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SENSOR SYSTEM FOR AUTOMATIC PAPER THICKNESS DETECTION BASED ON UNIVERSAL SENSORS AND TRANSDUCERS INTERFACE

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SENSOR SYSTEM FOR AUTOMATIC PAPER THICKNESS DETECTION BASED ON UNIVERSAL SENSORS AND TRANSDUCERS INTERFACE

S. Yu. Yurish

Abstract: A low cost, automatic, transmissive paper thickness sensor system with increased reliability and a short detection time (~ 15 ms) is described in the paper. The sensor system is based on a cheap light-to-frequency converter and universal sensors and transducers interfacing IC. The designed automotive paper thickness sensor system has a wide dynamic range of 5 000 000 : 1, immunity against high noises, high resolution and minimum component interface. Due to low price, minimum possible conditioning and interfacing hardware such sensor system can be used not only in photo- but also in office laser and ink printers.

Keywords: Paper thickness optical sensor, Light-to-frequency converter, Universal sensors and transducers interface

СЕНСОРНАЯ СИСТЕМА ДЛЯ АВТОМАТИЧЕСКОГО ОПРЕДЕЛЕНИЯ ТОЛЩИНЫ БУМАГИ НА БАЗЕ УНИВЕРСАЛЬНОГО СЕНСОРНОГО ИНТЕРФЕЙСА

С. Ю. Юриш

Аннотация: в статье описана недорогая автоматическая сенсорная система повышенной надежности и быстродействия (~ 15 мс) для определения толщины бумаги. Сенсорная система содержит недорогой преобразователь освещенности в частоту и интегральную микросхему универсального сенсорного интерфейса. Разработанная сенсорная система имеет широкий динамический диапазон 5 000 000 : 1, высокую помехоустойчивость и разрешающую способность, а также минимальные аппаратурные затраты. Благодаря невысокой цене и минимальному числу электронных компонентов, такая сенсорная система может использоваться не только в фотопринтерах, но и в офисных лазерных и струйных принтерах.

Ключевые слова: оптический датчик толщины бумаги, преобразователь освещенность-частота, универсальный сенсорный интерфейс

СЕНСОРНА СИСТЕМА ДЛЯ АВТОМАТИЧНОГО ВИЗНАЧЕННЯ ТОВЩИНИ ПАПЕРУ НА БАЗІ УНІВЕРСАЛЬНОГО СЕНСОРНОГО ІНТЕРФЕЙСУ

С. Ю. Юриш

Анотація: у статті описана недорога автоматична сенсорна система підвищеної надійності та швидкодії (~ 15 мс) для визначення товщини паперу. Сенсорна система містить недорогий перетворювач освітленості в частоту й інтегральну мікросхему універсального сенсорного інтерфейсу. Розроблена сенсорна система має широкий динамічний діапазон 5 000 000 : 1, високу завадостійкість і роздільчу здатність, а також мінімальні апаратурні витрати. Завдяки невисокій ціні й мінімальному числу електронних компонентів, така сенсорна система може використовуватися не тільки у фотопринтерах, але й в офісних лазерних і струминних принтерах.

Ключові слова: оптичний сенсор товщини паперу, перетворювач освітленість-частота, універсальний сенсорний інтерфейс

1. Introduction

Modern photo printers have automatic paper-type optical sensors that detect a type and thickness of paper. These sensors are able to recognize plain paper, coated paper, glossy/photo paper and transparencies in the in-tray. Whether using plain paper or specialty papers such as photo papers or transparencies, the paper type will be detected and the printer will automatically make the appropriate driver settings to produce a high quality print. This detection is not always a perfect process — the sensor nearly always reads “plain paper” when it shouldn’t. For instance, it will misread paper that is marked, scratched, or wrinkled; paper that has letterhead or markings at the top; and paper that is dark (or that contains metallic filaments). Photo printers will print in lower quality (or “draft mode”) for plain paper, because they cannot handle the resolution and ink quantity that is needed for a real photo-quality image. In addition, reflective configuration type sensors give an opportunity to recognize only photo paper, plain paper or transparencies but not its real thickness; and the sensing process adds up to 5 s to the print process.

In order to eliminate the mentioned problems a new, low cost, automatic, transmissive configuration paper thickness sensor system with an increased reliability and short detection time was design.

2. Sensor System Design

The proposed sensor system consists of visible light source (red light emitting diode (LED)), low-cost light-to-frequency converter (LFC) TSL237 (TAOS, Inc., USA) [1], and universal sensors and transducers interface (USTI) IC [2].

The LED is an ideal monochromatic light source for such application because of its high energy efficiency, small size, low operating voltage and cost [3].

A traditional automatic paper-type reflective sensor configuration is shown in Fig. 1 (a); but in order to be able detect a paper’s thickness and count the number of paper sheets in in-tray it is expediently to use a proposed transmissive type sensor with a configuration shown in Fig.1 (b). The automatic paper-type sensor works by the following way. An LED shines onto the surface of the paper. The transmissive through the paper light is captured and recognized. This gives the printer information about the paper thickness and characteristics for the particular paper. This information is compared to a reference table of paper types that the printer has stored internally. Then, based on the information, the printer determines color mapping, half-toning, and number of print passes to produce the best output for the paper being used.

Nevertheless analog photodiodes or light-to-voltage converters can be used as a sensing element in such sensor systems, an output informative parameter as frequency on light-to-frequency converter’s output has many advantages in comparison with analog output of sensing elements, namely: high noise immunity, power of signal and reference accuracy; wide dynamic range; multiparametricity; simple interfacing, integration and coding [4].

In the traditional solution, the current from a photodiode is very small (μA), making it susceptible to picking up noise, particularly if the transimpedance amplifier is separated from the photodiode by a considerable distance. In some applications, it is necessary to add shielding around the photodiode

to keep electromagnetic interference and radio frequency interference from interfering with the signal. However, additional shielding is not needed with a light-to-frequency converter as long as adequate power supply is provided [5].

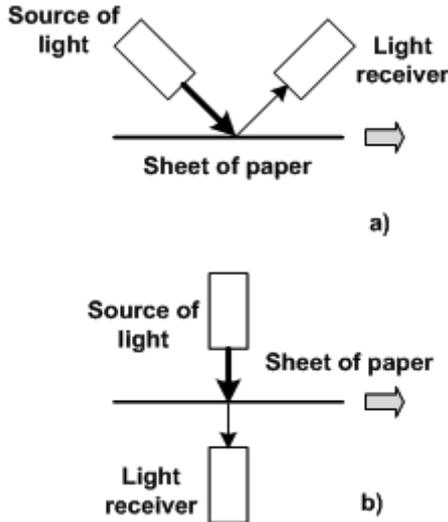


Fig. 1. Automatic paper-type sensor configurations: (a) tradition reflective type sensor; (b) proposed transmissive type sensor.

The TSL237 light-to-frequency converter combines a silicon photodiode and a current-to-frequency converter on a single monolithic CMOS integrated circuit. Output is a square wave (50 % duty cycle) with frequency directly proportional to light intensity (irradiance) on the photodiode. The digital output allows direct interface to a microcontroller or other logic circuitry. The device has been temperature compensated for the ultraviolet-to-visible light range of 320 nm to 700 nm and responds over the light range of 320 nm to 1050 nm [1]. The frequency at the output pin (OUT) is given by:

$$f_o = f_d + (R_e) \cdot (E_e), \quad (1)$$

where f_o is the output frequency; f_d is the output frequency for dark condition ($E_e = 0$); R_e is the device responsivity for a given wavelength of light given in kHz/($\mu\text{W}/\text{cm}^2$); E_e is the incident irradiance in $\mu\text{W}/\text{cm}^2$.

The dark frequency f_d is a constant error term in the output frequency calculation resulting from leakage currents, and is independent of light intensity. The TSL237 die is trimmed to minimize the magnitude of this dark frequency component so that it can be neglected in the transfer function calculation. In many applications, measurement of the actual dark frequency may be impractical due to

measurement times ranging from several seconds to several minutes, and the fact that some devices may never transition (zero dark frequency).

The output of the device can be changed in a wide frequency range from 0.1 Hz to 2 Hz (dark frequency typical range) and from 0.5 to 1 MHz (maximum output frequency) and is designed to drive a CMOS logic input over short distances. Due to a wide dynamic range of ~120 dB this device is well suited for this paper thickness sensor system application.

The choice of interface and measurement technique depends on the desired resolution and data-acquisition rate. Maximum resolution, conversion speed and accuracy will be obtained by using the USTI especially designed for such kind of sensors applications. The IC can measure frequency in a wide range from 0.05 Hz to 9 MHz without prescaling; with constant programmable relative error (from 1 to 0.0005 %) in the whole frequency range, scalable resolution and non-redundant conversion time [2]. The USTI is based on the patented modified method of the dependent count [6]. It allows a high-resolution direct interface to these types of light sensors and its digital output also allows a simple interface to popular sensors serial buses as SPI, I²C and RS-232. The designed sensor system is shown in Fig.2 and its main components — in Fig. 3.

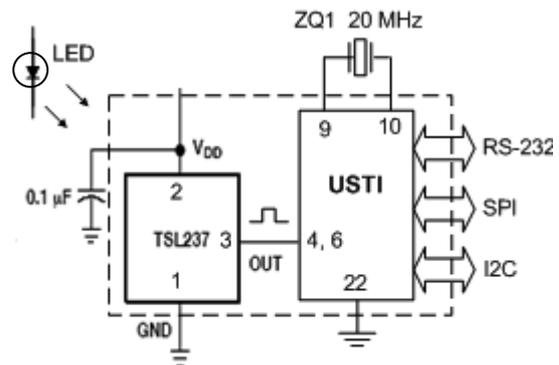


Fig. 2. Automatic paper thickness sensor system circuit diagram.

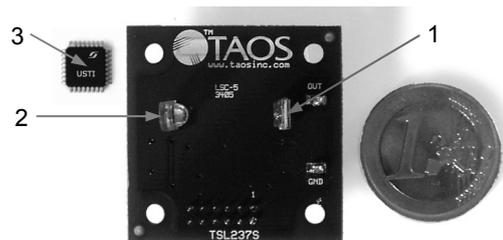


Fig. 3. Main sensor system components: light sensor TSL237 (1); LED (2); USTI (3).

Power-supply lines of TSL237 must be decoupled by a 0.01 μF to 0.1 μF capacitor with short leads placed close to the TSL237 (Fig. 2). A low-noise power supply is required to minimize jitter on output pulse.

Taking into account that the USTI has two identical channels, another light sensor TSL237 can be connected to the second measuring channel (for example, in the reflective type configuration working with the same LED) or color sensor with frequency output, for example, TCS230. Such advanced mul-

tisensors system configuration lets improve significantly reliability for paper-type recognition and make possible to control a paper quality at paper manufacturing processes and real-time measurement of paper sheet content at paper sorting and recycling.

The commands and appropriate comments for the USTI working with the RS232 interface (slave mode) in two-channel configuration for paper type and thickness determination are shown in Figure 4.

```

>A03          ; Set the relative error for the 1st channel  $\delta = 0.1\%$ 
>M00          ; Choose the frequency measuring mode in the 1st channel
>S            ; Start measurement
>R            ; Read result in Hz
100000.0254

>A03          ; Set the relative error for the 2nd channel  $\delta = 0.1\%$ 
>MOE          ; Choose the frequency measuring mode in the 2nd channel
>S            ; Start measurement
>R            ; Read result in Hz
70128.966

```

Fig. 4. Commands for USTI working with the RS232 interface (slave mode) in two-channel configuration.

It is also expediently to use the additional command “C” between “S” and “R” commands to check the measurement status. It returns “r” if the result is ready and “b” if the measurement is in a progress. It is especially important at measurements in low frequency range.

The detection time should be calculated according to the following equation:

$$T_{\text{detection}} = t_{\text{conv}} + t_{\text{comm}} + t_{\text{calc}}, \quad (2)$$

where t_{conv} is the frequency-to-digital conversion time; t_{comm} is the communication time; t_{calc} is the calculation time.

The conversion time for the USTI can be calculated according to the following equation:

$$\begin{cases} t_{\text{conv}} = \frac{1}{f_x} & \text{if } \frac{N_\delta}{f_0} < T_x \\ t_{\text{conv}} = \frac{N_\delta}{f_0} + (0 \div T_x) & \text{if } \frac{N_\delta}{f_0} \geq T_x, \end{cases} \quad (3)$$

where $N_\Delta = I/\Delta$ is the number proportional to the required programmable relative error Δ ; $T_x = I/f_x$ is the period of converted frequency; $f_0 = 600$ kHz is the internal reference frequency for USTI.

The communication time for a slave communication mode (RS232 interface) can be calculated according to the following equation:

$$t_{\text{comm}} = 10 \cdot n \cdot t_{\text{bit}}, \quad (4)$$

where $t_{\text{bit}} = 1/300, 1/600, 1/1200, 1/2400, 1/4800, 1/9600, 1/14400, 1/19200, 1/28800$ or $1/38400$ is the time for one bit transmitting; n is the number of bytes ($n=13 \div 24$ for ASCII format). As usually, at the right chosen of baud rate (maximum possible for a certain application) the $t_{\text{comm}} \leq t_{\text{conv}}$. For example, the communication time at 38400 baud rate will be $t_{\text{comm}} = (0.0034 \div 0.00625)$ s.

The communication time for SPI interface should be calculated as:

$$t_{\text{comm}} = 8 \cdot n \cdot \frac{1}{f_{\text{SCLK}}}, \quad (5)$$

where f_{SCLK} is the serial clock frequency, which should be chosen for the USTI in the range from 100 to 500 kHz; $n=12 \div 13$ is the number of bytes. The number n is dependent on measurement result format: BCD ($n=13$) or binary ($n=12$).

The communication standard mode speed for I²C interfaces can be determined according to the following equation:

$$t_{\text{comm}} = 8 \cdot n \cdot \frac{1}{f_{\text{SCL}}}, \quad (6)$$

where f_{SCL} is the serial clock frequency, which should be equals to 100 kHz for the USTI; $n=12 \div 13$ is the number of bytes for measurement result: BCD ($n=13$) or binary ($n=12$).

The calculation time depends on operands and is as usually $t_{calc} \leq 4.5$ ms.

As it visible from (3) the conversion time is mainly determined by the programmable relative error Δ . The dependence of conversion time on relative error is shown in Figure 5.

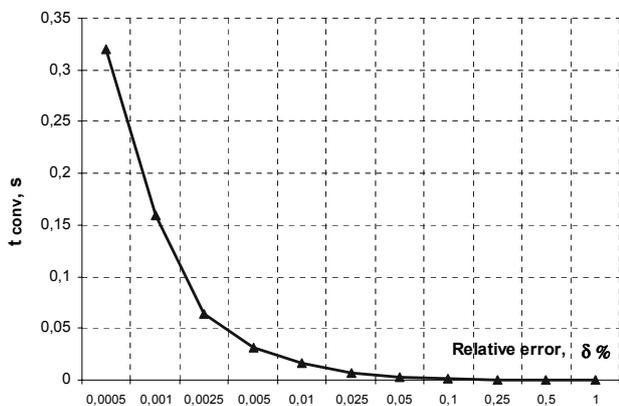


Fig. 5. Dependence of conversion time t_{conv} on relative error Δ .

The USTI is also suitable for working with multiparametric optical sensors in which the output frequency is proportional to the light intensity (luminance) and duty-cycle at the same sensor's output is proportional to the spectral distribution (chrominance), for example, described in [7]. The colour information is obtained using the wavelength dependence of the absorption coefficient in the silicon in the optical part of the spectrum, so no filters are required [8]. At the use of such optical sensors, one mentioned multiparametric reflective type sensors can be connected to the 1st USTI's channel and other light sensor of transmissive type (for example) can be connected to the 2nd USTI's channel.

The similar sensor systems can be designed also based on any frequency output light or infrared sensors such as TSL230, TSL235, TSL238, TSL245 (TAOS, Inc., USA), S9705 (Hamamatsu Corp., Japan) and MLX75304 (Melexis, Belgium) [9]. These low-cost sensors have become attractive for such application, combining with the high-performance frequency-to-digital conversion based on the USTI to achieve the required accuracy and reduced conversion time at a lower overall system cost.

3. Experimental Results

The measurement set up that was used in experimental investigations is based on the light-to-frequency evaluation module from TAOS, Inc. [10]. A

motherboard with an appropriate device-specific daughterboard, which were used in experiments is shown in Fig. 6. The mother board was connected via USB port to a host PC running the Windows compatible host software application, which was used mainly for the ambient light subtraction in order to get rid of the effect of ambient light, and strobe LED control during all measurements. According to the algorithm, each time the sensor is measured, and extra measurement is made with the LED off. The value "Ambient" is then subtracted from the actual frequency measurement. The calculation used is as follows:

$$\text{Reading} = (\text{Signal} + \text{Ambient}) - \text{Ambient}, \quad (7)$$

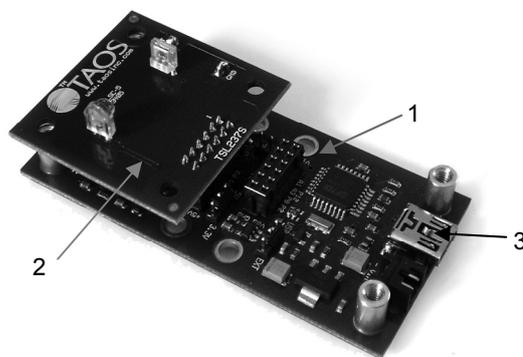


Fig. 6. Evaluation module's motherboard (1) with TSL237 daughterboard (2) and USB connector (3).

The sensor's output was directly interfaced to the first USTI's channel working in a frequency measurement mode with programmable constant relative error 0.1 % in the whole frequency range. Taking into account the sensor's error, this frequency-to-digital conversion error can be neglected at sensor system accuracy evaluation. The USTI was connected via RS-232 to the same host PC running the Terminal V1.9b software. The measurement set up for automatic paper thickness sensor system investigation is shown in Figure 7.

During experiments 8 paper patterns with different thickness from 0.086 to 0.217 mm including standard office types of paper 70 and 80 g/mm² were investigate. The oscillograms at sensors output correspond to paper sheets with maximal and minimal thickness are shown in Fig. 8. The dependence of sensor output on paper thickness is shown in Fig. 9.

A reference table of paper types can be stored in the USTI's or printer's memory.

In addition to the paper thickness the developed sensor can detect the number of paper sheets

of the same thickness, for example, office paper with 0.095 mm thickness (Fig. 10). The maximum counted number of sheets is $N=24$ for 0.086 mm thickness and $N=20$ for 0.095 mm thickness at the distance between LED and LFC in 15 mm. This number can be increased by decreasing the distance between light source and sensing element. In spite of the fact that at $N > 8$ the dependence of frequency on number of sheets is not so well expressed, the USTI is capable to distinguish such changes due to a high resolution and low absolute error (± 2 Hz at $f_x=2000$ Hz) at relative error 0.1 %.

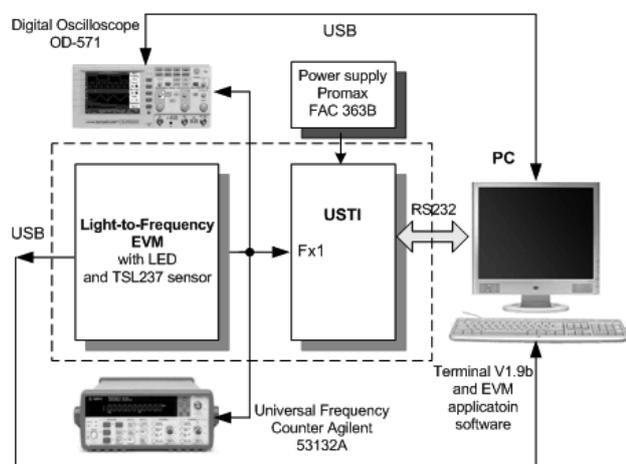


Fig. 7. Measurement set-up for automatic paper thickness sensor system investigation.

The detection time in both experiments together with communication time does not exceed 15 ms at 0.1 % error for frequency-to-digital conversion.

The designed sensor can be also used for detection of paper sheets sticking in order to eliminate two leaves feeding at the same time.

In order to validate a high accuracy for frequency-to-digital conversion in a wide frequency range the frequency measurements for maximum possible sensor output frequency $f_{x\max} \approx 520$ kHz (paper absent status) and the minimum possible sensor output frequency $f_{x\min} \approx 0.27$ Hz (low dark frequency $f_o = f_D$) for the light sensor were taken every second by the USTI and high precision calibrated counter (Agilent 53132A) until totaling 60 measurements. The measuring results are shown in Figure 11 (a, b). The measurements errors were evaluated from histograms and appropriate statistical characteristics. In both cases it does not exceed the programmable relative error $\Delta \leq 0.1$ %, therefore it can be neglected in comparison with the light sensor's error. Statistical characteristics are added in Table 1.

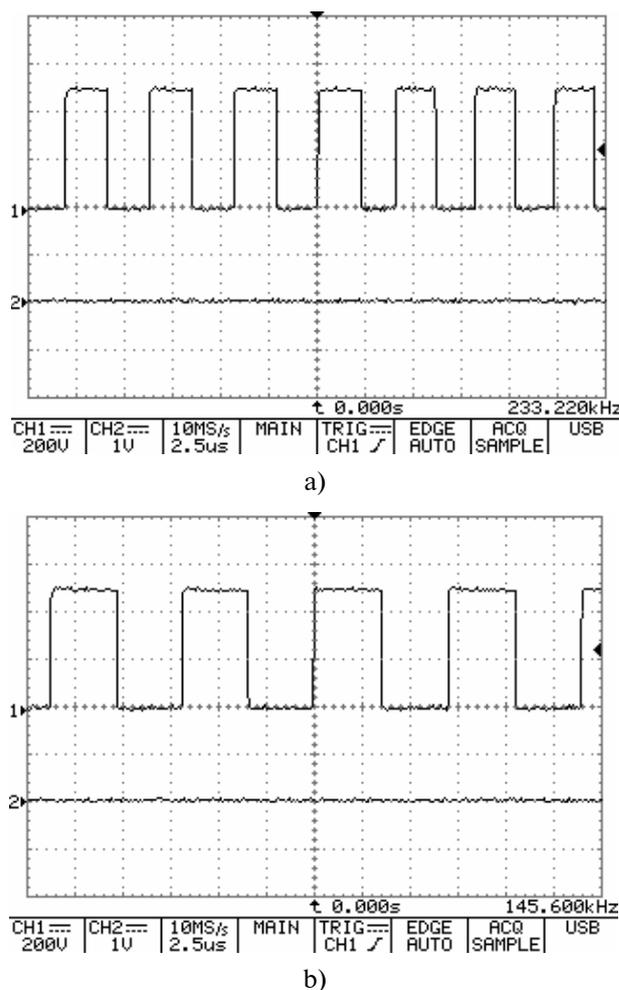


Fig. 8. Sensor output signals at 0.086 mm (a) and 0.217 mm (b) paper sheet thickness.

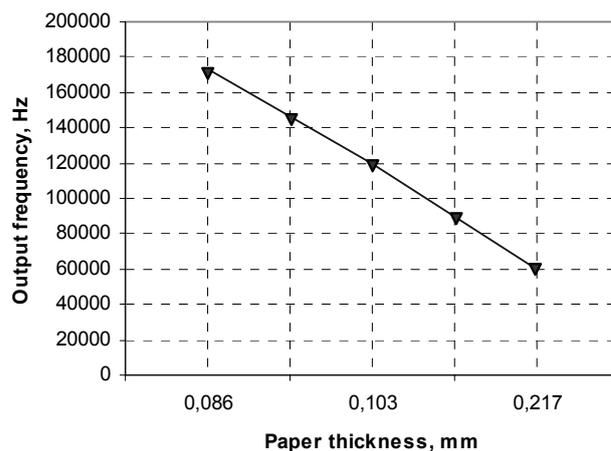
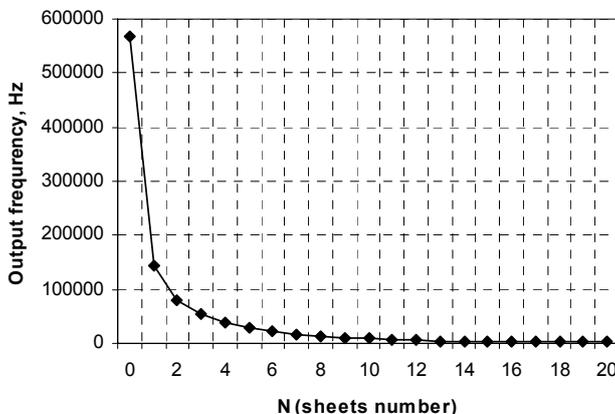


Fig. 9. Sensor output vs. paper thickness.

The χ^2 -test for goodness of fit was applied to investigate the significance of differences between observed data in histograms and the theoretical frequency distribution for data from a normal population. At five equidistant classes ($k=5$) and

a probability $P = 97 \%$, according to the χ^2 -test, $S < \chi^2_{max}$, where $S = 6.1584$ and 1.1586 is the sum of deviations between the data set and the assumed distribution for minimum and maximum fre-

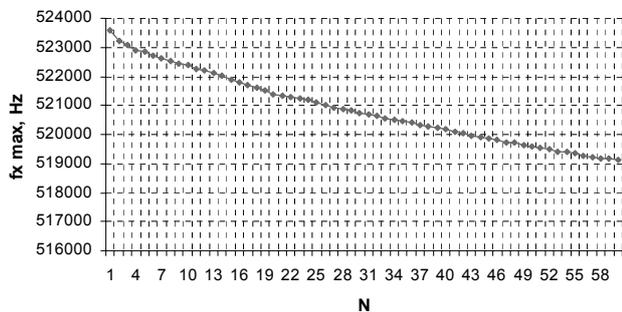
quency measurement accordingly; $\chi^2_{max} = 7.0$ is the maximal possible argument of the χ^2 distribution. Hence, the hypothesis of Gaussian (normal) distribution can be accepted in both cases.



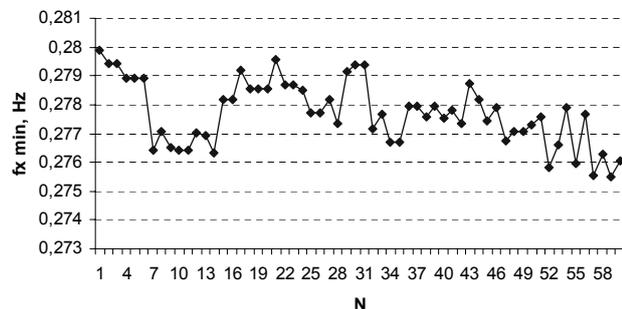
Data Table:

N	1	2	3	4	5	6	7	8	9	10
f_y, Hz	143000	81100	55500	39400	29500	22400	17350	12600	10350	8300
N	11	12	13	14	15	16	17	18	19	20
f_y, Hz	6900	5800	4600	3980	3400	2850	2510	2150	2000	1900

Fig. 10. Sensor output vs. sheets number (at 0.095 mm thickness).

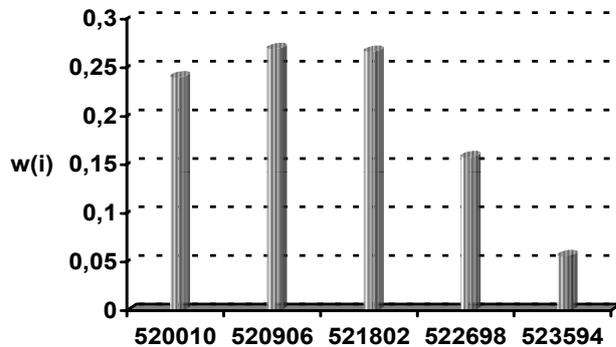


a)



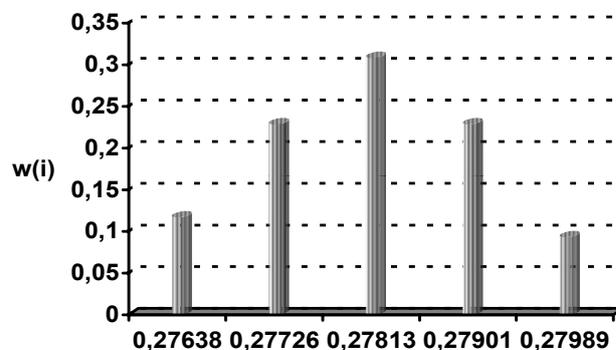
b)

Fig. 11. Measurement results for $f_{x\ max} \approx 520$ kHz and $f_{x\ min} \approx 0.27$ Hz.



fx max, Hz

a)



fx min, Hz

b)

Fig. 12. Distribution functions $w[i]$ changes.

Table 1

Statistical characteristics

Parameter	$f_{x_{max}}$	$f_{x_{min}}$
Number of measurements, N	60	60
Minimum f_x (min), Hz	519114.393	0.2755
Maximum f_x (max), Hz	523594.121	0.2799
Sampling Range, f_x (max) – f_x (min), Hz	4479.7277	0.0044
Median	0	0
Arithmetic Mean, Hz	520887.935	0.2777
Variance	1497556.04	1.2E-0006
Standard Deviation	1223.7467	0.0011
Coefficient of Variation	425.6501	251.5468
Confidence interval for arithmetic mean at $P=97\%$	$520545.093 \leq f_x \leq 521230.777$	$0.2774 \leq f_x \leq 0.278$
Relative error, %	0.07	0.1

Table 2

 χ^2 -test results: for $f_{x_{max}}$ (a) and $f_{x_{min}}$ (b)

Classes	Observed incidence $b[i]$	Distribution function changes $w[i]$	Expected incidence $c [i]$	Deviation $A[i]$
1. 520010.33931	18	0.236644	14.20	1.018
2. 520906.28486	15	0.269337	16.16	0.083
3. 521802.2304	12	0.266525	15.99	0.996
4. 522698.17595	9	0.157958	9.48	0.024
5. 523594.12149	6	0.056031	3.36	2.070

a)

Classes	Observed incidence $b[i]$	Distribution function changes $w[i]$	Expected incidence $c [i]$	Deviation $A[i]$
1. 0.27638	7	0.116967	7.02	0
2. 0.27726	14	0.22875	13.72	0.006
3. 0.27813	17	0.308403	18.50	0.122
4. 0.27901	14	0.228827	13.73	0.005
5. 0.27989	8	0.093383	5.60	1.025

b)

Due to low cost and minimum hardware the designed paper thickness sensor system can be used in high quality modern photo- as well as in office budget laser or ink jet printers. A short detection time (~ 15 ms) do not introduce an additional significant time to the print process in comparison with traditional automotive paper thickness sensor system.

4. Conclusions

The designed automotive paper thickness sensor system has a wide dynamic range of 5 000 000 : 1, immunity against high noises, high resolution and minimum component interface. Due to low price, minimum possible conditioning and interfacing hardware such sensor can be used not only in photo- but also in office laser and ink printers. In turn,

low-cost light- and color-to-frequency converters have become attractive for different applications, combining with high-performance frequency-to-digital conversion based on the USTI to achieve the required accuracy, true digital output according to three popular serial sensors buses at a lower overall system cost.

Further research aims towards a fully integrated light-, color-to-frequency converters and USTI in CMOS technology as well as creation multisensor systems for different applications on its basis.

Acknowledgment

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