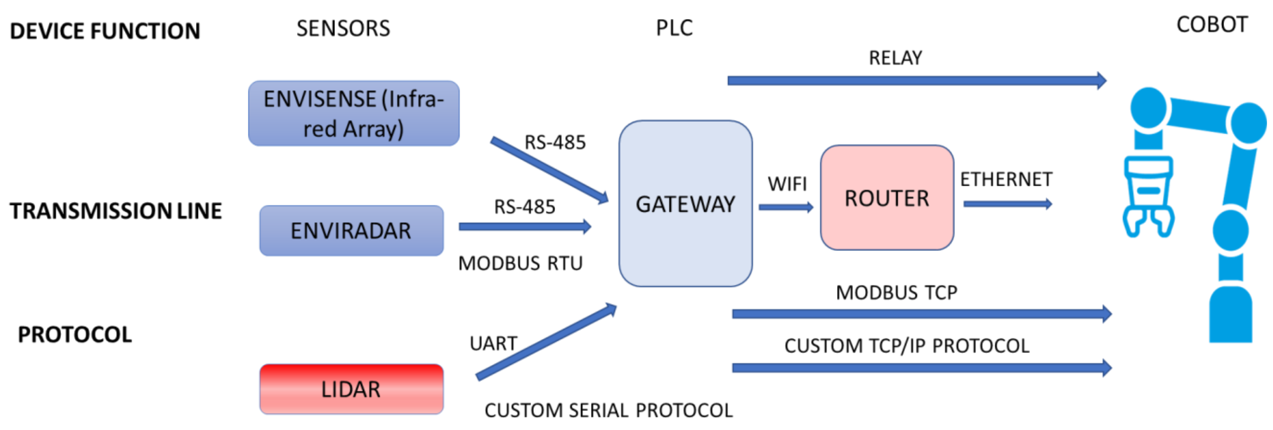


Figure 2 Architecture Scheme

In the Figure 2 the architecture scheme is shown. The scheme is divided in three main columns, one for sensors, one for telecommunications devices and the last one for the COBOT. Connections between each column refer to the transmission line and the communication protocol. Connections are divided in 3 rows, the first is about simple wired on/off communication, the second one is about complex transmission lines and the last one is about the protocol. All combinations have been tested.

SENSORS	LINE	PROTOCOL
ENVISENSE	RS-485	Modbus RTU
ENVIRADAR	RS-485	Modbus RTU

LIDAR	UART	Custom Serial

Table 1 – Sensor communication interfaces

In the table above communication interfaces of sensors have been resumed. EnviSense and EnviRadar are products designed and developed by Cognimade Srl; they are Modbus RTU Slave devices responding to queries of a Modbus Master with baud rates up-to 115200. They have low latency, with no more than 5 ms of response-time. The master can poll frequently the human operator position returned with coordinates relative to the reference axis of the sensor.

The LiDAR has been bought from a third-party company; its communication interface is based on a custom serial protocol.

The Gateway has been designed and developed by Cognimade Srl in order to act as a RS-485 Modbus RTU Master and data forwarding capabilities to Internet with a Wifi interface and a Radio NB-IoT interface. It has also been equipped with one solid state relays. The computing core is a dual-core micro-controller with enough power to support all communication interfaces, to process al sensors data, and to apply rules in order to control the COBOT movement.

The Router is a third-party COTS router that introduces some milliseconds of latency. Wifi and Ethernet are not the best communication choice for real-time applications since they have an unpredictable latency, depending on the network congestion, radio interferences and other variable parameters. The industrialized version of the sensors system will support some industrial field-bus.

3.1.1 EnviSense

Figure 3 – EnviSense device

EnviSense is a multi-functional environmental box equipped with many sensors. The infra-red array sensor samples the thermal image with size 8x8 pixels of the environment with a frequency of 10 Hz and a resolution of 0.25°C. On the micro-controller of the device a people tracking algorithm identifies people by detecting their thermal profile and track their movement inside the detection area, as shown in the Figure 4. On the Modbus RTU interface the real-time position of maximum 8 persons and their movement vector are available.

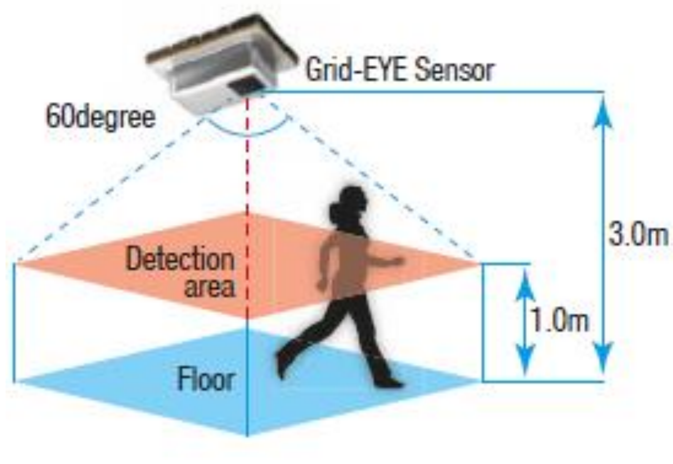


Figure 4 – Infra-red array sensor characteristics

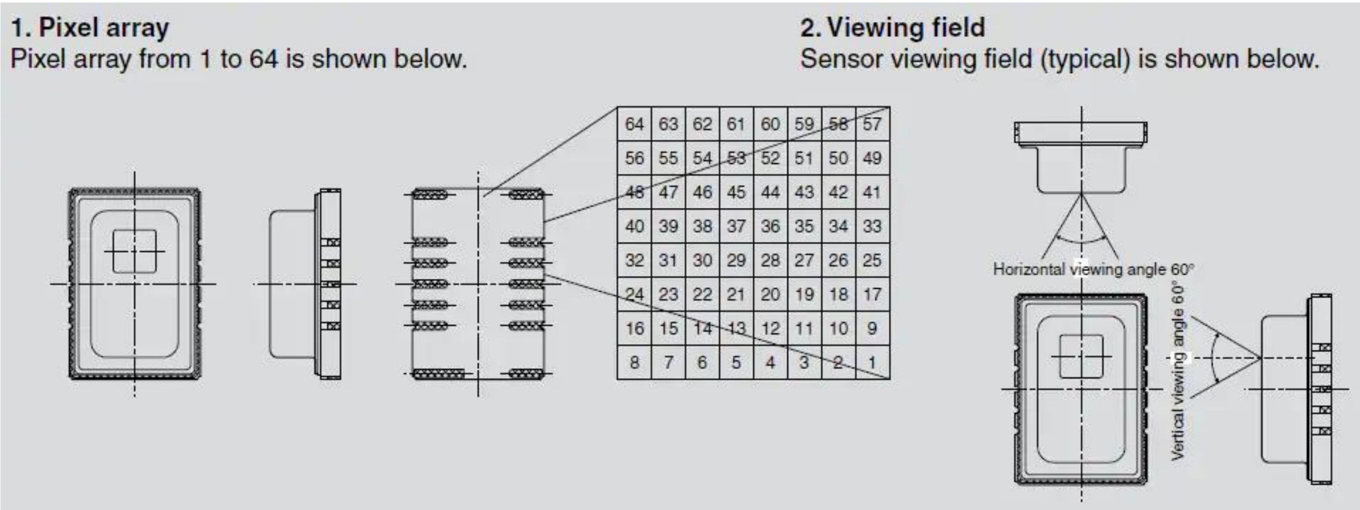


Figure 5- Infra-red array thermal image

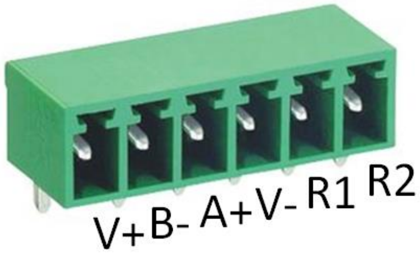
The viewing angle of the sensor is 60°, so the detection area depends on the mounting height. Also the detection accuracy ranges from 10cm to 70cm depending on the mounting height.

The algorithm is updated after each sampling and the computational time after each frame is about 25 ms. Considering the sampling frequency and the Modbus polling period the maximum total latency introduced by the device is:

$$\tau = {}^{1}/_{f_s} + \tau_{PROC} + \tau_{POLL}$$

And for a polling period of 100ms the maximum total latency is 225ms.

The device can be mounted on the ceil with screws, Velcro or adhesive. The maximum height of the ceil is 5 meters.



Connector Pinout	
V+	Power Source 5V-24V
B-	RS-485 B-
A+	RS-485 A+
GND	Power Ground
R1	Relay Output +
R2	Relay Output -

Figure 6 – EnviSense wiring pinout

The device must be wired with a proper cable, RS-485 needs a twisted and isolated cable for longer wiring. Connect the Power source (pin V+ and V-) to a power adapter and, connect the RS-485 line (pin B- and A+) to the Gateway.

After powering the device, the detection area must be empty for about 10 seconds for the background calibration.
The main limits of the sensing technology are:

- Affected by heat sources;
- Performance loss with environmental temperature above 30°C;
- False targets or missing targets when used near thermal gradients (border between indoor and outdoor, near the air-conditioner);
- Cannot detect robots;
- Slow sampling speed;
- Low accuracy and dependency from the installation height.

The main benefits of the sensing technology are:

- Low cost;
- Not affected by barriers or obstacles;
- Cannot detect robots;
- Good field of view;
- Detect more people.

“Cannot detect robots” can be considered also a benefit because used in association with another technology detecting robots (such as a Radar) it can discriminate the target.

3.1.2 EnviRadar

EnviRadar is an electronic device in a small package equipped with a 60 GHz FMCW Radar. The radar data processing is done on-board and the result is a set of target points reflecting the radar signal. Each point has associated range and azimuth coordinates and the signal strength. The points set is refreshed every 20 milliseconds, including the processing time.

Considering the sampling frequency and the Modbus polling period the maximum total latency introduced by the device is:

$$\tau = {}^{1}/_{f_s} + \tau_{POLL}$$

And for a polling period of 100ms the maximum total latency is 120ms.

The nominal viewing angle of the sensor is +-80° but it is limited by the azimuth angular resolution equal to 29°, it works with high accuracy along the range direction, in order to cover a 180° area 3 or 4 radars shall be used.

The device can be mounted on a table or on a pedestal, or directly to the COBOT base with a Velcro. The maximum range of a detected person is 10 meters and the range accuracy is 10mm.

Connector 1 Pinout	
V+	Power Source 5V (3 A)
B-	RS-485 B-
A+	RS-485 A+
GND	Power Ground

Connector 2 Pinout	
R1+	Relay 1 Output +
R1-	Relay 1 Output -
R2+	Relay 2 Output +
R2-	Relay 2 Output -

The device must be wired with a proper cable, RS-485 needs a twisted and isolated cable for longer wiring. Connect the Power source (pin V+ and V-) to a power adapter and, connect the RS-485 line (pin B- and A+) to the Gateway.

This device can be used stand-alone, adding some processing to the firmware and connecting output relays directly to the COBOT, in order to have a very low response time, under 100ms.

The main limits of the sensing technology are:

- Affected by barriers or obstacles;
- Limited field of view.

The main benefits of the sensing technology are:

- High Range Accuracy;
- Very fast response time;
- Detect robots;
- Not affected by harsh environment, such as fog, dust, heat sources.

3.1.3 RP-LiDAR A2

The device has been chosen because it is provided with a serial port and protocol documentation, especially targeted for developers. The sensor is basically a rotating laser scanner measuring continuously distance from a reflector placed in any place around the sensor (360°) at a maximum distance of 12 meters from a minimum of 20 cm. In the project it has been used with a rotational speed of 10 Hz, and with an angular resolution of 0.45°. Data is continuously transmitted to the Gateway with a UART serial port. The field of view of this sensor is 360°, for this reason it is especially mounted on AMR for positioning and space mapping functions.

Considering the rotation frequency and the Modbus polling period the maximum total latency introduced by the device is:

$$\tau = {}^{1}/_{f_{ROT}} + \tau_{TX}$$

The total latency is 170ms.

The device can be mounted on a table, or directly to the COBOT base with a Velcro. The maximum range of a detected person is 12 meters and the range accuracy is 2.5% of the distance, for example when the person is 2m far from the sensor the accuracy is 5cm.

The main limits of the sensing technology are:

- Affected by barriers or obstacles;
- Detect more people only if they are not in the same range line;
- Response time depends on the rotational speed, the maximum of this Lidar is 15 Hz and it needs very fast UART serial ports;
- The transmission line is not fast and it is not suited for this kind of application;
- Affected by harsh environment such as fog and dust.

The main benefits of the sensing technology are:

- Good Range Accuracy;
- Detect robots;
- Full viewing angle of 360°.

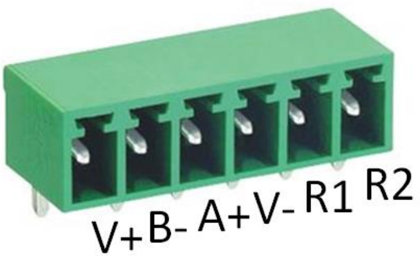
3.1.4 Gateway

The Gateway is a device designed for Industrial IoT applications; it is based on a dual-core micro-controller running at 240 MHz of frequency clock. It supports the following telecommunication interfaces:

- RS-485 Half-Duplex Serial Port;
- Wifi;
- NarrowBand IoT.

It also has an Output Relay (230VAC, 270 mA).

The device is powered from an external power supply (from 5VDC to 24VDC) or from a Lithium Battery. The battery can be used as a Primary Battery or a Backup Battery.



Connector Pinout	
V+	Power Source 5V-24V
B-	RS-485 B-
A+	RS-485 A+
GND	Power Ground
R1	Relay Output +
R2	Relay Output -

Figure 7 – Gateway Connector Pinout

It can be installed on a table or on a well with screws or Velcro. The RS485 line coming from sensors shall be connected to pin B- and A+. The Relay Output shall be connected to the Safety Input of the COBOT controller.

In the sensors system it is used as a sensors data collector, data processing and COBOT external controller. The firmware running on the device has been customized for the project purposes, and it is composed by the following parts:

- Modbus RTU Master polling EnviSense and EnviRadar data every 100ms;
- LiDAR Serial data reader using an optional UART available on the device board;
- Data Fusion algorithm execution;
- Modbus TCP Master writing registers to the COBOT controller;
- Custom TCP/IP Protocol for real-time communication with the COBOT controller;
- Output Relay Control;
- User Interface.

All parts are divided in concurrent tasks running on top of FreeRTOS.

The Modbus TCP communication interface is used for changing the COBOT program, while the Custom TCP/IP Protocol is used for stopping or slowing the COBOT. In fact, the Modbus TCP interface can write registers on the COBOT controller, those registers can be parsed in the PLC program executing the COBOT movement, but only between two instructions. The movement of the COBOT from a point to another is one instruction, so during a movement from a point to another the COBOT program cannot be changed. The Custom protocol has instead a quite low latency and can stop or slow down the COBOT at any time.

With the User Interface the following configurations can be set:

- Networking parameters (Wifi AP, Wifi password, IP, NetMask);
- IP Address of the COBOT;
- TCP/IP Ports of the COBOT for both Modbus TCP and Custom protocol;
- RS-485 Parameters: Baud Rate, Parity, Stop Bits;
- EnviSense Slave Id;
- EnviRadar Slave Id;
- Stop Command Rules: Enable/Disable, Fixed Distance/Automatic, Single Sensor Mode (with the choice of the sensor), Data Fusion Mode (Speed, Accuracy), Output Type (Relay, Protocol);
- Slowing Command Rules: Enable/Disable, Fixed Distance/Automatic, Single Sensor Mode (with the choice of the sensor), Data Fusion Mode (Speed, Accuracy), Percentile of the Original Speed;

- Program Change Rules: Fixed Distance, Single Sensor Mode (with the choice of the sensor), Data Fusion Mode (Speed, Accuracy), New Program Name;
- Robot position;
- All sensors position.

Sensors and Robot position shall refer to a common reference axis (for example the base of the robot), the sensors position can be measured with a manual laser distance meter, while the robot position is the nearest point in the path of the robot to the human operator.

If the Single Sensor Mode is enabled, one of the following sensors shall be chosen:

- Infra-red Array;
- Radar;
- LiDAR.

With the same interface the User can set the following commands:

- Start/Stop the System;
- Start the Calibration;

3.2 Calibration and Alignment

Calibration is needed by the sensors in order to set the technological parameters and to acquire the scene background, such as the thermal background in the case of the infra-red array. It is carried out by all devices at start-up. All devices must be powered in a clean scenario without the presence of humans, obstacles or heat sources. The COBOT must be stopped.

The alignment is composed by two main operations:

- Temporal alignment;
- Spatial alignment.

These operations must be accomplished by the gateway reading data from all sensors at the same time and in the same scenario. The alignment is required if the Data Fusion algorithm is used, otherwise if only one sensor is used no alignment is required.

The alignment requires a human operator is inside the area monitored by all sensors. By starting the calibration with the User Interface of the Gateway the system will acquire data from all the sensors for about 10 seconds, during that time starting from a stationary position the operator shall move slowly inside the area.

Each data coming from sensors has a corresponding timestamp, the start of the movement of the operator will correspond to a different timestamp from each sensor, the gap from timestamps will be the offset used to align all next timestamps.

The spatial alignment is done by estimating a translation 2D vector and a rotation 2D vector for each sensor, so that applied to coordinates pointing to the position of the operator detected by each sensor will provide the same point coordinates.

4. **RULES AND STANDARDS – ISO/TS 15066**

The ISO 15066:2016 technical specification specifies safety requirements for collaborative industrial robot systems and the work environment. It is a dedicated extension of the ISO 10218-1 and ISO 10218-2 regarding industrial robotic devices. For the realization of this project the most important part of the document is included in the chapter 5.5 and it is about the concept of the protective separation distance. During automatic operation, the hazardous parts of the robot system shall never get closer to the operator than the protective separation distance. The protective separation distance can be calculated based on the concepts used to create the minimum distance formula in ISO 13855, modified to take into account the following hazards associated with speed and separation monitoring.

If the separation distance between a hazardous part of the robot system and any operator falls below the protective separation distance, then the robot system shall:

- Stop the manipulator;
- Reduce speed;
- Execute an alternative path which does not violate the protective separation distance, continuing with active speed and separation monitoring.

When the actual separation distance meets or exceeds the protective separation distance, robot motion may be resumed.

$$S_p(t_0) = S_h + S_r + S_s + C + Z_r + Z_d$$

The formula defines the protective separation distance between the human operator and the robot S_p as the sum of various terms:

- S_h is the contribution to the protective separation distance attributable to the operator's change in location;
- S_r is the contribution to the protective separation distance attributable to the robot system's reaction time;
- S_s is the contribution to the protective separation distance due to the robot system's stopping distance;
- C is the intrusion distance, as defined in ISO 13855; this is the distance that a part of the body can intrude into the sensing field before it is detected;
- Z_r is the position uncertainty of the robot system, resulting from the accuracy of the robot position measurement system;
- Z_d is the position uncertainty of the operator in the collaborative workspace, as measured by the presence sensing device resulting from the sensing system measurement tolerance;

Where:

- $S_h = \int_{t_0}^{t_0+T_r+T_s} v_h(t)dt$ and
  - T_r is the reaction time of the robot system, including times required for detection of operator position, processing of this signal, activation of a robot stop, but excluding the time it takes the robot to come to a stop;

  - T_s is the stopping time of the robot, from the activation of the stop command until the robot has halted; Ts is not a constant, but rather a function of robot configuration, planned motion, speed, end effector and load;
  - v_h is the directed speed of an operator in the collaborative workspace in the direction of the moving part of the robot, and can be positive or negative depending on whether the separation distance is increasing or decreasing.
- $S_r = \int_{t_0}^{t_0+T_r} v_r(t)dt$ and
  - v_r is the directed speed of the robot in the direction of an operator in the collaborative workspace, and can be positive or negative depending on whether the separation distance is increasing or decreasing.

The Sensors System affects the formula term S_h with the response time and Z_d with accuracy errors.
The term Z_r if not real-time monitored is the nearest position to the human operator in the robot's path.
If the robot's speed is not being monitored, the system design shall assume that v_r is the maximum speed of the robot. This value depends on the application and is validated by the risk assessment.
If the person's speed is not being monitored, the system design shall assume that v_h is 1,6 m/s in the direction that reduces the separation distance the most.

5. SYSTEM VALIDATION

The result of the validation are some qualitative and quantitative characteristics of the system, evaluated by experiments and measurements. The system is validated by applying metrics to the scenario, at least 30 repetitions are required in order to evaluate the average and the standard deviation. The standard deviation shall be considered and its contribution added to results.

5.1 Metrics

The qualitative performance of the sensor system is evaluated in terms of:

- Operation in harsh environmental conditions (dust, fog, heat);
- Ease of installation;
- Integration flexibility;
- Scalability on different models of COBOT and robots.

The quantitative performance of the sensor system is evaluated in terms of:

- Response time [ms];
- Distance Measurement Accuracy [cm].

The response time is defined as the time elapsing from the human operator cross of the position corresponding to the minimum protective separation distance, and the effect on the robot behaviour (stop, slowing of program changing).
The Distance Measurement Accuracy is defined as the standard deviation of the measurement error.
Since the accuracy affects the response time, it has been evaluated independently measuring the error of the localization of the human operator.
Then the response time has been evaluated averaging a set of repetitions, by recording the video of those repetitions and visually detecting the number of video frames between the switching on of the light indicating the human operator fixed distance crossing and the robot stopping, slowing or changing direction. Since the video recording has been sampled with a frequency of 60 Hz the time resolution is 16.6 ms.
Both of them have then been used for the protective separation distance calculation in the Automatic Mode.

5.2 Goals

Two main goals have been set for the experiment:

- Response time < 300ms;
- Distance Measurement Accuracy < 50cm.

The response time affects the formula of the protective separation distance with an offset equal to the human operator speed multiplied to the response time.

The Distance Measurement Accuracy affects the formula with an offset equal the Accuracy itself.
In the case the speed of the operator is 1.6 m/s (worst case in the standard) the offset is 50cm, so the additional separation distance contribute of the sensors system is 1 meter. Anyway, better or worst result are acceptable, they will affect the formula with a different distance contribute, better sensor system performances will stop the COBOT at smaller distances.
The Response Time and the Distance Accuracy can be used in the ISO/TS 15066 formula to automatically compute the separation distance and stop/slow down the robot depending on the detected human speed and the robot position and speed if available.

6. USE-CASES & RESULTS

The sensors system has been validated in four use-cases, while the scenario is the same manufacturing process of Cognimade Srl. A CNC machine works on standard plastic cases in order to apply some holes, the machine shall be loaded with new cases, and after the job it shall be unloaded. The COBOT will load and unload the machine, taking new cases from a box, and putting modified cases into another box. A Software developed by Cognimade Srl synchronizes all the process by communicating with the CNC Controller and the COBOT Controller.

6.1 Scenario Description

Figure 8 - Overall manufacturing scenario

The CNC is placed on a table, the COBOT is near the table and the CNC.

Figure 9 – Robot moving towards the collaborative workplace

The COBOT can work on the CNC and it can rotate reaching another table (as shown in the Figure 9) where the new cases box and the worked cases box are placed. This table is also the collaborative workplace, since a human operator occasionally reaches the table, as shown in the Figure 10, in order to load and unload boxes, and do some jobs on the worked boxes:

- Check the quality of the CNC job;
- Apply the product sticker;
- Mount the device PCB.

Figure 10 – Human operator approaching the collaborative workplace

The video-camera used for tests recording is placed sideways in order to record simultaneously the human operator position and the COBOT movement.

In the Figure 11 the scenario scheme from above is shown-.

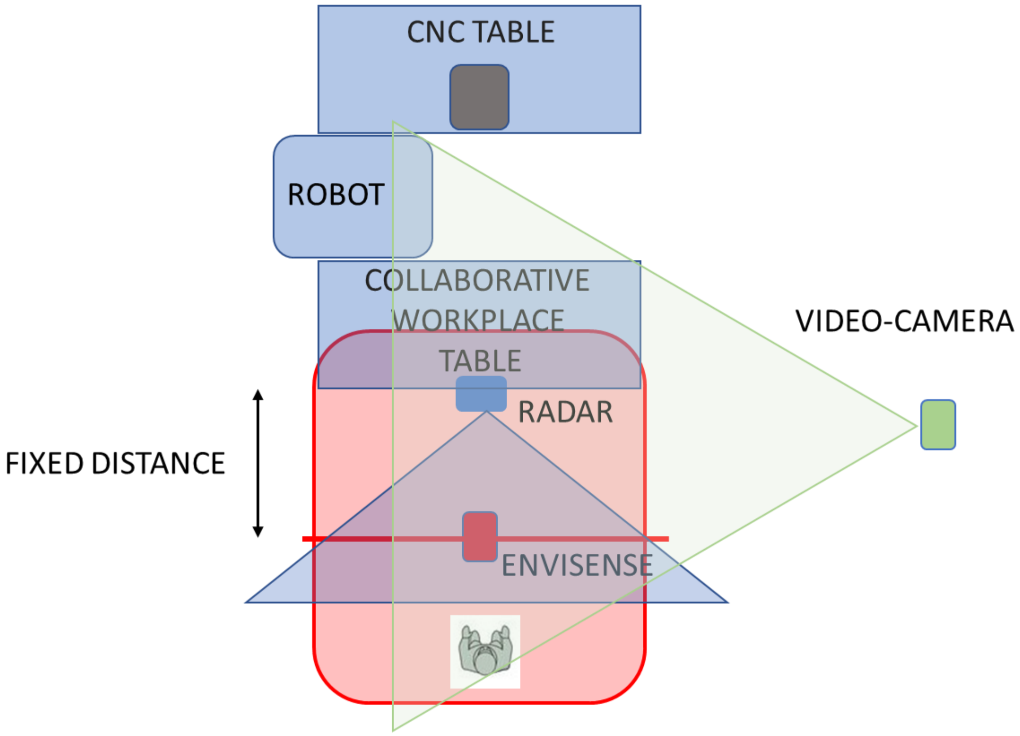


Figure 11 – Scenario Geometry

6.1.1 Sensor's placement

The RS-485 line (2 wires) is placed on the same cable with the Power line (2 wires) working at 5VDC.

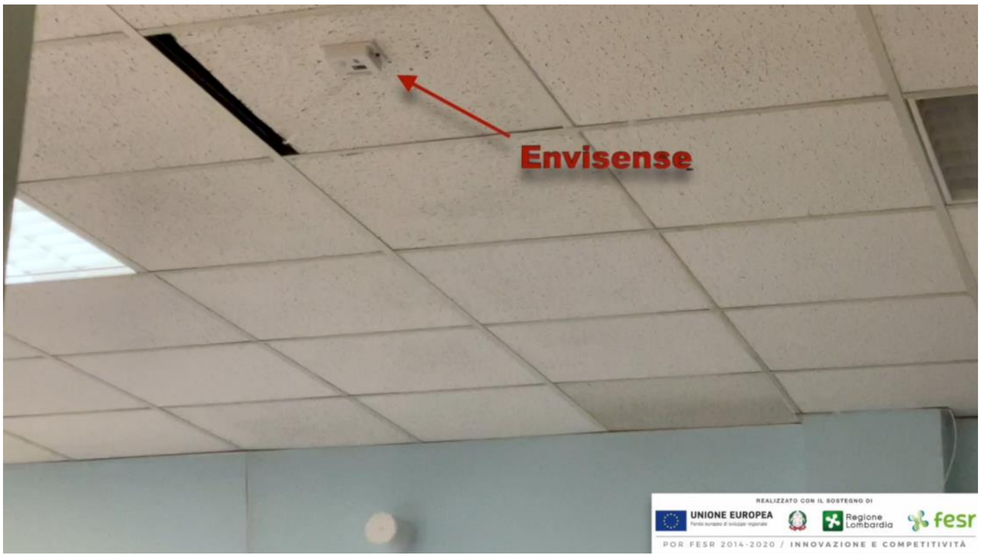


Figure 12 – Envisense position

The EnviSense device has been placed on the false ceiling as shown in the Figure 12. The cable crosses above the false ceiling, then it goes down along the wall and finally it reaches the EnviRadar adherent to the working table show in the Figure 13 with Velcro.

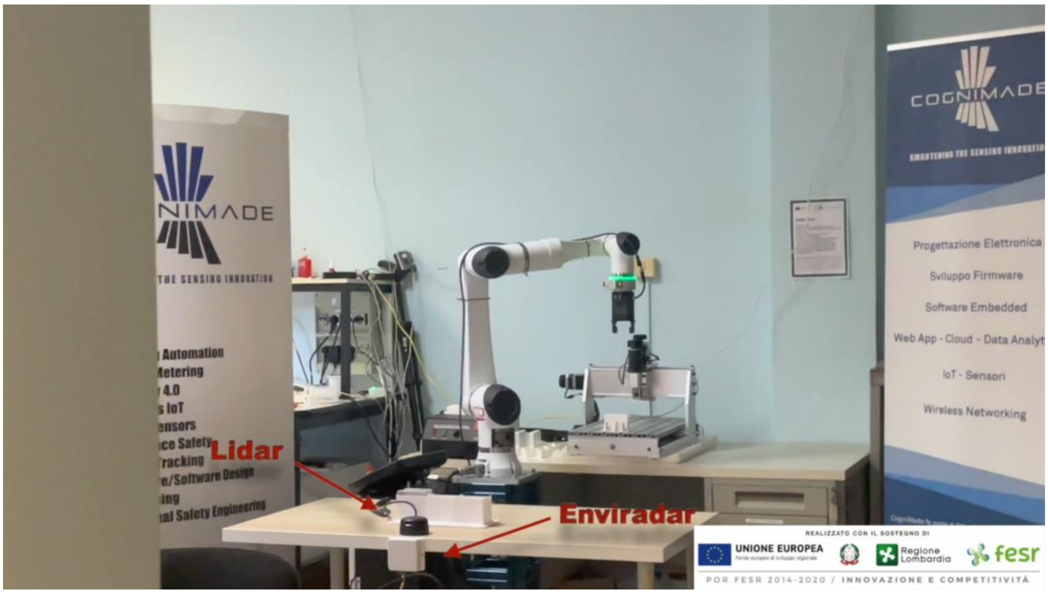
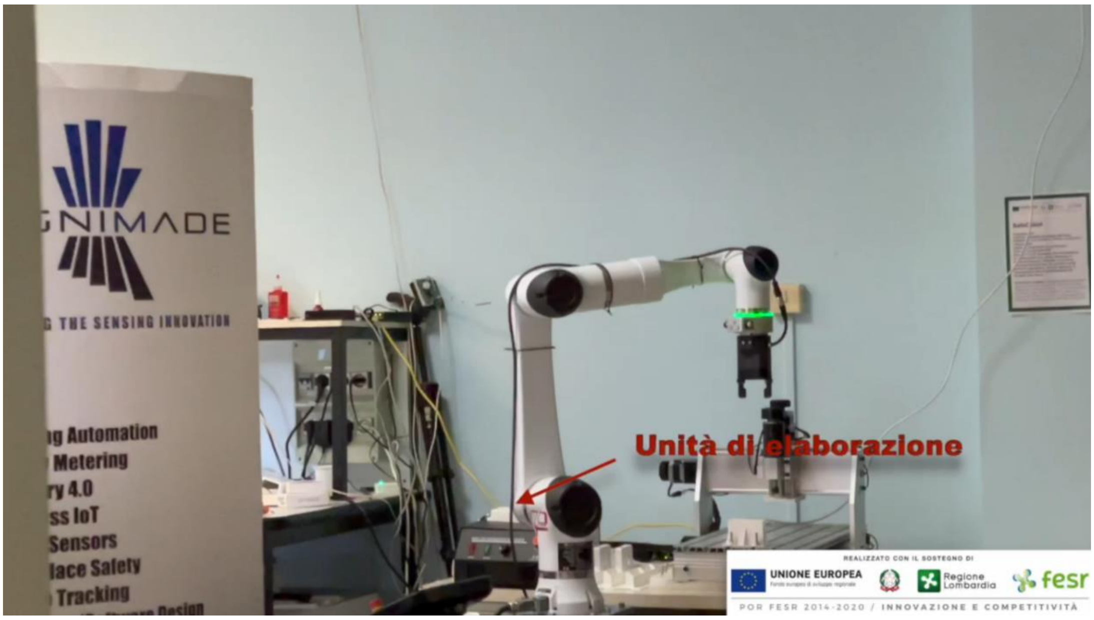


Figure 13 – EnviRadar and LiDAR positions

From the EnviRadar connector the cable reaches the Gateway.

The LiDAR is placed on the collaborative workplace, the table between the human operator and the robot, looking towards the direction of arrival of the human operator. Its cable is halved in two parts, the serial line goes directly into the Gateway connector while the power line goes to the power adapter.



The Gateway is placed near the COBOT and the Power Adapter, the Relay cable (2 wires) goes from the Gateway to the COBOT Controller.

6.2 Use-Case 1

In the first use-case the system has been validated for the distance measurement accuracy.

6.2.1 Test Description

The Gateway has been configured in order to output on the User Interface the current evaluated distance of the human operator from the robot by the system. The human goes at a fixed distance of 100cm from the robot and for each Single Sensor Mode the output measurement will be compared to 100cm. The absolute value of the difference is the accuracy.

TEST	MODE	REPETITIONS
1	Single (EnviSense)	30
2	Single (Radar)	30
3	Single (LiDAR)	30
4	Data Fusion (Speed)	30
5	Data Fusion (Accuracy)	30

Table 2 – Use-Case 1 Tests List

6.2.2 System Configuration

The system has been configured in order to work on the company LAN, the Gateway and the COBOT are in the same subnet.

The RS-485 line is configured at 115200 Baud rate, 1 stop bits e parity none.

The stopping rules and the slowing rule are set to Single Sensor Mode, choosing for each test the corresponding sensor. Then they are set to Data Fusion modes.

6.2.3 Tests Result

TEST	MODE	ACCURACY
1	Single (EnviSense)	30cm
2	Single (Radar)	5cm
3	Single (LiDAR)	10cm
4	Data Fusion (Speed)	5cm
5	Data Fusion (Accuracy)	3cm

6.3 Use-Case 2

In the second use-case the system has been validated for response time evaluation in both stopping and slowing functions.

6.3.1 Test Description

Two sets of tests are executed:

- Stopping function tests;
- Slowing function tests;

For each of the first two sets, 30 repetitions are executed for each sensor, by choosing the sensor in the selector. All tests are repeated for each Ouput Type available for the function. The overall tests list is shown in the Table 3.

TEST	**FUNCTION**	**MODE**	**OUTPUT TYPE**	**REPETITIONS**
1	Stopping	Single (EnviSense)	Relay	30
2	Stopping	Single (Radar)	Relay	30
3	Stopping	Single (LiDAR)	Relay	30
4	Stopping	Single (EnviSense)	Protocol	30
5	Stopping	Single (Radar)	Protocol	30
6	Stopping	Single (LiDAR)	Protocol	30
7	Slowing	Single (EnviSense)	Protocol	30
8	Slowing	Single (Radar)	Protocol	30
9	Slowing	Single (LiDAR)	Protocol	30

Table 3 – Use-Case 2 Tests List

6.3.2 System Configuration

The system has been configured in order to work on the company LAN, the Gateway and the COBOT are in the same subnet.

The RS-485 line is configured at 115200 Baud rate, 1 stop bits e parity none.

The stopping rules and the slowing rule are set to Single Sensor Mode, choosing for each test the corresponding sensor, and Fixed Distance. In the case of Stopping rule the distance is set to 75cm, in the Slowing rule is set to 125 cm.

6.3.3 Test Results

TEST	**RESPONSE TIME**
1	266 ms
2	133 ms
3	183 ms
4	316 ms
5	183 ms
6	233 ms
7	516 ms
8	383 ms
9	433 ms

Table 4 – Use-Case 2 Tests Result

6.4 Use-Case 3

In the third use-case the system has been validated for the stopping/slowing functions using the Data Fusion algorithm. The Response Time and the Distance Accuracy estimated after the Use-Case 1 are used in the algorithm in order to evaluated the separation distance. The sensor’s placement is the same of the Use-Case 1.

6.4.1 Test Description

Two sets of tests are executed:

- Stopping function tests;
- Slowing function tests;

For each of the first two sets, 30 repetitions are executed for each data fusion mode, by choosing the mode in the selector. All tests are repeated for each Ouput Type available for the function. All tests are repeated for each Data Fusion mode.

The overall tests list is shown in the Table 5.

TEST	FUNCTION	MODE	OUTPUT TYPE	REPETITIONS
1	Stopping	Data Fusion Speed	Relay	30
2	Stopping	Data Fusion Accuracy	Relay	30
3	Stopping	Data Fusion Speed	Protocol	30
4	Stopping	Data Fusion Accuracy	Protocol	30
5	Slowing	Data Fusion Speed	Protocol	30
6	Slowing	Data Fusion Accuracy	Protocol	30

Table 5 – Use-Case 2 Tests Lists

6.4.2 System Configuration

The system has been configured in order to work on the company LAN, the Gateway and the COBOT are in the same subnet.

The RS-485 line is configured at 115200 Baud rate, 1 stop bits e parity none.

The stopping rules and the slowing rule are set to Data Fusion, choosing for each test the corresponding mode, and Automatic Distance.

6.4.3 Test Results

TEST	RESPONSE TIME
1	160 ms
2	290 ms
3	210 ms
4	350ms

5	420ms
6	550ms

Table 6 – Use-Case 2 Tests Result

6.5 Use-Case 4

In the fourth use-case the system has been validated for the program change function. The sensor's placement is the same of the Use-Case 1.
Since the program change is not a fast operation due to the way it can be changed the validation is verified if the program is changed correctly. For a fast response to program change request the COBOT movement shall be programmed with many little point-to-point paths.

7. FUTURE IMPROVEMENT

The system will be further developed in order to improve the performancce, the following enhancements are planned:

- Better Modbus Field-Bus performance. Modbus RTU can be used with a shorter polling period, but some limits cannot be overcome, due to the Baud Rate limit, the cable connection length, and the Modbus packet guard times;
- Ethernet based Field-Bus support. EtherCAT will be supported at the Gateway level, but also at EnviRadar level with new version of both products. With EtherCAT the delay introduced by the polling time, in this case called cycle-time, will be less than 500 microseconds;
- EnviRadar will be able to work in the whole system or stand-alone;
- EnviRadar will be re-designed following the IEC 61508 functional safety standard;
- Industrial Automation IDE support, some widely spread software such as Codesys and TwinCAT, will be supported for the integration of the system in nigger and more complex manufacturing processes.

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