ACQUISITION THE PROFILE OF SURFACES WITH COMPLEMENTARY SENSOR FUSION TECHNIQUES

FONSECA, J.; MARTINS, J. & COUTO, C.

Abstract: *This paper presents complementary sensor fusion techniques for the acquisition of the profile of surfaces with minimum error using low cost sensors ultrasonic sensors. These surfaces are composed by areas with different depths, corners and specular surfaces. To minimize the constraints of sonar sensors, it was developed dedicated software and hardware, as well as an empirical model was obtained from real data. This model is based in two proposed concepts: Points of Constant Depth (PCD) and Areas of Constant Depth (ACD). Having this sonar model in mind, four sensor fusion techniques are used separately to validate the PCDs and decide the ACDs: average and variance, fuzzy controller and heuristic method based in rules. In this work a PUMA 560 manipulator was equipped with a CCD video camera on the shoulder and four ultrasonic sensors on the wrist, to acquire data to model the geometry of the part's surface, exploiting the mobility of the robot. The CCD camera view defines the working area, while the ultrasonic sensors enable the acquisition of the surface profile. For the acquisition of the profile of surfaces with a minimum error different and complementary sensor fusion techniques are implemented and applied separately, namely the average and variance, kalman filter, fuzzy controller and heuristic method based in rules.*
Key words: *Sensor fusion, Profile surface, Ultrassonic sensors, Kalman Filter and Fuzzy Controller*

Authors´ data: Asist. Prof. Dr. **Fonseca** J.[aime], Prof. Dr. **Martins** J.[úlio], Prof. Dr. **Couto** C.[arlos], University of Minho, Dept. of Industrial Electronics, Campus de Azurem, 4800-058 Guimarães, Portugal, Jaime@dei.uminho.pt, jmartins@dei.uminho.pt, ccouto@dei.uminho.pt

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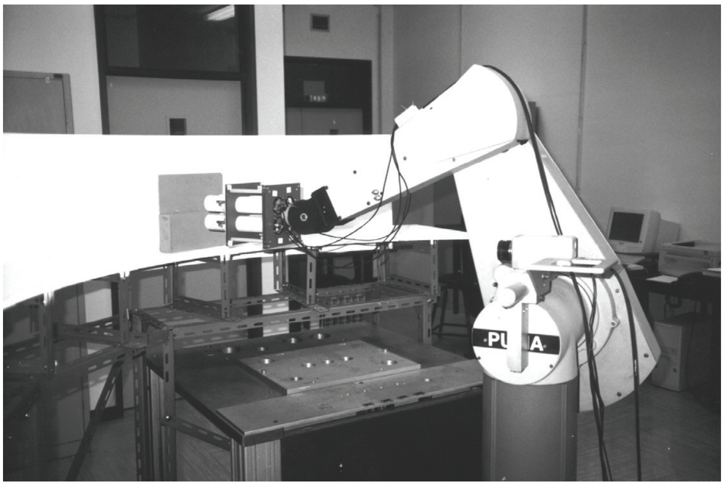
1. Introduction

To widen the range of applications of robotic devices, both in industry and research, it is necessary to develop systems with high levels of autonomy and ability to operate in unstructured environments with little *previous* information. To achieve this degree of independence, the robot system must have an understanding of its surroundings, by acquiring and manipulating a model of its environment. For that purpose a variety of sensors is needed to be able to interact with the real world as well as mechanisms to extract meaningful information from the data collected. The main need for manipulators and for mobile robots is the ability to acquire and handle information concerned with the presence and location of objects, and empty spaces in the scope of the device. This is extremely important for fundamental operations that involve spatial and geometric reasoning. Typically, due to limitations intrinsic to any kind of sensor, it is important to process the information coming from multiple readings, and build a coherent world-model. Furthermore, from an economical point of view, may be interesting to replace a single highly accurate but expensive sensor by several less precise low cost sensors together with additional post processing electronics and algorithms. The usage of several low-cost sensors combined with intelligent post processing can compensate the low accuracy of such low cost sensors. These sensors can be either of the same type or give complementary information. With the same type of sensors the goal is to increase the quality of the resulting sensor information. Of course, the improvement must be reasonable when compared with the increased complexity of the measurement system, in order to keep the overall cost still attractive. As the computing power cost is everyday decreasing and low cost sensors are bound to proliferate in the near future, multisensor systems and sensor fusion techniques should become more and more popular. Several sensor fusion methods have been reported that deal with this kind of problems. Durrant-Whyte has developed a Bayesian estimation technique for combining touch and stereo sensing (Durrant-Whyte, 2002). Tang and Lee proposed a generic framework that employs a sensor independent, feature based relational model to represent information acquired by various sensors (Tang & Lee, 1990). A Kalman filter update equation was developed to obtain the correspondence of a line segment to a model (Crowly, 1989), and this correspondence was then used to correct position estimation. An extended Kalman filter was used to manipulate image and spatial uncertainties (Skordas et al., 1989).

In this work a PUMA 560 manipulator was equipped with a CCD video camera on the shoulder and four ultrasonic sensors on the wrist, to acquire data to model the geometry of the part's surface, exploiting the mobility of the robot. The CCD camera view defines the working area, while the ultrasonic sensors enable the acquisition of the surface profile. For the acquisition of the profile of the surface with a minimum error complementary sensor fusion techniques are implemented and applied separately, namely the average and variance, Kalman filter, fuzzy controller and heuristic method based on rules. Some wood objects were used to test the implemented sensorial system. These objects present corners and small depth differences between two or more areas in the surface making hard the acquisition of the surface profile by the ultrasonic sensors.

2. Hardware setup

The work cell used is composed by the following elements (see Fig 1): a PUMA 560 manipulator used to position the 4 ultrasonic sensors mounted on the wrist of the robot in order to acquire the surface profile; a controller area network (CAN) used for data acquisition and some basic control; a video camera mounted on the shoulder of the manipulator to define the working area. The PUMA 560 is used as a scanner where the ultrasonic sensors acquire data for internal representation of the part's surface geometry. The ultrasonic sensors setup relative to the robot grip axis is a square as shown in the Fig 1. For this reason, it is only possible to acquire information relative to surfaces with square or rectangular shapes, because only in these cases it is possible to divide each part of the surface in smaller areas of identical shape. The maximum size of these areas depends on the setup and diameter of the sonar sensors.



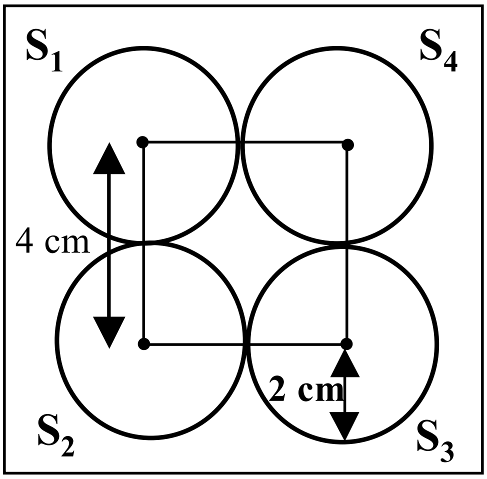


Fig. 1. Work cell

The sensors used in this work are made by Polaroid Ultrasonic Ranging Units, which have a range of about 0.35 m to 10 m when the emission frequency is 52 kHz. A specific kit provided by Polaroid Corp controls the ultrasonic transducers. This kit is based on the Intel 80C196 microprocessor and is easy to configure by software. It is possible to configure the following parameters: transmission frequency, pulse width, blanking time, amplifier gain, sample rate and trigger source (internal/external). This kit is connected to the external world via RS-232. An analogue output proportional to the measured distance is also available. To avoid any eventual interference between emission and echo waves, the sensors are triggered sequentially, leaving just one unit to measure at a time.

The computing hardware includes two CAN boards, the Universal CAN I/O board outside the computer and the PC-CAN Interface PCI02 inside the PC. Both boards are based on the Intel 80592, products of STZP (Steinbeis Transferzentrum Prozessautomatisierung).

The Universal CAN I/O board deals with the Polaroid's kit receiving the data sent and assuring the sequential triggering of the transducers. In reply to a trigger signal, several measurements are made and the average value is calculated. This pre-processed data is then sent to the PC via the CAN net at a baud rate of 1Mbit. This CAN I/O board has the following features: 16 digital inputs, 16 digital outputs, 8 analogue inputs and 2 pulses with modulated outputs.
The software was developed in IAR C for the Universal CAN I/O board and in Borland C for the PCI02 board.
The software for communication is developed in IAR C and Borland C for the Universal CAN I/O board and PCI02 board.
This configuration was only used for testing purposes but could also be adapted for several applications, namely, pistol spray painting and glue application.

3. Surface profile

All needed steps to acquire the profile of surface are described in this section: object search and robot positioning, surface scanning for depth acquisition.
The robot is positioned at the centre of a ring table, in which objects whose surface has to be acquired should be positioned. This table has 100 cm of height, 95 cm of internal radius and 125 cm of external radius.

3.1 Search for the object and robot positioning
The incremental rotational movement of the robot's base and the processing of the acquired images allow the location of the object performing the search process.
After the object detection, the system stops the rotational movement of the robot and centres the object in the vision field of the camera, as shown in the Fig 2. Next, the dominant points of the contour are extracted in order to create a 2D representation of the part's surface.
The extraction of the dominant points is implemented by the combination of two algorithms. The first algorithm performs segmentation, which is achieved by Otsu global thresholding (Santos et al., 1997), selected on the basis of a comparative study covering Otsu, Maximum Entropy, Uniform Error and Minimum Error Threshold selection methods described in (Monteiro, 1997). The second algorithm, developed for the extraction of the dominant points, is again a combination of two algorithms. The first marks pixels as candidates for dominant points and it is an improved version of the classical splitting method presented by Duda and Hart (Otsu, 1978). The second provides the selection and is based on slope (Lima & Campilho, 1994). This arrangement was devised to provide a process for dominant point's extraction suitable for most sort of object shapes. The dominant points are depicted in Fig 2.

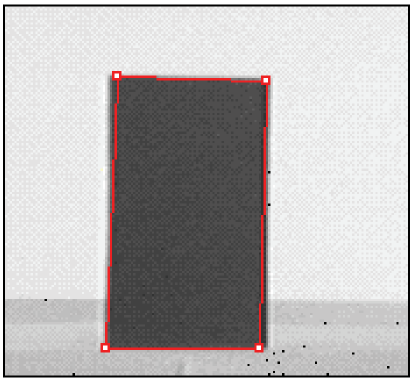


Fig. 2. Object extraction from background: Dominants points

The method implemented for calibration allows the object to present the correct dimensions once positioned on the worktable.
The process described confines the work area of the manipulator, and sets the system ready for horizontal scanning of the object.

3.2 Surface scanning for depth acquisition

The 3D acquisition is accomplished by making the manipulator scan the 2D shape with its ultrasonic sensors. The overall result of this task is the building of a surface map that shall support the generation of the surface profile.

3.2.1 Points of Constant Depth (PCD) and Areas of Constant Depth (ACD)

Many researchers have made the following comments about the measures with ultrasonic sensors (Leonard and Durrant-whyte, 1992):

1. Ultrasonic sensors offer many shortcomings a) poor directionality that limits the accuracy in the determination of the spatial position on an edge to 10-50 cm, depending on the distance to the obstacle and the angle between the obstacle surface and the acoustic beam b) Frequent misreading c) Specular reflections that occur when the angle between the wave front and the normal to a smooth surface is too large.
2. Ultrasonic range data are seriously corrupted by reflections and specularities.
3. The use of a sonar range finder represents, in some sense, a worst case scenario for localization with range data.

The general conclusion of these works is that sonar is plagued by two problems: beam opening angle affecting the angular resolution and specularity. To minimize the problems caused by the mentioned sonar sensors limitations and considering the proposed hardware, the following options were made:

1. A tube with about 20 cm was placed in front of each sensor (Fig 3);
2. The operating frequency was increased from 50 kHz to 63 kHz;
3. 8 pulses instead of 16 were used and the blanking time was decreased from 2.38 ms to 1.38 ms;
4. The global and exponential gains as well as the minimum limit for the detection were properly adjusted for the received echo (in the electronic module).

5. A new experimental model for the ultrasonic sensors was defined involving two new concepts: Points of Constant Depth (PCD) and Areas of Constant Depth (ACD).

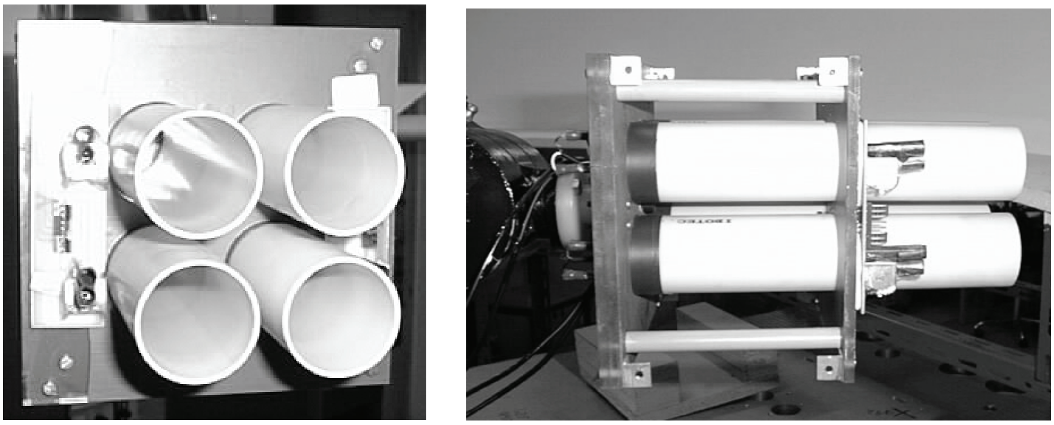


Fig. 3. Detail of the sonar sensors on the wrist

The main objective of options 1 and 2 is to reduce the opening angle value in order to increase the directionality in the intended operating range. The operating frequency increase also improves the angular resolution but, on the other hand, there is a greater attenuation of the transmitted wave and a decrease in the value of the maximum measurable distance. This attenuation doesn't cause any problem in referred kind of applications, because the maximum value to measure never exceeds 80 cm, while the maximum value measured with this configuration can go up to approximately 2 m (value obtained in practice).

With option 3 the minimum measurable distance could be reduced from 40 cm to 25 cm. In addition the opening angle is also reduced for the same operating range and the resolution is increased. As a result of the procedure suggested in point 3 the sample time could also be increased.

Finally, the procedure described in 4 guarantees that the echo is properly received within the intended measuring range and that the noise (acoustic and electric) is minimized.

The model for the ultrasonic sensors will be not explained in detail because it was already explained in a previous publication (Fonseca et al., 2001).

3.3 Surface scanning for depth acquisition

The 3D acquisition is accomplished by making the manipulator to scan the 2D shape with its ultrasonic sensors. The overall result of this task is the building of a surface map that shall support the generation of the surface profile. The algorithm implemented calculates the next position for acquisition using a fixed step. This step has the same value for the z and y coordinates. For each horizontal scan line, the start point is always defined by one extreme of the calculated boundary and the robot will step along evenly spaced points, till the end of the scan line. The definition of this step is done "a priori" and it depends on the desired precision for acquisition and the minimum resolution allowed to the surface. A fixed step s equal to the diameter of the sensors (4 cm) was used. In the scanning process we have the following problems for correct validation of PCD and ACD:

- Sometimes, with different ultrasonic sensors in the same position we obtain different measurements, namely in transitions points between areas with different depths or in the boundary of the object. The question is: Which one is the most correct sensor?
- With a fixed ultrasonic sensor sometimes we obtain greater variation in one or two measurements relatively to the other measurements. For example we acquire 10 measurements, 8 measurements have small variation and two measurements have a big variation. The question is: Which measurements are the correct ones?
- The measurements acquired with a fixed ultrasonic sensor have may have some variations. The question is: What is the measurement estimated for this position?

After several experimental tests, the implemented algorithm to solve the above problems is composed by the following steps (Fig 4):

1) Obtain ten measurements produced by two different ultrasonic sensors at the same position obtained by rotation of the wrist.
2) Calculate the average and variance.
3) Select the multisensor fusion technique.
4) Repeat measurements for the 4 sensing points on the wrist.
5) Check if the four points set an ACD.
6) Check if some points are in the boundary of the object.

The algorithm in pseudo code for the selected multisensor fusion technique is the following:

```
1.Begin
2. m_X = average of sensor X
   m_Y = average of sensor Y
   v_X = variance of X
   v_Y = variance of Y
3. IF ((m_X≠0) and (m_Y≠0)) then
          IF ( |m_X – m_Y | > 1.5 cm) then
                 Result = Fuzzy
          Else
                 IF ((v_X ≠0) or (v_Y ≠0))
                        Result = Kalman Filter
                 Else
                        Result = Average
   Else
          IF (m_X = 0 cm) then
                 Result = m_Y
          Else
                 Result = m_X
  End
```

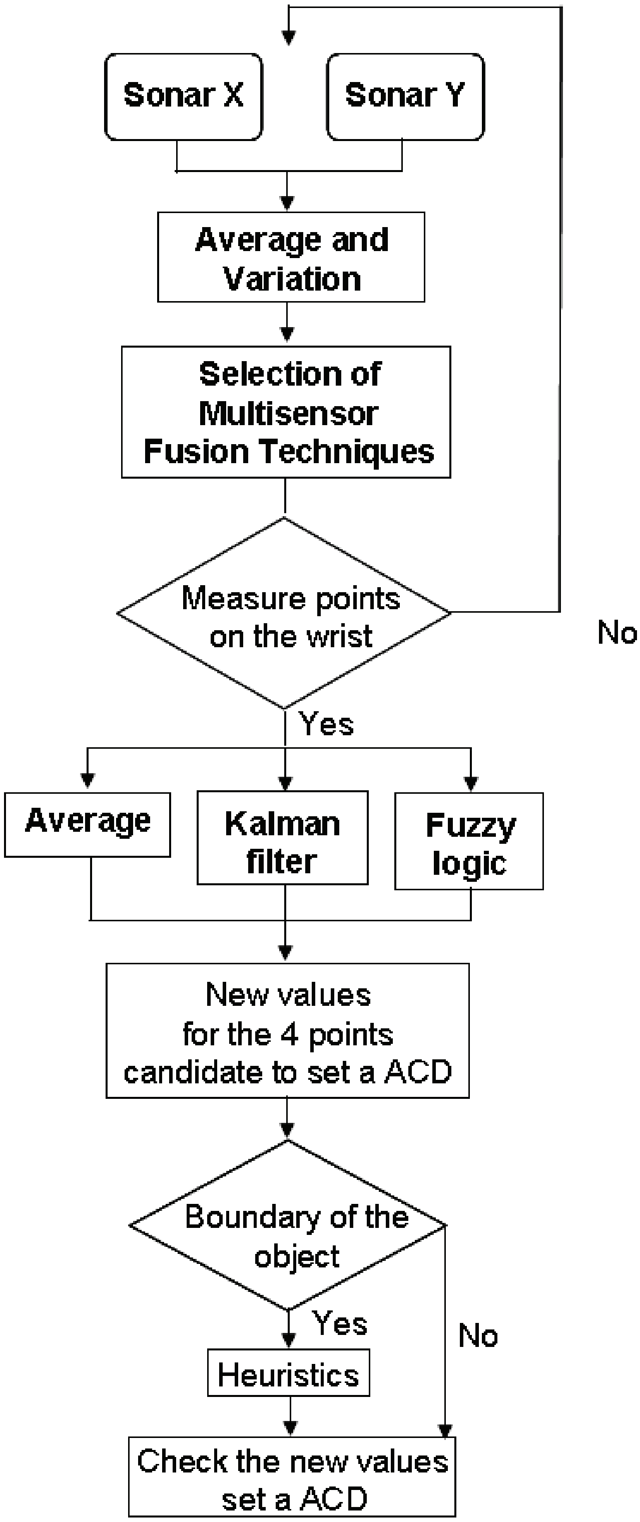


Fig. 4. Flowchart of the multisensor fusion process

3.3.1 Kalman filter

The ultrasonic sensors X and Y, provide redundant information relative to each other concerning the profile of the objects. The state to be estimated is the surface profile of an object and can be assumed to remain constant over the time, that is $x_k = x$ for all k. The profile measurement z_x and z_y from ultrasonic sensors X and Y, respectively, can be modelled as

$$z_x = x + v_x \quad \text{and} \quad z_y = x + v_y \tag{1}$$

where v_x and v_y are independent zero-mean Gaussian random variables with variances σ_x^2 and σ_y^2, respectively. Assuming that the measurement from X is initially available, $\hat{x}_0 = z_x$ and $P_0 = \sigma_x^2$ can be considered the *a priori* information available about *x* before the reception of the measurement from Y. When the measurements from Y becomes available, the optimal estimate of *x* is given by (Luo & Kay, 1995)

$$\begin{aligned} \hat{x} &= \hat{x}_0 + K\left[z_y - H\hat{x}_0\right] \\ &= \hat{x}_0 + P_0 H^T \left(H P_0 H^T + R\right)^{-1}\left[z_y - H\hat{x}_0\right] \\ &= z_x + \sigma_x^2\left(\sigma_x^2 + \sigma_y^2\right)^{-1}\left[z_y - z_x\right] \\ &= \frac{\sigma_y^2}{\sigma_x^2 + \sigma_y^2} \times z_x + \frac{\sigma_x^2}{\sigma_x^2 + \sigma_y^2} \times z_y \end{aligned} \tag{2}$$

where $R = \sigma_y^2$.

The variances σ_x^2 and σ_y^2 in the estimate of $\hat{x}$ can be interpreted as providing a mean of weighing each measurement z_x and z_y so that the measurement with the least variance is given the greatest weight in the fused estimate.

In this work the measurements z_x and z_y are equal to the average of the ten measurements provided by each ultrasonic sensor X and Y, respectively. The σ_x^2 and σ_y^2 are the variance of the ten measurements acquired by the ultrasonic sensors X and Y.

3.3.2 Fuzzy controller

The fuzzy controller is only applied when the average of the measurement performed by the first sensor minus the average of the measurement performed by the second sensor is greater than 1.5 cm, when the same point is measured. The decision the value of 1.5 cm is based on experimental results and it is also used to validate the ACD areas (it is the reference value). This situation arises in transition points, between areas with different depths or in the boundary of the object. The question to be asked is: Which one is the correct measurement?

The selection between the two values can be decided based on the information acquired by the neighbouring sensors (Fig 5). The information from these points can be used to set the confidence degree for each measurement in P_1. If the measurement from the neighbour sensors P_2 and P_4 are correct, the membership degrees vary inversely with difference between measurements *P_1 and P_2* and *P_1 and P_4*: the lower the is difference the higher is set the corresponding membership degree.

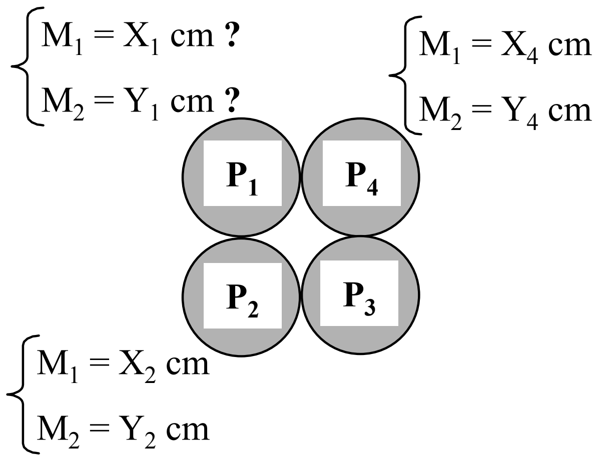


Fig. 5. Example – The P_1 point has different measurement (M_1 and M_2)

A fuzzy controller is implemented for estimation of measurement of P_1 point. The fuzzyTECH tool was used to design the fuzzy logic controller. It is a full graphical tool that supports all design steps for fuzzy system engineering: structure design, linguistic variables, rules definition, and interactive debugging. Moreover, this tool generates ANSI C-code (fuzzyTECH, 1996) (Altrock, 1995).

Fig 6 and Fig 7 shows the input and the output membership functions. The input membership function is defined taking into account the maximum variations possible between the measurement performed of point P_1, P_2 and P_4. The output membership function gives the degree of confidence of the measurement performed of point P_1.

Triangular membership functions (MFs) were employed for the input and Singleton Membership functions (which can be considered as a special case of Triangular MFs) were employed for the output. Dif-neighbouring uses 5 MFs: zero (ZE), positive small (PP), positive medium (PM), positive big (PG), and positive very big (PMG). Deg-confidence is described with 5 MFs: zero (ZE), positive small (PP), positive medium (PM), positive big (PG), and positive very big (PMG).

The method of defuzzification used was the CoM (Centre of Maximum), which considers only the maximum value positions of the MFs. In this case the use of Singleton or Triangular MFs for the output produces the same results.

Table 1 shows the fuzzy controller rules. They were set according to the understanding of the behaviour of the system. For small input values (Dif-neighbouring ≤ 0.7 cm) the degree of confidence is greater (Deg-confidence ≥ 0.42 cm); for higher input values (Dif-neighbouring > 0.7 cm) the degree of confidence is small (Deg-confidence < 0.42 cm). When the input value is greater than 1.2 cm the output value is always 0.

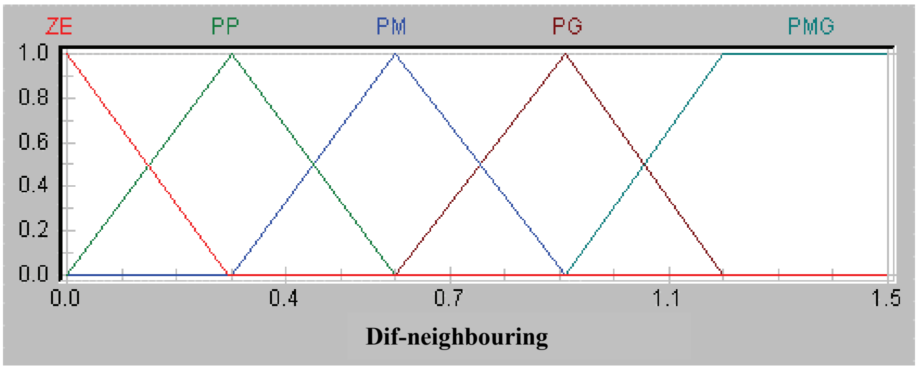


Fig. 6. Fuzzy logic controller – input membership function

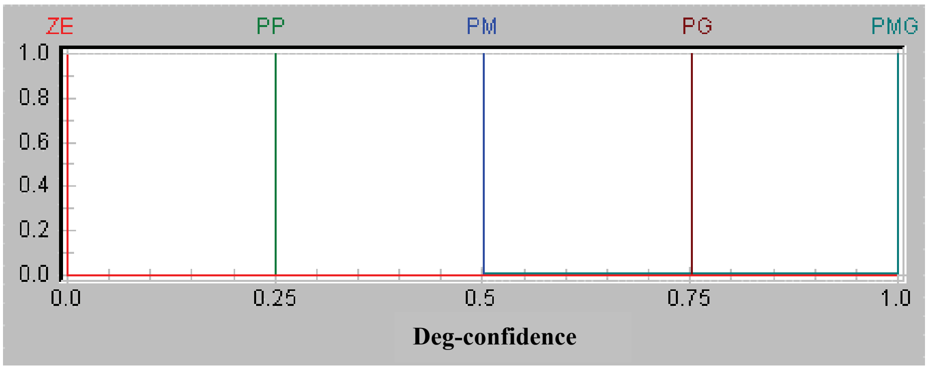


Fig. 7. Fuzzy logic controller – output membership function

IF	Then	
Dif-neighbouring	**DoS**	**Deg-confidence**
ZE	1	PMG
PP	1	PG
PM	1	PM
PM	1	PP
PMG	1	ZE

Table 1 – Fuzzy rules

The estimated measurement of P_1 point (this is an example) is determined by the expression

$$D_{Pos(1\,2\,3\,4)} = \frac{(C\_1 + C\_2 + C\_3 + C\_4)}{C\_T} \times M\_X + \frac{(C\_5 + C\_6 + C\_7 + C\_8)}{C\_T} \times M\_Y \qquad (3)$$

Where,

DPos(1 2 3 4) – Estimated measurement of position 1, 2, 3 or 4.

C_1 a C_8 – Partial degree of confidence. These values are set by the deffuzification process.

C_T = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8.

M_X - Average of the measurement performed by the ultrasonic X when pointing to the position 1, 2, 3 or 4.

M_Y – Average of the measurement performed by the ultrasonic Y when pointing to the position 1, 2, 3 or 4.

3.3.3 Average

The average is only used when the variance is equal to zero. The mathematical expression for the average is the following:

$$Pos_{(1234)} = \frac{M\_X + M\_Y}{2} \quad (4)$$

Where,

Pos (1,2,3,4) - Estimated measurement for position 1, 2, 3 or 4.

3.3.4 Heuristic method

This method is based on rules and is only used in the boundary of the object. For example:

```
If (upper limit) then
      Measurement of Pos. 1 = Measurement of Pos. 2
      Measurement of Pos. 3 = Measurement of Pos. 4
Else
      ……
```

4. Experimental results

Experimental results were achieved with three objects. The first has a flat square surface without areas with different depth. The second has a square surface with a rectangular zone at a different depth. The third has a square surface too, but with multiple areas with different depths and corners. The depth is the distance from the wrist of the robot to the object. The following figures depicts the mapping achieve for the above mentioned objects.

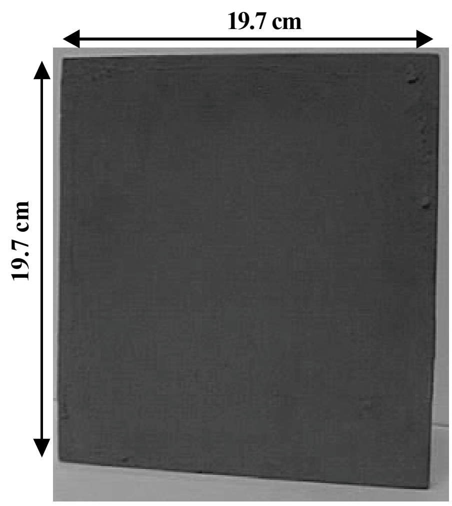


Fig . 8. The model and your dimensions.

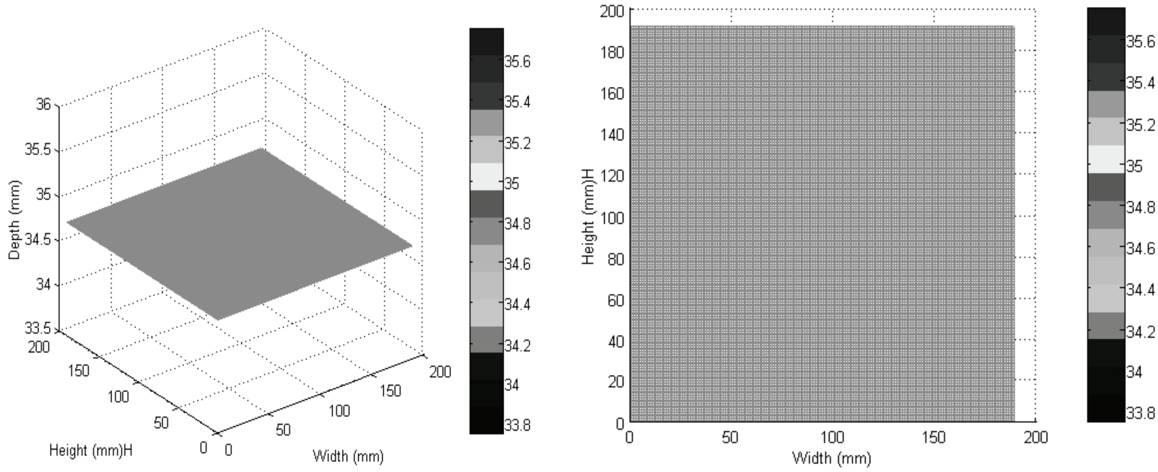


Fig. 9. The profile in 3D and the visualization in 2D.

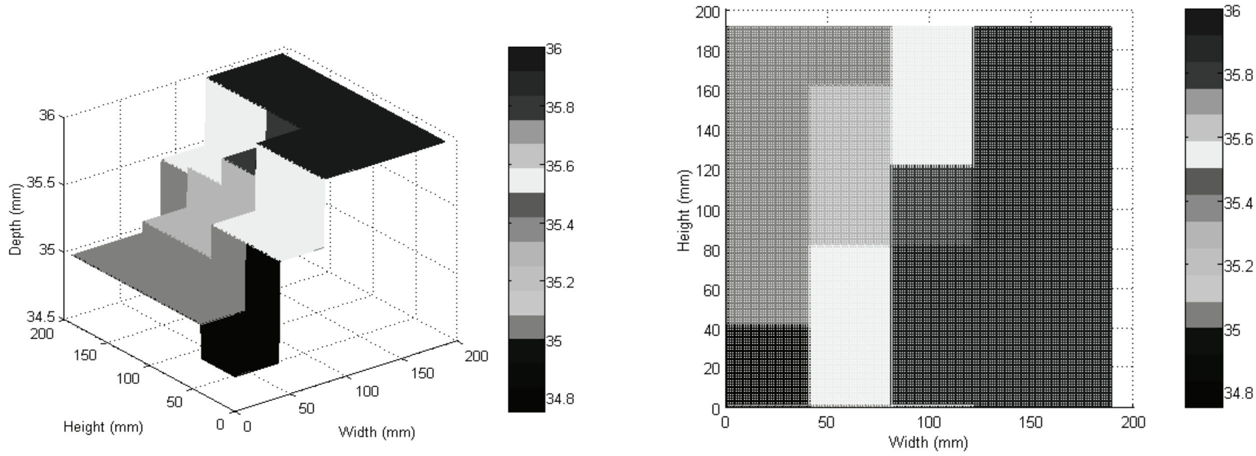


Fig. 10. The profile in 3D and the visualization in 2D without sensor fusion.

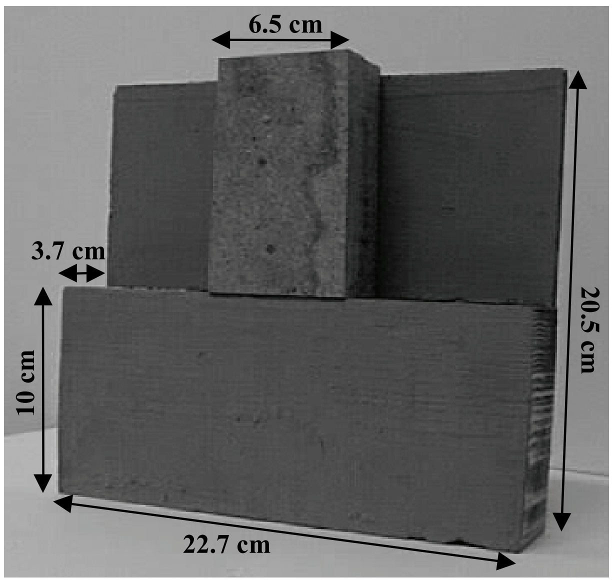


Fig . 11. The model and your dimensions.

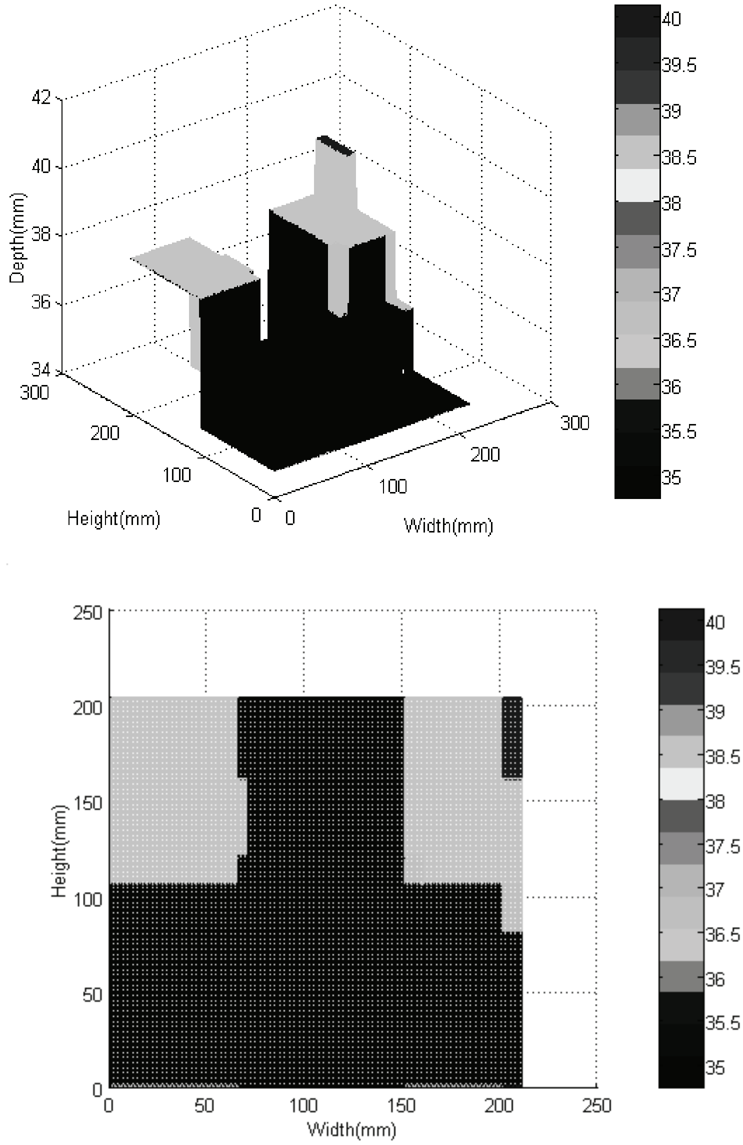


Fig. 12. The profile in 3D and the visualization in 2D.

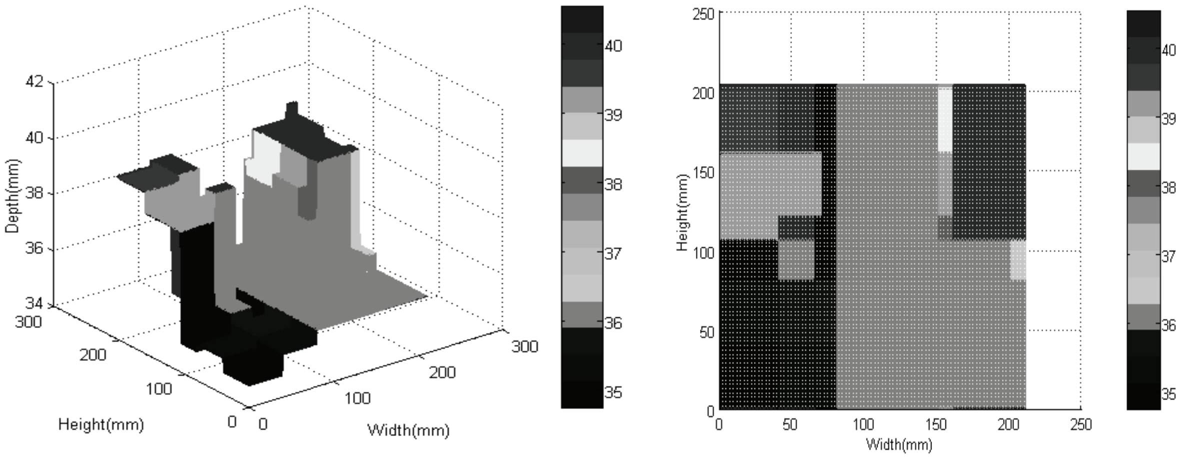


Fig. 13. The profile in 3D and the visualization in 2D without sensor fusion.

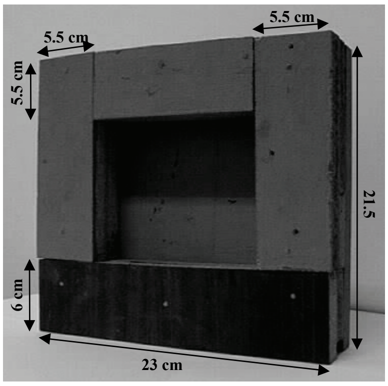


Fig . 14. The model and your dimensions.

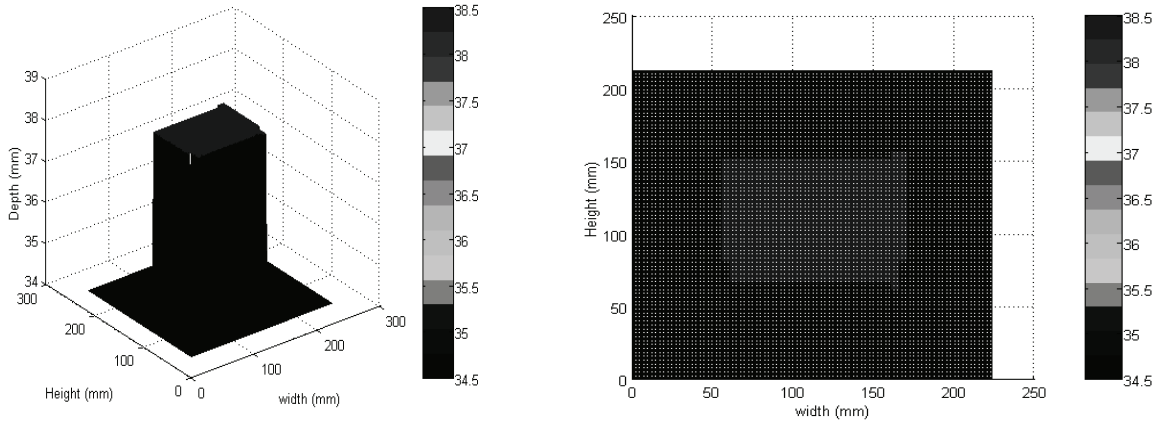


Fig. 15. The profile in 3D and the visualization in 2D.

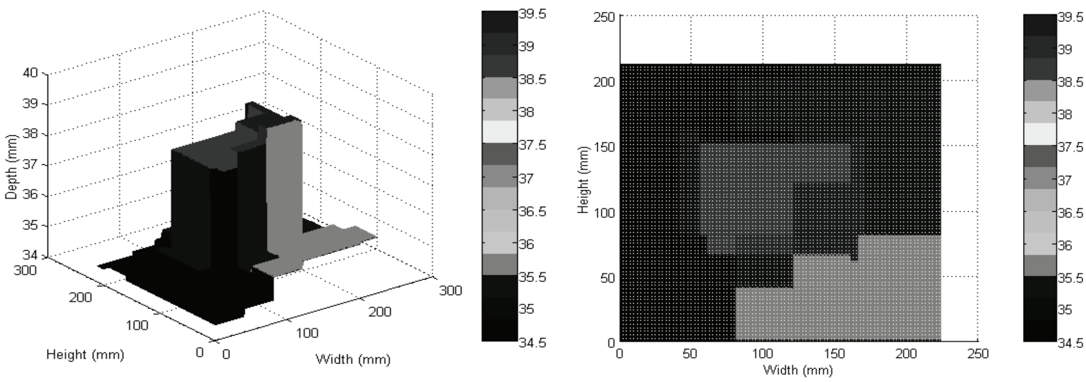


Fig. 16. The profile in 3D and the visualization in 2D without sensor fusion.

5. Conclusions

A sensor system has been designed and built to acquire the profile of surfaces, based on a CCD camera for object boundary-determination and ultrasonic sensors for depth measurement. In order to reduce the measurement error resulting from the beam opening angle of ultrasonic sensors, these were covered with a tube of 20 cm, as well with an increase in the working frequency. The surface profile acquisition with this technique is a quite slow process, essentially due to the low speed of the sound wave and to the number of the measurements needed for extraction of the RPCs (approximately 240 ms). The time spent scanning an object is greater if the object surface has many areas with different depths. For example, the time spent for the acquisition the first object presented in this paper was 8 min while for the second object was 30 min. The accuracy of the surface map obtained with this system is approximately 1.5 cm when measured from a distance of 35cm±1cm. This accuracy is acceptable for several operations with industrial relevance, namely: recognition of objects, pistol spray painting and glues or diluents application. However the achieved resolution is not acceptable for several other applications, such as: welding process, surface grinding and polishing.

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