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A Parallel Ultrasonic Sensors System: Prototypal Realization and Validation Tests

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Abstract: In this paper the idea of using a particular signal for exciting an ultrasonic sensor is proposed. The particular signal is a white noise-like one and the distance measurement is performed by a correlation between the emitted and the received echo signals. The advantages, from a theoretical point of view, are: distance and attenuation are measured at the same time; each sensor measurement is not affected by the presence of similar sensors in the same field, being two independent white noises not correlated; once n sensors are used simultaneously, making use of cross correlation functions between all the emitted and all the reflexed received signals, it is possible to measure n^2 distances from each sensor to any other one. Such theoretical results have been tested on a prototypal realization, here described, and the results are illustrated. They show the real applicability of such idea.

Key–Words: Ultrasonic sensor, white noise, sensor array.

1 Introduction

Ultrasonic sensors are widely used in several applications. It is well known how they work ([1, 2]): a burst (pulse) signal is emitted while a counter is started. If the sound waves hit a surface, an echo is produced. Once such an echo is received, the counter is halted and the time between the emission and the echo return, multiplied by the sound speed in the air (or the material in which the measurement is performed) gives, in a first approximation, the double of the distance between the sensor and the surface of reflexion.

Such a way to operate needs some attentions when more that one sensor of this kind operate in the same area, making interferences between them possible. Such interferences arise because all those sensors use the same kind of signal, making impossible for a sensor to distinguish between its own pulse and the other’s ones.

The idea proposed in this paper is to let each ultrasound sensor emit a different signal, easily distinguishable from the one transmitted by any other sensor, without any coordinations between them. In fact, if this were the case, all the above described problems in presence of several sensors would be eliminated, since each sensors could know its own emitted signal.

Such an idea is based, from a theoretical point of view, on the use of a white noise signal. In fact, let us consider one sensor and suppose it generates an ultrasound signal $n(t)$, being a white noise. Such a signal propagates in the air, being attenuated by dissipation, till it hits an obstacle. Then, it is reflected back and, after a further attenuation, it is received by the sensor. The signal received is of the form $An(t-T)$ with $A < 1$ due to the attenuation and $T > 0$ the *flying time* of the sound in the air. Denoting by v_{air} the velocity of the sound in the air, the distance between the sensor and the obstacle is given by

$$d = \frac{1}{2} v_{air} T$$

The way to get the value of T is to compute the cross correlation $\varphi(t)$ between the emitted signal ($e(t) = n(t)$) and the received one ($r(t) = A\, n(t-T)$), i.e.

$$\begin{aligned}\varphi_{e,r}(t) &= \int_{-\infty}^{\infty} e(\tau) r(t+\tau) d\tau = \\ &= \int_{-\infty}^{\infty} n(\tau) A n(t+\tau-T) d\tau\end{aligned}$$

which results to be, theoretically, an impulse centered in $t = T$ and with amplitude $\frac{A}{2\pi}$, i.e.

$$\varphi_{e,r}(t) = \frac{A}{2\pi}\delta(t-T)$$

Let us now consider two sensors. The first one generates the sound $e_1(t) = n_1(t)$, while the second one the sound $e_2(t) = n_2(t)$. Being white noises generated by two independent generators, their cross correlation is equal to zero, i.e.

$$\varphi_{e_1,e_2}(t) = \varphi_{n_1,n_2}(t)0 \quad (1)$$

The sound e_1, after reflexion, reaches the first sensor, which receives $r_{1,1}(t) = A_{1,1}n_1(t - T_{1,1})$, and the second sensor, which receives $r_{1,2}(t) = A_{1,2}n_1(t - T_{1,2})$. The same happens with the second sound e_2, for which the first sensor receives $r_{2,1}(t) = A_{2,1}n_2(t - T_{2,1})$ and the second sensors receives $r_{2,2}(t) = A_{2,2}n_2(t - T_{2,2})$. Then, the whole signal received by the first sensor is given by

$$\begin{aligned} r_1(t) &= r_{1,1}(t) + r_{2,1}(t) = \\ &= A_{1,1}n_1(t - T_{1,1}) + A_{2,1}n_2(t - T_{2,1}) \end{aligned}$$

while for the second sensor one has

$$\begin{aligned} r_2(t) &= r_{1,2}(t) + r_{2,2}(t) = \\ &= A_{1,2}n_1(t - T_{1,2}) + A_{2,2}n_2(t - T_{2,2}) \end{aligned}$$

Computing now $\varphi_{e_1,r_1}(t)$ and making use of 1, one gets

$$\varphi_{e_1,r_1}(t) = \int_{-\infty}^{\infty} e_1(\tau)r_1(\tau + t)d\tau =$$

$$\begin{aligned} &= \int_{-\infty}^{\infty} n_1(\tau)\left(r_{1,1}(\tau + t) + r_{2,1}(\tau + t)\right)d\tau = \\ &= \int_{-\infty}^{\infty} n_1(\tau)A_{1,1}n_1(\tau + t - T_{1,1})d\tau + \\ &\quad + \int_{-\infty}^{\infty} n_1(\tau)A_{2,1}n_2(\tau + t - T_{2,1})d\tau = \\ &= \frac{A_{1,1}}{2\pi}\delta(t - T_{1,1}) \end{aligned}$$

In the same way, the computation of $\varphi_{e2,r2}(t)$ gives

$$\varphi_{e_2,r_2}(t) = \frac{A_{2,2}}{2\pi}\delta(t - T_{2,2})$$

Such computations can be performed for any given number of sensors, giving the same kind of results. Then, as it can be easily seen, each sensor can work without any influence from any other one.

The above results apply to theoretical signals. In next two sections the description of a prototype for ultrasound sensor working with an approximation of a white noise is given and its characterization will be presented.

2 The prototype

In this section a prototypal realization will be described. It is important to underline that the main scope was to have a sensor (actually two) working according to the above presented principles. This means that circuit can, and will be, improved, but also in the present simple form it works quite well.

The noise generation is based on a zener diode that, in particular working conditions, is characterized by aleatoric changes in the number of mobile charges, producing casual voltage changes (casual rectangular pulses of casual length).

The generator section, together with its amplification, is shown in figure 1

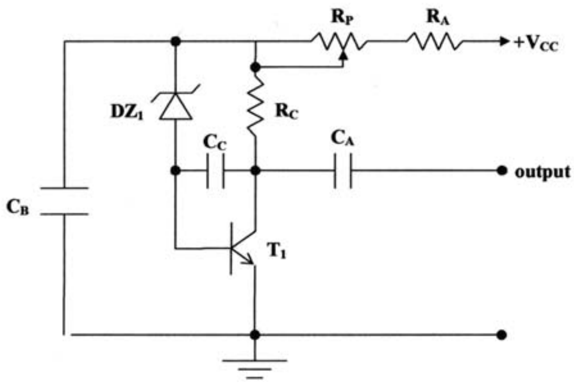

Figure 1: Amplified noise generator

The emitter and the receiver used are depicted in figure 2; they are based on piezoelectric effect. The whole scheme is then given in figure 3. The PCB scheme is also reported in figure 4

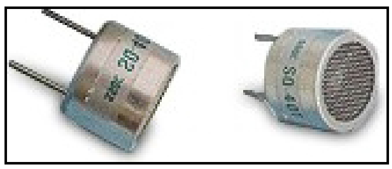

Figure 2: Piezoelectric emitter and receiver

The mounted circuit has the aspect as in figure 5

The circuit is closed in a box from which only the piezoelectric devices and the required connectors are accessible. It can be seen on figure 6

In this first phase, for which the comparison between the real behavior of such sensors and the theoretical one is the main aspect, two sensors have been realized.

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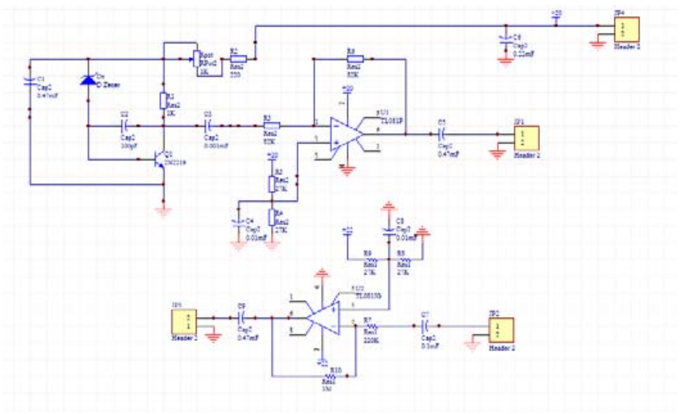

Figure 3: Final scheme

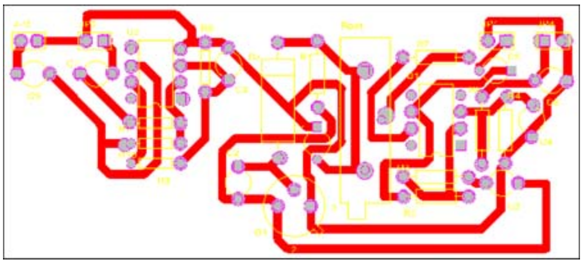

Figure 4: PCB scheme

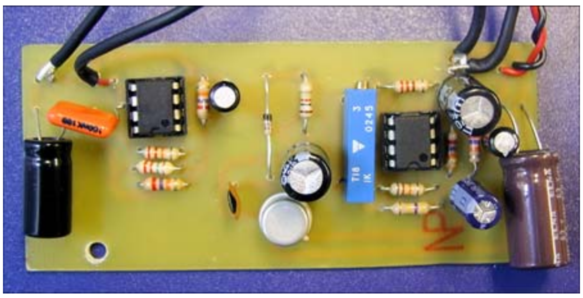

Figure 5: Sensor (electronics)

Figure 6: Sensor (full)

3 The sensors at work

As previously said, the aim of the experimental tests is to validate the behavior of such sensors and compare it to the theoretical results.

A National Instruments acquisition card, the NI PXI-6070E, and software Labview 7.1 have been used for data acquisition from the sensor ([3, 4]).

The main actions were directed toward the calibration of the sensors (subsection 3.1) and the verification of the independent measures possibility (subsection 3.3).

As previously illustrated, the possibility of the estimation of the distance of an obstacle from the sensor in our case is based on the evaluation of the correlation and autocorrelation functions, from which the delay must be extracted. In the case that, when a signal is sent, it hits an obstacle, it will be reflected and received by the ultrasound transducers (see figure 7).

The real situation differs from the theoretical one described in the Introduction by two main aspects. The first is that the received signals have an additional noise contribution generated by all the environment around the sensor. The second is that all the computations of the correlations are performed in a discrete time form, after a signal sampling, and extended over a finite time interval Δ instead of a theoretical infinitive one. The results of the presence of such a non ideal behavior will be discussed after that the experimental results are presented.

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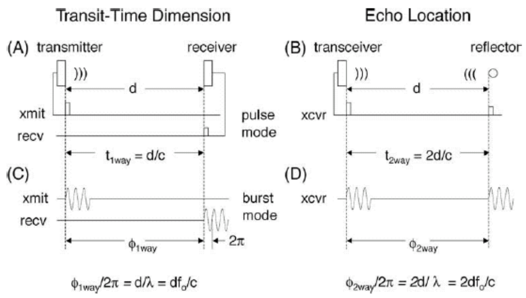

Figure 7: Flying time

3.1 Static Characteristic

The first step in the sensor analysis is the computation of its static characteristic.

The static characteristic can be given in graphic form or in analytic form, representing the relationship between the real value of the variable y (the true distance in our case) and the corresponding value y_m given by the instrument (in our case the distance given by the sensor).

The set of operations that allow one to obtain the characteristic is called *calibration*.

In the present case a measure range from 3 cm to 1 m has been considered.

According to standard procedures, several (in this case 10) different measurements $y_{m,i}$ have been performed for the same distances in the same conditions and both the mean value $\overline{y}_m$

$$\overline{y}_m = \frac{1}{N}\sum_{i=1}^{10} y_{m,i}$$

and the standard deviation m_{y_m}

$$m_{y_m} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{10}(y_{m,i} - \overline{y}_m)^2}$$

have been computed. The characteristic $y_m = C(y)$ has been obtained noticing that the distribution of the measured values are distributed in the plane (y, y_m) in a linear way. So, choosing the function $C(y) = ky+h$ and minimizing the mean square error

$$\varepsilon^2 = \sum_{i=1}^{N}(C(y_i) - y_{m_i})^2 =$$

$$= \sum_{i=1}^{N}((ky_i + h) - y_{m_i})^2$$

one can get the values for k and h and then, making use of the standard deviations, one can get also the linearity error of the characteristic.

3.2 Calibration of first sensor

The above described procedure has been applied to the first of the two sensors. The results are reported in table 8

DISTANZA (cm)	MISURE SENSORE 1										Valor medio	Varianza	Deviaz. Standard
	1	2	3	4	5	6	7	8	9	10			
3	7,755	7,755	7,755	7,755	7,755	7,755	7,755	7,755	8,250	9,075	7,937	0,184222	0,429211
5	10,560	10,560	10,560	9,735	10,560	10,560	10,560	10,560	10,560	10,560	10,478	0,068062	0,260888
10	14,850	15,510	14,685	13,860	14,685	14,685	14,685	14,685	14,685	15,510	14,784	0,21901	0,467985
20	24,750	24,750	24,255	25,080	25,905	24,255	25,080	23,430	24,255	23,595	24,536	0,544802	0,738107
30	35,310	34,485	34,485	34,485	34,815	33,495	34,815	33,990	34,485	34,485	34,485	0,23595	0,485747
40	46,200	42,900	44,550	45,375	42,900	45,870	44,220	44,220	45,045	45,045	44,633	1,247812	1,117055
50	52,800	53,625	54,450	54,450	51,810	53,460	53,460	54,285	52,635	52,635	53,361	0,78771	0,88753
60	62,535	64,185	62,535	63,690	62,040	62,535	63,360	62,535	63,360	64,185	63,096	0,58201	0,762896
70	71,445	73,425	73,425	71,445	71,940	71,445	71,940	72,270	71,115	71,445	71,990	0,683952	0,827014
80	82,005	82,005	82,005	82,170	81,180	82,005	80,355	81,180	82,500	82,005	81,741	0,40656	0,637621
90	91,575	92,400	91,905	92,400	91,575	91,905	90,750	90,750	90,750	90,750	91,476	0,46706	0,683418
100	101,475	100,980	101,145	100,650	101,145	101,475	101,145	101,475	101,475	101,475	101,244	0,07986	0,282595

Figure 8: Table of measurements for first sensor

The static characteristic obtained is reported in figure 9

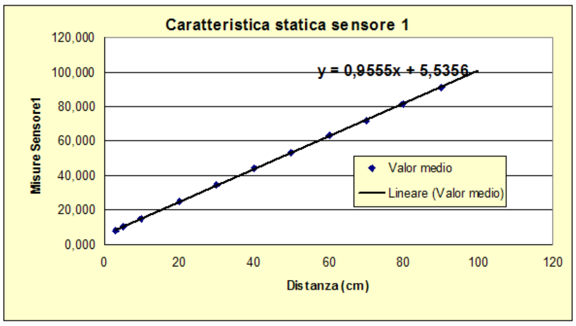

Figure 9: Characteristic of first sensor

Together with the time delay, and then the distances, for every measurement also the autocorrelation amplitude has been computed. Applying the same procedure as above, the resulting characteristic with respect this variable is reported in 10

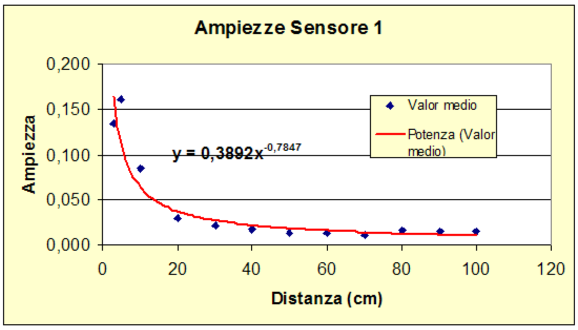

Figure 10: Characteristic w.r.t. the amplitude of the autocorrelation

The measured values used for the calibration (time delays and amplitudes) have been obtained making use of Matlab 7.1 for the correlations computations. Two examples are reported in figures 11 and 12 for a distance of 30 cm and 90 cm respectively; they show the correlation functions obtained.

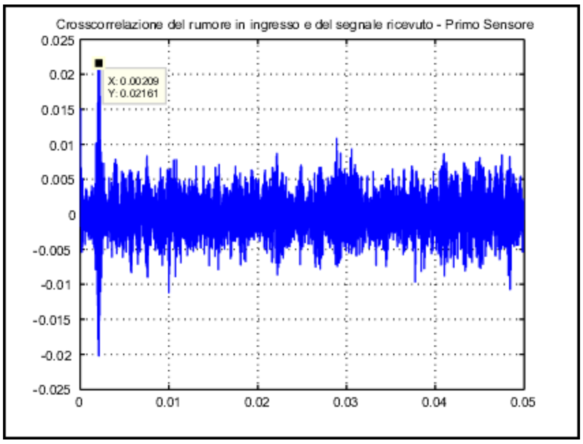

Figure 11: Cross correlation for a distance of 30cm

3.3 Simultaneous usage

The possibility of computing also the flying times between different sensors has been investigated. Clearly in this case each sensor must know the signal emitted by any other one. Computing the cross correlation

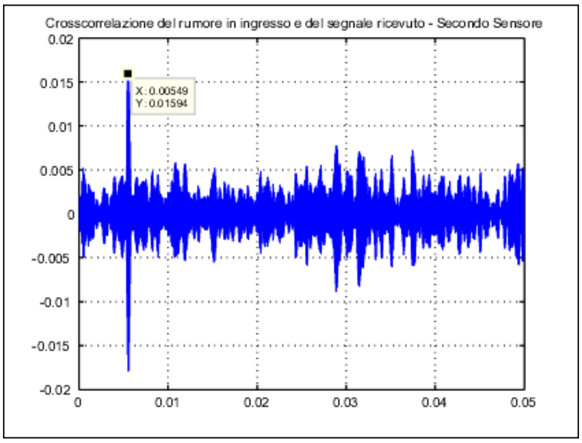

Figure 12: Cross correlation for a distance of 90cm

between the signal generated by the first sensor and the signal received by the second sensor the following table 13 has been obtained for the distances

As far as the characteristic is concerned, the result is reported in figure 14

A the same time it is possible to perform the dual operations, i.e. the cross correlation between the signal generated by the second sensor and the signal received by the first one. The results obtained are in 15 for the distances The characteristic in this case is reported in figure 16

DISTANZA (cm)	MISURE CROSS (I1,R2) 1	2	3	4	5	6	7	8	9	10	Valor medio	Varianza	Deviaz. Standard
3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
5	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
10	16,500	15,510	16,500	15,510	16,500	15,675	15,840	16,335	15,510	16,500	16,038	0,217	0,465
20	24,750	25,080	25,080	25,080	25,080	25,080	25,080	24,585	24,585	24,585	24,899	0,057	0,239
30	34,815	34,815	34,815	34,815	35,145	35,145	35,145	35,475	34,650	34,650	34,947	0,071	0,267
40	44,550	44,550	44,550	44,550	43,725	45,210	44,880	44,880	44,880	44,880	44,666	0,158	0,397
50	53,955	53,955	53,130	53,130	53,790	53,790	52,965	54,615	52,965	52,965	53,526	0,328	0,573
60	61,545	63,195	63,195	62,370	62,370	63,195	61,545	63,195	62,370	63,195	62,618	0,461	0,679
70	72,270	71,610	72,435	71,610	72,435	72,435	71,940	73,920	71,115	71,940	72,171	0,570	0,755
80	82,170	82,005	82,005	80,850	80,355	80,025	81,510	81,510	82,005	80,355	81,279	0,661	0,813
90	90,750	91,410	91,905	92,400	92,730	91,740	92,235	92,235	91,410	92,235	91,905	0,345	0,587
100	101,475	100,320	100,650	100,320	100,320	100,320	100,815	100,815	100,320	100,320	100,568	0,147	0,383

Figure 13: Table of measures from cross correlation between emission of the first and reception of the second sensor: distances

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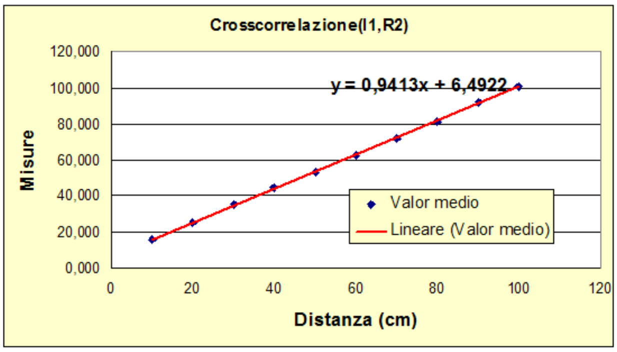

Figure 14: Cross characteristic sensor one - sensor two: distances

		MISURE CROSS (I2,R1)										Valor medio	Varianza	Deviaz. Standard
		1	2	3	4	5	6	7	8	9	10			
DISTANZA (cm)	3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	5	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	10	15,675	14,850	15,675	15,675	15,675	18,150	16,500	15,675	15,675	16,500	16,005	0,787	0,887
	20	24,750	24,420	23,595	23,595	25,245	26,895	23,595	25,245	23,295	23,595	24,423	1,287	1,134
	30	34,650	35,475	34,650	33,825	34,155	34,980	33,330	34,155	34,980	34,980	34,518	0,416	0,645
	40	46,530	44,385	45,705	44,880	44,880	45,540	45,540	45,540	45,540	45,540	45,408	0,338	0,581
	50	54,285	54,285	53,460	55,110	54,120	54,945	53,295	53,295	53,295	54,120	54,021	0,455	0,675
	60	63,525	63,525	63,525	62,700	63,525	63,525	63,525	62,700	63,525	63,525	63,360	0,121	0,348
	70	71,280	71,610	71,610	72,105	72,105	72,600	72,930	71,280	71,280	72,600	71,940	0,381	0,617
	80	82,170	82,170	81,345	81,510	80,520	82,665	82,170	82,170	81,345	82,170	81,824	0,396	0,629
	90	92,565	91,740	92,235	91,740	92,235	92,400	91,740	92,565	92,565	92,565	92,235	0,133	0,365
	100	102,135	101,145	101,145	101,145	102,795	100,320	100,815	100,320	100,320	100,320	101,046	0,715	0,846

Figure 15: Table of measures from cross correlation between emission of the second and reception of the first sensor: distances

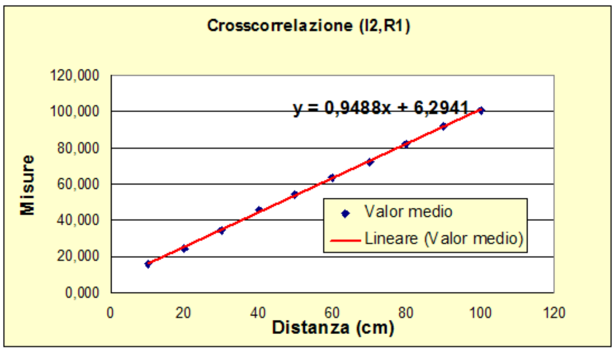

Figure 16: Cross characteristic sensor two - sensor one: distances

4 Conclusions

In this work the possibility of using a multi device measurement system based on ultrasound sensors has been presented. Using the white noise spectral characteristics, it has been illustrated how it is possible to estimate the distance from the target obstacle by computing correlations, being able to estimate at the same time also the material in which the sound propagates, measuring the attenuation produced.

Prototypal realizations have been produced to perform all the validating tests which have evidenced the real possibility of the use of parallel measurement with ultrasound sensors.

The use of correlations to compute the required measurements makes the sensor very robust w.r.t. any kind of perturbation noise present in the area under measurement.

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