Multifactorial Fuzzy Logic Distance Correction for UWB Positioning System

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Abstract**—**The paper aims to present the application of fuzzy logic to correct distances obtained from the UWB system. Positioning using the Ultra-Wideband (UWB) system for automotive purposes has many applications (including support for Advanced Driver-Assistance Systems (ADAS) applications in making driving decisions more safe and comfortable). Based on the research carried out by the authors of the article, it appears that the data maintain high precision in certain ranges, but they depend on the many factors like environment, obstacles and the distance in which the positioned objects are located. By using data fusion using fuzzy logic, it is possible to improve the distance value of the UWB system as presented in this article. The result of the research and the proposed correction is the receipt of a wireless system enabling the determination of distances with accuracy to centimeters for a large range of distances.

Index Terms**—**Fuzzy Logic, lidar, localization, ultra-wideband

I. Introduction

Thanks to the widespread use of civilian navigation technologies, more and more cars are equipped with dedicated, factory-fitted navigation systems. They usually use technology based on satellite navigation (GPS, Galileo, Baidu), but there are also systems using the fusion of several different sensors (those based on driving parameters [1] as well as position data obtained from the GSM module [2], information provided by radar [3], [4], lidar [5], microelectromechanical (MEMS) systems [6], [7] or video image changes [8] etc.) However, these solutions face certain restrictions, such as the unavailability of the GPS signal in places such as underground parking lots or tunnels, time to first fix [9], restrictions of video, lidar or radar systems due to adverse weather conditions [10], [11], low GSM signal accuracy, especially in areas with low base station density [12]. An example of a system that can be used as a missing element in the field of location and thus has a chance to become popular in the automotive industry in the near future is Ultra-Wideband (UWB) [13]. UWB is using the transmission of low-energy high-frequency pulses is characterized by high accuracy in determining the position of objects [14]-[17]. This technology allows to solve the above-mentioned problems of other methods used in localization. By using tags in built-up areas or those where the GPS signal is not available, it is possible to maintain continuity in determining the position of e.g. cars passing through tunnels, people entering buildings, employee monitoring or support smart city solutions [18], [19]. In addition, the signal characteristics make it resistant to adverse weather conditions [13] in which, for example, vision or lidar systems may have a problem with the interpretation of the data obtained [20]. An additional advantage that does not occur when using solutions based on GPS, lidar or radar is the possibility of two-way transmission. Thanks to this, the system also allows the transmission of additional data, which in the case of cars allow the application of many additional solutions in the field of V2V (vehicle to vehicle) or V2I (vehicle to infrastructure) communication. This will allow faster propagation of information about the current road situation in the vicinity of objects that are a potential threat, or even the behavior of the vehicle ahead of it before detecting a potential maneuver, e.g. by analyzing the distance from the radar. An example of work on the use of this technology by automotive industry leaders could be, key fob positioning for the construction of a keyless vehicle service system based on UWB technology [21]. Another example could be an attempt to develop a positioning algorithm to minimize energy consumption for a similar device [22]. Maintaining particularly high precision can be crucial in confined areas, where a car traveling at a low speed must maintain high position accuracy, e.g. as a component of the ADAS system during autonomous parking. Precise distance information is also needed in the context of safety, especially when two vehicles equipped with UWB will have to exchange information about their proximity. All these aspects prompt researchers to intensify their work on this technology and the problems it faces. An example would be the behavior of the system based on DecaWave DWM1000 devices. The paper describes the problem with determining the distance that can be encountered at relatively small distances (less than 1 m) or system behavior in an environment that reflects different road conditions such as tunnels or underground parking lots. As part of this paper, the authors presented how to reduce the error encountered using rules based on fuzzy logic. The document first presents the devices used and the tests carried out, together with the presentation of statistical results for raw data in two cases - changes only in

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distance, and both distance and other parameters. Next, the assumptions were made regarding the fuzzy logic used. The authors present a selection of roles for an analogous division of data characteristics - for a variable distance and in addition to changing the payload parameter value and the occurrence of interference. A final conclusion is made, summarizing the results obtained and presenting the possible areas of application of the proposed solutions.

II. Materials and Methods

A. *Used Modules*

During the research, the following sensors and equipment were used:

- Lidar - LIDAR-Lite v3HP device was used that has a classified by EN/IEC 60825-1 2014 laser. It has accuracy of +/- 2.5 cm – used for the dynamic and / or environment measures, reference.
- Rangefinder – the digital rangefinder Bosch PLR 50 C was used with measuring the accuracy of +/- 2 mm – used for the static measures, reference.
- UWB –DecaWave DWM1000 was used together with the managing microcontroller - STM32F103 (see on Fig. 1). The device worked on the default antenna, while the program that was used for transmission came from sample materials provided by the manufacturer.

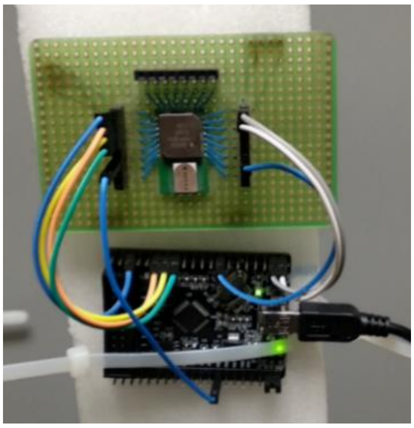


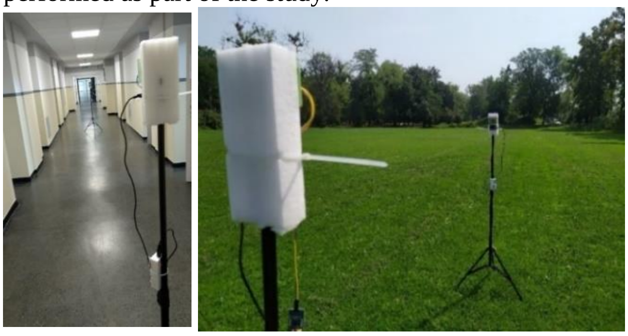
Fig. 1. UWB module DecaWave DWM1000 with STM microcontroller.

B. *Preformed Measures*

As part of the study, a measuring series containing over 11,000 samples were carried out. Then, samples from the beginning and end of the measurement (containing unwanted interference due to the presence of the equipment operator) were discarded for each of the measurement series. The target series included in further studies contained 10,000 samples. The authors wanted to check the behavior of UWB modules in many scenarios. It is worth noting, however, that all tests were carried out on the default UWB antenna. Literature, on the other hand, deals with this subject in a comprehensive way [23], [24].

Two measuring environments. The first corresponding to the measurement in closed space conditions such as a tunnel or underground car park with waveguide characteristics (see in Fig. 2a). The width and height of the corridor is 260 cm. The second one corresponds to the open space without infrastructure elements such as buildings - an example is a higher class road, e.g. a highway (see on Fig. 2b).

The measurement depends on the height at which both UWB antennas are located – it was to check if a different height from the ground affects the quality of the received signal. Measurement with an obstacle – this measurement checked whether the presence of an obstacle in the form of the human body in the line of sight both antennas affects the behavior of the system and the results obtained. During this study, the man stood halfway between the transmitter and receiver. Payload size – this study examined whether the size of the payload being transferred has an impact on the distance received. All of the above were decided to be performed first independently in one environment, and then, based on the results obtained, decide which measurement series should be repeated (and in what combination) in the other environment. In total, over 200 measurement series were performed as part of the study.



a b

Fig. 2. Test environment a – corridor reflecting tunnel or underground car park – indoor; b - open space in the distance from buildings – outdoor.

C. *Obtained Results–Distances*

First, static measurements were performed, without interference, without affecting the size of the payload for a tripod at a height of 100 and 150 cm for distances from 25 cm to 30 m. As an example, the obtained results for the indoor and outdoor enjoinment are presented for the 150 cm tripod in Table I, where the average (mean) value was calculated from standard equation (1), where x is the value and n number of elements.

$$\bar{x}=\frac{\sum_{i=1}^{n}x_i}{n} \quad (1)$$

In the Table I, special attention should be paid to the underestimation of initial values - for low distances. This happens both for the environment inside the building and for measurements taken outside the building. Similar behavior can be seen as the distance increases. Here, however, can be seen the different behavior of the system in outdoor and indoor conditions. In the case of outdoor tests from a distance of 25 m, the average distance value obtained is lower than the set value - similarly as in the case of short distances.

TABLE I: AVERAGE DISTANCE VALUES OBTAINED FOR POINT-TO-POINT MEASUREMENT FOR TRIPODS AT A HEIGHT OF 150 CM IN AN OUTDOOR AND INDOOR ENVIRONMENT WITHOUT INTERFERENCE

Distance [mm]	Outdoor Avg [mm]	Indoor Avg [mm]	Outdoor Real – Avg [mm]	Indoor Real – Avg [mm]
250	**58.19**	**101.83**	**191.81**	**148.17**
500	**341.87**	**356.41**	**158.13**	**143.59**
750	**595.63**	**657.20**	**154.37**	**92.80**
1000	**898.82**	973.78	**101.18**	26.22
1500	**1396.81**	1543.52	**103.19**	-43.52
2000	1953.65	2015.19	46.35	-15.19
4000	4022.87	3994.24	-22.87	5.76
5000	5026.15	5045.40	-26.15	-45.40
6000	6085.09	5981.90	-85.09	18.10
8000	8161.51	7985.25	-161.51	14.75
10000	10036.99	9980.25	-36.99	19.75
15000	15047.59	**15225.05**	-47.59	**-225.05**
20000	19973.66	**20126.38**	26.34	**-126.38**
25000	**24830.18**	**25097.55**	**169.82**	**-97.55**
30000	**29835.72**	**30107.99**	**164.28**	**-107.99**

However, in the case of tests carried out inside a building from the distance of 15 m the results we get are greater. The Table I indicates those series from the beginning and end of the measurement scale in which the difference was more than 5 cm, but for the initial values, the average result and the set distance are almost identical (25 cm real for the outdoor and 19 cm difference of the avg value). This is confirmed by the Table II with the mean absolute and relative error in percentage, that was calculated from equation (2).

$$\Delta x = \frac{\sum_{i=1}^{n} |y - x_i|}{n} \tag{2}$$

where the y is the real value, x is the value obtained from the system and n is the number of samples in series.

TABLE II: AVERAGE DISTANCE ERROR OBTAINED FOR POINT-TO-POINT MEASUREMENT FOR TRIPODS AT A HEIGHT OF 150 CM IN AN OUTDOOR AND INDOOR ENVIRONMENT WITHOUT INTERFERENCE

	Outdoor		Indoor	
Distance [mm]	Avg Error [mm]	Avg Error [%]	Avg Error [mm]	Avg Error [%]
250	**191.81**	**76.7%**	**148.17**	**59.3%**
500	**158.13**	**31.6%**	**143.59**	**28.7%**
750	**154.37**	**20.6%**	**92.80**	**12.4%**
1000	**101.18**	**10.1%**	26.46	2.6%
1500	**103.19**	**6.9%**	43.58	2.9%
2000	46.41	2.3%	18.76	0.9%
4000	23.36	0.6%	19.31	0.5%
5000	26.54	0.5%	45.40	0.9%
6000	85.09	1.4%	20.82	0.3%
8000	161.51	2.0%	22.14	0.3%
10000	37.25	0.4%	27.81	0.3%
15000	47.65	0.3%	225.05	1.5%
20000	28.20	0.1%	126.38	0.6%
25000	169.82	0.7%	97.63	0.4%
30000	164.28	0.5%	108.02	0.4%

The Table II shows the percentage of error in the distance measured using the UWB system. For both low and high distances, a difference was noticeable in the case of numerical values, while in the case of a percentage of relative error it is only noticeable for measurements over a short distance - up to 1 meter. You can also see how changing the environment affects the error you receive. Due to the distortion characteristics (underestimation of distance) occurring in the indoor multipath environment during our study, it has a positive effect on real values. However, both for indoor and outdoor examinations require distance correction.

D. Obtained Results–Obstacles

Another of the tests was to check the system behavior in the event that there is an object between the transmitting antenna and the receiver forcing the system to operate in non-line of sight conditions. The study was decided to be carried out for 10, 15 and 20 m. It also checked the system behavior for different payload parameter values (10, 25, 50 and 80B, respectively), and also analyzed the effect of the height at which the antenna is mounted on the quality of the received signal. All of the above combinations of scenarios were multiplied by two types of environment - as in the previous case it was outdoor and indoor. Example results are presented in Table III.

TABLE III: IMPACT OF OBSTACLE ON UWB SIGNAL IN DIFFERENT ENVIRONMENTS AND WITH DIFFERENT PAYLOAD PARAMETER VALUES

Dist. [m]	Outdoor [m]				Indoor [m]			
	W/O P25	W P25	W/O P50	W P50	W/O P25	W P25	W/O P50	W P50
10	10.34	10.37	10.33	10.38	10.40	10.55	10.35	10.84
15	15.32	15.36	15.36	15.36	15.44	15.47	15.47	15.50
20	20.29	20.32	20.32	20.37	20.12	20.66	20.14	20.61

where W/O – Without obstacles W – with obstacles PX – X is an amount of payload in B.

For both tests carried out inside and outside the building, the occurrence of an obstacle had a negative impact on the acquired information about the distance between UWB devices. However, for the Indoor environment, the impact was much more noticeable. You can very well notice the occurring relationship by presenting the data graphically. Fig. 3 presents the results for a distance of 20 m.

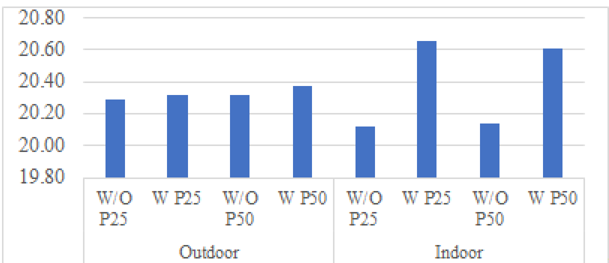


Fig. 3. The difference between distance with and without the obstacle, for tests inside and outside the building at different payload values and 20 m distances.

The distance results for different mounting heights of the receiver and transmitter antennas are shown in Table IV, and their absolute values of differences are presented in Fig. 4.

For the distance values for various antenna mounting heights on tripods (100 vs 150 cm) can be said that the differences that resulted from them were in almost all cases less than 1 cm (average absolute value was 0.39cm), which is why the authors assumed that this parameter was omitted in further analysis).

TABLE IV: INFLUENCE OF THE MOUNTING HEIGHT OF THE UWB TRANSMITTER-RECEIVER ON THE OBTAINED DISTANCE VALUES

Dist. [cm]	Indoor Payload 10 [cm]		Indoor Payload 25 [cm]		Outdoor Payload 50 [cm]		Outdoor Payload 80 [cm]	
	H100	H150	H100	H150	H100	H150	H100	H150
500	53.2	52.9	53.6	53.2	52.2	53.1	53.1	53.1
1000	104.6	103.8	104.0	104.0	103.9	103.3	104.0	103.8
1500	153.4	156.2	154.9	154.4	153.0	153.6	153.5	153.8
2000	202.7	203.8	202.3	201.2	203.9	203.2	204.0	203.4

where Payload x – x is the amount of data in B, Hxxx - xxx is the height of the UWB mounting point on the tripod in cm.

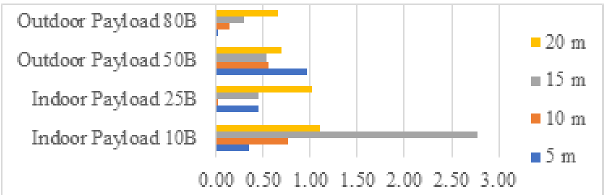


Fig. 4. Absolute values of differences in mean values between the antenna at a height of 100 and 150 cm.

III. FUZZY LOGIC ASSUMPTIONS

Based on the analysis of the obtained and previous work with the UWB system, the authors decided to consider four parameters in the fuzzy logic rules - information about the environment in which the device is currently located, information about the obstacle between the transmitter and receiver of the UWB system, information about payload transmitted by devices and information about the distance. In this paper, we decided to use a Mamdani fuzzy inference method, which is considered as the most commonly seen fuzzy methodology due to its simple structure. It was implemented in the Matlab toolbox. Proposed membership functions in the Fuzzy Inference System (FIS) based on the following membership functions (3, 4).

- Trapezoidal

$$f(x;a,b,c,d)=\begin{cases} 0, & x\le 0 \\ \frac{x-a}{b-a}, & a\le x\le b \\ 1, & b\le x\le c \\ \frac{d-x}{d-c}, & c\le x\le d \\ 0, & d\le x \end{cases} \quad (3)$$

- Gaussian and Gaussian combination

$$f(x;\sigma,c)=e^{\frac{-(x-c)^2}{2\sigma^2}} \quad (4)$$

TABLE V: LIST OF FIS INPUT FUNCTION PARAMETERS

FIS variable name	Environment	Obstacle	Payload	UWB Distance
Range	[0 1]	[0 1]	[0 8]	[0 50]
Translation into real values	Binary – 0 as an indoor, 1 as an outdoor	Binary – 0 as a no obstacle, 1 as an obstacle	P_t	UWB_t
Number of functions	2	2	5	8
Functions types	1, 2 Singleton represented by Trapezoidal	1, 2 Singleton represented by Trapezoidal	1 – 5 Gaussian	2 – 5 Gaussian and 1, 6 – 8 Gaussian combination

Proposed membership functions parameters based on the conducted research are presented in Table V. The Payload (P_t) and UWB Distance (UWB_t) translation are given in equation (5). Where p is the current payload (in B) and d is the current distance (in mm).

$$P_t = \frac{p}{10} \qquad UWB_t = \frac{d}{1000} \quad (5)$$

Based on the analysis, the following functions have been proposed for the given variables:

- Environment
  - (1) [0 0 0 0] – Indoor
  - (2) [1 1 1 1] – Outdoor
- Obstacle
  - (1) [0 0 0 0] – No obstacle
  - (2) [1 1 1 1] – Obstacle
- Payload
  - (1) [1 0] – Up to 10 B
  - (2) [1 1] – from 10 B to 25 B
  - (3) [1 2.5] – from 25 B to 50 B
  - (4) [1 5] – from 50 B to 80 B
  - (5) [1 8] – above 80 B
- UWB Distance
  - (1) [1 -1 1 0.25] – from 0 to 25 cm
  - (2) [1 0.5] – from 25 cm to 50 cm
  - (3) [1 0.75] – from 50 cm to 75 cm
  - (4) [1 1] – from 75 cm to 1 m
  - (5) [0.5 1.5] – from 1 m to 1.5 m
  - (6) [1 2 2 15] – from 2 m to 15 m
  - (7) [2 20 2 25] – from 20 m to 25 m
  - (8) [2 30 1 50] – above 30 m

As an output from the system, 9 membership functions from -1 to 1 were used. Ultimately, the function output was to be scaled to values in the range from -25 cm to 25 cm, which was to be added to the distance we obtained from the UWB system. As 0, the function without changing the value was proposed, while the following followed were Small, Medium, Big and Huge, marked with + and - respectively, depending on the range in which they were. The whole, based on gauss functions, was as follows (from left to right):

- Negative Huge [0.1062 -1]
- Negative Large [0.1062 -0.8]
- Negative Medium [0.1062 -0.6]
- Negative Small [0.1062 -0.4]
- Negative Tiny [0.1062 -0.2]

- No Change [0.1062 0]
- Positive Tiny [0.1062 -0.2]
- Positive Small [0.1062 0.4]
- Positive Medium [0.1062 0.6]
- Positive Large [0.1062 +0.8]
- Positive Huge [0.1062 +1]

IV. Rules and Results

Based on the analysis of the conducted research, the following rules (presented in a graphical way on Fig. 5) were proposed reflecting the behavior of the UWB system.

Each of the rules was created in such a way that if the tests for a given distance showed an error higher than 100 mm, the rule was based on the next linguistic variable of the output parameter in the direction in which the value of the average distance was lower than the expected value.

```
1. (UWBDistance==below0.25) & (Payload==UpTo10) & (Environment==Outdoor) &
(Obstacle==NoObstacle) => (output1=Medium+) (1)
2. (UWBDistance==0.5) & (Payload==UpTo10) & (Environment==Outdoor) &
(Obstacle==NoObstacle) => (output1=Small+) (1)
3. (UWBDistance==0.75) & (Payload==UpTo10) & (Environment==Outdoor) &
(Obstacle==NoObstacle) => (output1=Small+) (1)
4. (UWBDistance==1) & (Payload==UpTo10) & (Environment==Outdoor) &
(Obstacle==NoObstacle) => (output1=Tiny+) (1)
5. (UWBDistance==1.5) & (Payload==UpTo10) & (Environment==Outdoor) &
(Obstacle==NoObstacle) => (output1=NoChange) (1)
6. (UWBDistance==2-15) & (Payload==UpTo10) & (Environment==Outdoor) &
(Obstacle==NoObstacle) => (output1=NoChange) (1)
7. (UWBDistance==20-25) & (Payload==UpTo10) & (Environment==Outdoor) &
(Obstacle==NoObstacle) => (output1=NoChange) (1)
8. (UWBDistance==30+) & (Payload==UpTo10) & (Environment==Outdoor) &
(Obstacle==NoObstacle) => (output1=Small+) (1)
9. (UWBDistance==below0.25) & (Payload==UpTo10) & (Environment==Indoor) &
(Obstacle==NoObstacle) => (output1=Small+) (1)
10. (UWBDistance==0.5) & (Payload==UpTo10) & (Environment==Indoor) &
(Obstacle==NoObstacle) => (output1=Small+) (1)
```

Fig. 5. Text presentation of some of the proposed rules for the UWB system in the no payload and no obstacle conditions.

An exemplary presentation of the rules in the form of a plane of the distance dependence obtained from the UWB system in relation to the environment in which system worked is presented in Fig. 6.

Based on the proposed rules, statistical analysis of the obtained data was re-developed. Then, for the data from static measurements, an error analysis was carried out which showed that in the vast majority of cases the proposed rules allowed to improve the obtained results.

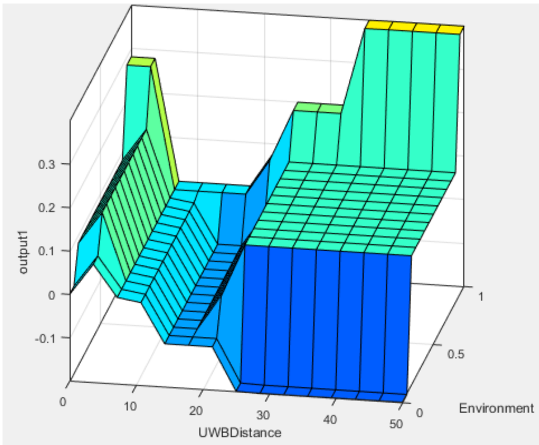


Fig. 6. Function output plane presenting the relationship of the distance obtained from the UWB system to the environment in which it worked.

Particular improvement is noticed for low distance values. where the error was 192 mm from the declared 250 mm, which was 77%, while after correction the error was corrected to only 6.3% what is about 15 mm. A shortlist of results is presented in Table VI.

Also, the results for higher distances improved, but here the percentage error was relatively small (in terms of error at low distances). These changes can be well observed in Table VII presenting the differences between the average distance obtained for raw data and the data processed by the proposed fuzzy logic.

Table VI: Distance Error After Performing Filtration using the Proposed Fuzzy Logic and the Relative Percentage Error for the Result before and after Data Processing

Dist.	Outdoor			Indoor		
[mm]	**Avg Error [mm]**	Corrected Avg Error [%]	Raw Avg Error [%]	**Avg Error [mm]**	Corrected Avg Error [%]	Raw Avg Error [%]
250	**15.66**	**6.3%**	**76.7%**	27.73	11.1%	59.3%
500	19.31	3.9%	31.6%	42.23	8.4%	28.7%
750	17.12	2.3%	20.6%	30.95	4.1%	12.4%
1000	53.10	5.3%	10.1%	9.47	0.9%	2.6%
1500	31.10	2.1%	6.9%	39.98	2.7%	2.9%
2000	62.06	3.1%	2.3%	14.36	0.7%	0.9%
4000	26.35	0.7%	0.6%	18.85	0.5%	0.5%
5000	26.62	0.5%	0.5%	45.47	0.9%	0.9%
6000	85.09	1.4%	1.4%	20.81	0.3%	0.3%
8000	161.51	2.0%	2.0%	22.14	0.3%	0.3%
10000	37.25	0.4%	0.4%	27.81	0.3%	0.3%
15000	47.65	0.3%	0.3%	41.02	0.3%	1.5%
20000	**28.20**	**0.1%**	**0.1%**	**33.34**	**0.2%**	**0.6%**
25000	**156.91**	**0.6%**	**0.7%**	**28.69**	**0.1%**	**0.4%**
30000	**23.95**	**0.1%**	**0.5%**	**31.48**	**0.1%**	**0.4%**

Then, a similar analysis was performed for data with different payload values and during disturbances. As part of the preparation of functions for data with a variable payload value, and for those for which we tested the system behavior with interference, first of all, 16 rules prepared for data without these changes were used. Then another 32 rules were created based on the distance errors that could be observed, according to the rule that every

100 mm difference from the expected value creates a rule by one value different at the output.

The example of the output for the proposed rules was presented in the Fig. 7.

An illustrative graphic was also prepared to present the influence of the payload parameter size in relationship of the occurrence of the obstacles on the function output (see in Fig. 8).

TABLE VII: THE DIFFERENCE BETWEEN THE MEAN DISTANCE BEFORE AND AFTER MAKING CORRECTIONS FOR STATIC MEASUREMENTS

Distance [mm]	Outdoor Average [mm]		Indoor Average [mm]	
	Raw	Corrected	Raw	Corrected
250	58.19	245.61	101.83	224.63
500	341.87	517.25	356.41	457.79
750	595.63	761.32	657.20	720.83
1000	898.82	1053.10	973.78	1000.24
1500	1396.81	1530.70	1543.52	1539.88
2000	1953.65	2062.06	2015.19	2003.77
4000	4022.87	4026.05	3994.24	3996.71
5000	5026.15	5026.25	5045.40	5045.47
6000	6085.09	6085.09	5981.90	5981.90
8000	8161.51	8161.51	7985.25	7985.25
10000	10036.99	10036.99	9980.25	9980.25
15000	15047.59	15047.59	15225.05	15218.29
20000	**19973.66**	**19973.67**	**20126.38**	**20032.00**
25000	**24830.18**	**24843.09**	**25097.55**	**24997.55**
30000	**29835.72**	**30017.19**	**30107.99**	**30007.99**

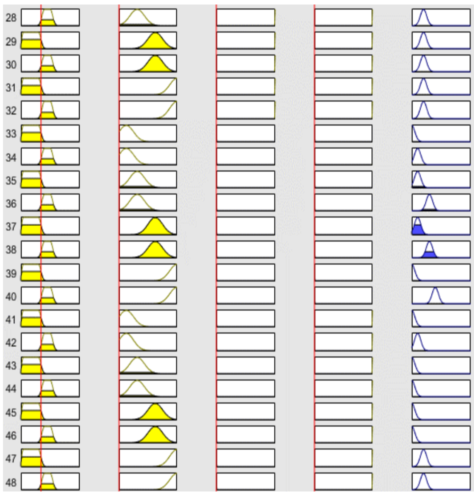


Fig. 7. Graphical presentation of proposed rules for the UWB system when the payload and obstacle conditions occur.

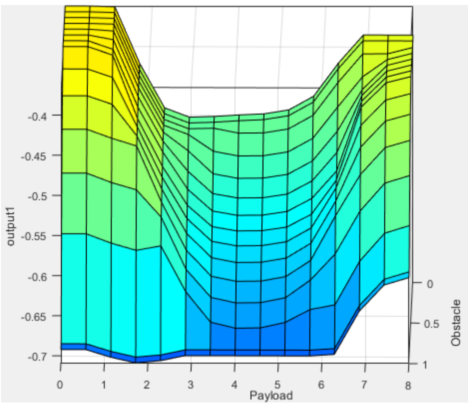


Fig. 8. Example function output plane presenting the relationship of the UWB payload to the obstacle if it occurs.

The results obtained confirmed the correct operation of the rules. However, a smaller improvement was observed here compared to the static measurement without interference, which most probably resulted from the randomness of the introduced changes (human body factor, not precise standing, different wave propagation in the near – man environment). The results obtained can be seen in Table VIII.

TABLE VIII: THE RELATIVE ERROR VALUE BEFORE AND AFTER DATA CORRECTION FOR DIFFERENT PAYLOAD AND OBSTACLE OCCURRENCE

[B]	Dist [m]	Outdoor				Indoor			
		No Obstacle		Obstacle		No Obstacle		Obstacle	
		Raw	Corr	Raw	Corr	Raw	Corr	Raw	Corr
	10	310.9	144.3	349.9	50.1	384.6	175.2	**466.3**	**29.6**
10	5	284.1	117.6	**319.2**	**24.3**	621.7	413.8	712.8	270.7
	20	256.2	89.5	**280.8**	**24.3**	377.8	120.2	**398.1**	**17.5**
	10	335.5	62.2	365.5	65.5	404.3	42.7	551.8	91.1
25	15	318.9	45.8	355.2	55.4	443.3	93.0	**465.4**	**21.8**
	20	**288.2**	**20.7**	**317.4**	**23.6**	**123.4**	**127.0**	658.4	234.5
	10	**332.5**	**32.8**	380.5	80.5	351.8	45.3	844.4	392.4
50	15	357.1	57.2	358.9	59.0	467.9	99.2	**498.5**	**45.1**
	20	**319.9**	**23.3**	373.0	73.1	138.5	74.1	613.2	159.6
	10	623.7	332.4	688.1	399.8	850.9	646.4	919.0	675.4
80	15	543.3	249.2	616.6	323.9	1092.9	818.9	1109.4	877.3
	20	609.7	320.3	629.0	340.4	1204.1	1160.2	1257.0	1022.6

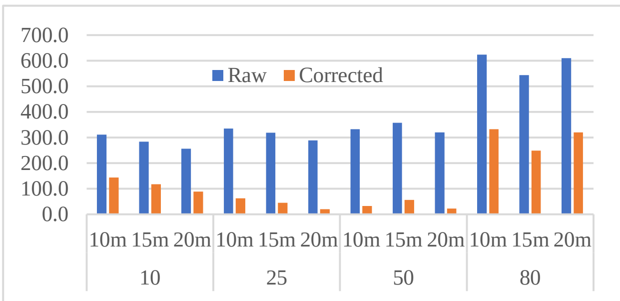


Fig. 9. Graphic presentation of error reduction for selected distances, various payload parameters without obstacles for the outdoor measurements.

Vlues in bold are those for which the improvement was over 90%. Graphic presentation of selected results can be seen in Fig. 9.

The improvement that was achieved with this type of data was on average 65%, where the best value was obtained for indoor data with payload 25 B at 15 m distance (was 465 mm of error, when now it was only 22 mm), while the worst result - and thus the only one that achieved a larger error before correction than after it - was also at payload 25 B, while at a distance of 20 m for no obstacles (was 123 mm now is 127 mm).

V. Conclusion

Based on the conducted tests, it can be indicated how the distance determination will behave based on the UWB system. The differences in the distance as well as in the amount of payload, the height of antennas, work environment and obstacles were checked. Based on the analysis, it can be said that the distance obtained is influenced by environmental factors and the occurrence of obstacles. A constant error has also been reported at very short distances. The solution proposed in the article based on fuzzy logic taking into account the aforementioned variables allowed in the vast majority of cases to reduce the resulting absolute error. The results that the authors of the paper managed to achieve were reduced errors in the most significant cases from over 76% to just 6.3% for short distances. Although in the case of data from greater distances (over 20 m), the relative error was only to 0.7%, it was possible to reduce it in each of the bad scenarios, mainly to 0.1%. Minimization of errors arising in this way enables wider positioning of objects based on UWB technology, especially in the context of technologies related to automotive, where high precision of distance determination - especially in the case of ADAS systems is a key element of their correct operation and allows independence of currently used solutions from the adverse atmospheric conditions. As part of the research, the authors intend to use the models created in this way in dynamic, real-time data analysis using the radar systems mentioned in the article, followed by multilateration of data to determine the precise position of the objects.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Tomczyk, Marciniak conducted the research; Hanzel analyzed the data and wrote the paper; Grzechca supervised the research; all authors had approved the final version.

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References

[1] M. Aftatah, A. Lahrech, and A. Abounada, "Fusion of GPS/INS/Odometer measurements for land vehicle navigation with GPS outage," in *Proc. 2nd International Conference on Cloud Computing Technologies and Applications (CloudTech)*, 2016, pp. 48-55.

[2] C. Yang, T. Nguyen, and E. Blasch, "Mobile positioning via fusion of mixed signals of opportunity," *IEEE Aerospace and Electronic Systems Magazine*, vol. 29, no. 4, pp. 34-46, Apr. 2014.

[3] A. Ziebinski, R. Cupek, D. Grzechca, and L. Chruszczyk, "Review of advanced driver assistance systems (ADAS)," in *Proc. AIP Conference Proceedings*, vol. 1906, pp. 120002, 2017.

[4] A. Ziebinski, R. Cupek, H. Erdogan, and S. Waechter, "A survey of ADAS technologies for the future perspective of sensor fusion," in *Proc. Computational Collective Intelligence*, 2016, pp. 135-146.

[5] J. Laneurit, C. Blanc, R. Chapuis, and L. Trassoudaine, "Multisensorial data fusion for global vehicle and obstacles absolute positioning," in *Proc. IEEE IV2003 Intelligent Vehicles Symposium (Cat. No.03TH8683)*, 2003, pp. 138-143.

[6] D. Grzechca, K. Tokarz, K. Paszek, and D. Poloczek, "Using MEMS sensors to enhance positioning when the GPS signal disappears," in *Proc. Computational Collective Intelligence*, 2017, pp. 260-271.

[7] D. Grzechca, T. Wrobel, and P. Bielecki, "Indoor localization of objects based on RSSI and MEMS sensors," in *Proc. 14th International Symposium on Communications and Information Technologies*, 2014, pp. 143-146.

[8] S. B. Kim, S. Y. Lee, T. H. Hwang, and K. H. Choi, "An advanced approach for navigation and image sensor integration for land vehicle navigation," in *Proc. IEEE 60th Vehicular Technology Conference*, 2004, vol. 6, pp. 4075-4078.

[9] M. Lehtinen, A. Happonen, and J. Ikonen, "Accuracy and time to first fix using consumer-grade GPS receivers," in *Proc. 16th International Conference on Software, Telecommunications and Computer Networks*, 2008, pp. 334-340.

[10] U. Lee, *et al*., "EureCar turbo: A self-driving car that can handle adverse weather conditions," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2016, pp. 2301-2306.

[11] J. C. Halimeh and M. Roser, "Raindrop detection on car windshields using geometric-photometric environment construction and intensity-based correlation," in *Proc. IEEE Intelligent Vehicles Symposium*, 2009, pp. 610-615.

[12] M. Ibrahim and M. Youssef, "CellSense: An accurate energy-efficient GSM positioning system," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 1, pp. 286-296, Jan. 2012.

[13] B. Yamauchi, "Fusing ultra-wideband radar and lidar for small UGV navigation in all-weather conditions," in *Proc. Unmanned Systems Technology XII*, 2010, vol. 7692.

[14] W. C. Chung and D. Ha, "An accurate ultra wideband (UWB) ranging for precision asset location," in *Proc. IEEE Conference on Ultra Wideband Systems and Technologies*, 2003, pp. 389-393.

[15] P. Pannuto, B. Kempke, L. X. Chuo, D. Blaauw, and P. Dutta, "Harmonium: Ultra wideband pulse generation with

bandstitched recovery for fast, accurate, and robust indoor localization," *ACM Trans. Sen. Netw.*, vol. 14, no. 2, pp. 11:1-11:29, Jun. 2018.

[16] D. Dardari, *et al.*, "High-accuracy tracking using ultrawideband signals for enhanced safety of cyclists," *Research Article, Mobile Information Systems*, 2017.

[17] ScenSor Module DWM1000 - WSN | DecaWave. [Online]. Available: https://www.decawave.com/products/dwm1000-module

[18] M. H. A. Wahab, N. S. Obin, R. Ambar, M. R. Tomari, M. Hairol, and A. A. Kadir, "GSM-based notification system and location tagging using GPS for smart recycle bin," *International Journal of Machine Learning and Computing*, vol. 8, no. 5, pp. 495-500, 2018.

[19] C. Deng, S. Wang, J. Liu, and Z. Yu, "A novel intelligent working monitoring and guarding system of smart substations based on UWB positioning and Aerial LiDAR data," *Journal of Communications*, vol. 11, no. 8, pp. 765-771, 2016.

[20] B. Yamauchi, "All-weather perception for man-portable robots using ultra-wideband radar," in *Proc. IEEE International Conference on Robotics and Automation*, 2010, pp. 3610-3615.

[21] D. Knobloch, "Practical challenges of particle filter based UWB localization in vehicular environments," in *Proc. International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, 2017, pp. 1-5.

[22] R. Mazraani, M. Saez, L. Govoni, and D. Knobloch, "Experimental results of a combined TDOA/TOF technique for UWB based localization systems," in *Proc. IEEE International Conference on Communications Workshops (ICC Workshops)*, 2017, pp. 1043-1048.

[23] M. A. Trimukhe and B. G. Hogade, "Design and simulation of effects corresponding to reduced conducting area using slotted meandering line for compact ultra -wideband (UWB) antenna," *Journal of Communications*, vol. 14, no. 4, pp. 318-323, 2019.

[24] Z. A. A. Hassain, M. M. Ali, and A. R. Azeez, "Single and dual band-notch UWB antenna using SRR / CSRR resonators," *Journal of Communications*, vol. 14, no. 6, pp. 504-510, 2019.

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