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ARTICLE · JULY 2011

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ISSN 1726-5479

SENSORS & TRANSDUCERS

7 vol. 130 / 11

Sensor Networks and Wireless Sensor Networks

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 130, Issue 7, July 2011 www.sensorsportal.com ISSN 1726-5479

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and on CD.

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Sensors & Transducers Journal, Vol. 130, Issue 7, July 2011, pp. 103-117

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

A New Shape Memory Alloy Based Smart Encoder for Sensing of Direction and Angular Motion

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Received: 13 June 2011 /Accepted: 22 July 2011 /Published: 29 July 2011

Abstract: This paper presents a novel technique for sensing direction, angle and velocity from rotation of shafts using simple Shape Memory Alloy (SMA) based micro-switches. Due to electro-mechanical coupling of SMA wires reflected in controlled force generation capacity, the SMA based devices can provide better alternatives for traditional relays, solenoid valves and opto-coupler isolators. The control algorithm involved in this sensing technique, reads the switch status for shaft rotation and sense the angular displacement thereafter. One of the advantages, this new sensor offers is its inherent robustness to vibration in the host platform. Experiments are carried out under vibrating conditions and obtained results are compared with conventional optical incremental encoder. The result shows that SMA based angle encoder works efficiently and gives more accurate results under disturbance while optical encoders are quite sensitive to similar platform vibration. Due to its compactness and lightweight, this concept of SMA wire based angle sensor is envisaged to be suitable for structural health monitoring applications where discrete angle information is needed at low RPM.

Keywords: Shape memory alloy, SMA based micro-switch, Angle encoder, Sensing of angular Motion, Miniature robotic manipulator.

1. Introduction

As a versatile smart material, Shape Memory Alloy (SMA) is used in variety of devices ranging from robotic manipulators [1], precision control of micro-system [2], energy absorbing and damping devices [3] and for sensing applications [4]. Our work mainly explores the capabilities of SMA as a rotational sensor which will be suitable in measuring the angular response of a slow moving smart rotating probe under vibrating condition [5]. In general, rotary encoders are used as standard rotational sensors in the Mechatronics systems such as in robots, numerically controlled machines and automobiles. High resolution, high precision and smaller size rotary encoders are currently in large demand for these Mechatronic systems. The high accuracy rotary encoders can be divided into two categories, magnetic rotary encoders, which are based on the principles of reading and writing to the magnetic media, and optical rotary encoders [6-9]. There also exists a range of ultra high resolution encoders, such as atomic level encoders based on principle of atomic force microscopy [10] and angular measurement based on internal-reflection effect [11]. However, from the fabrication point of view, all these encoders are quite complex and expensive in nature. The optical encoders are not suitable for small-scale production; because, it is necessary to fabricate an original of the code disk regardless of the volume of production [12]. Also, optical method, generally, does not have sufficient accuracy for monitoring the instantaneous velocity or angular position of the shaft when the motor turns slowly [13].

We present a new Shape Memory Alloy based rotational encoder in this paper. An SMA wire can yield large force if it encounters any external resistance during phase transformation and this force is utilized here to activate micro switches. SMA based micro-switch have several characteristics that make them attractive, especially for miniature applications. These are compact size, extremely high fatigue resistance to cyclic operation and have smooth, clean and noiseless performance. The first part of the paper describes the design aspects of SMA wire operated micro switches and various parameters which affects their performance characteristics. Subsequently, the SMA actuated switches are used in the design of angle encoder. This paper describes the procedure to obtain direction, angle information and shaft RPM using the SMA based angle encoder. The pulses obtained from the angle encoder are processed by a microcontroller P89c51RD2 and results are then feeded to a computer via LabviView supported DAQ card M-6251. The robustness of the proposed sensor for angle encoding under noisy environment is discussed and compared with the performance of a standard optical angle encoder.

2. Development of SMA Based Micro-switch

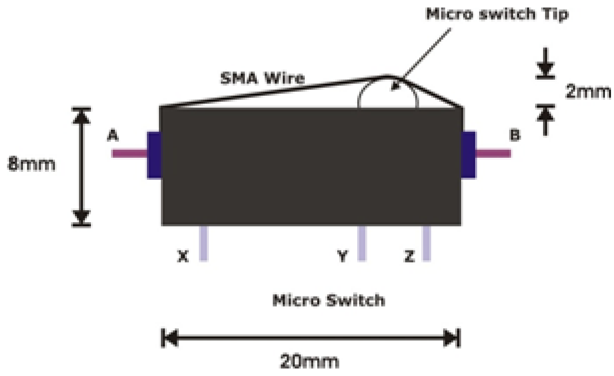
SMA based micro-switch is the most important component of the proposed angle sensor. The response time, current rating, and ON-OFF delay time of micro-switches are important factors in the design of such sensors which influences the accuracy, repeatability and power dissipation of the angle sensor.

2.1. Basic Principle

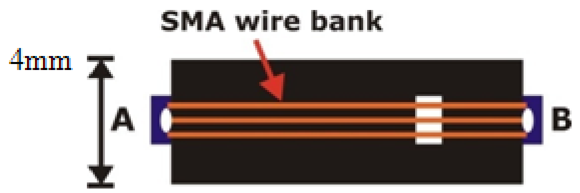
The phase transformation in SMA wire caused by thermal heating or electrical resistance heating results in generation of large force if it encounters any external resistance during this phase transformation. This force (also known as blocking force) is utilized to mechanically activate the micro-switch. As SMA wire gets fired, it turns on the switch which results in closing of the electric circuit. This controlled closing of circuit can be utilized in many applications like relays and commutators.

2.1.1. Design and Working

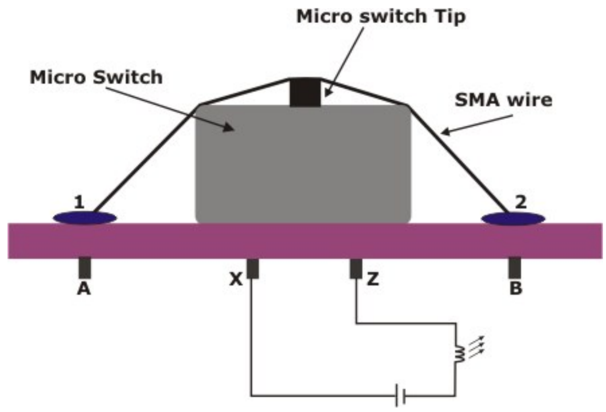
The procedure for designing of SMA wire operated switch is as follows. The basic structure of the SMA wire operated micro-switch is shown in the schematic diagrams of Fig. 1(a) to 1(c); in which the SMA wire is shown to be fixed over the tip of the micro-switch. When current is passed to the SMA wire between terminals 1 and 2, the wire gets contracted and activates the switch which provides the continuity between the two terminals X and Z and results in closing of the circuit.



(a). Front View of the micro-switch.



(b). Top View of the system.



(c). Complete View of the micro-switch.

Fig. 1. SMA micro switch with limited SMA wire length.

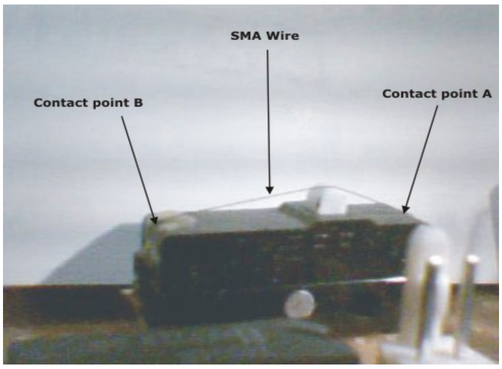


Fig. 2. SMA based Micro Switches developed in the laboratory.

2.2. Force Estimation of the Micro-switches

A simple equilibrium condition can be used to estimate the force required by the SMA wires to trigger the tip of a micro switch. By resolving the force components and solving, the final equation can be obtained as

$$F=2\sum_{i=1}^{n} T_i \sin\theta_i \,, \tag{1}$$

where, F is the force required for pressing the switch, T_i is the force generated by each SMA wire to trigger the tip of the switch; θ_i is the angle between each SMA wire and horizontal axis as explained in Fig. 3 and *n* is the total number of SMA wires.

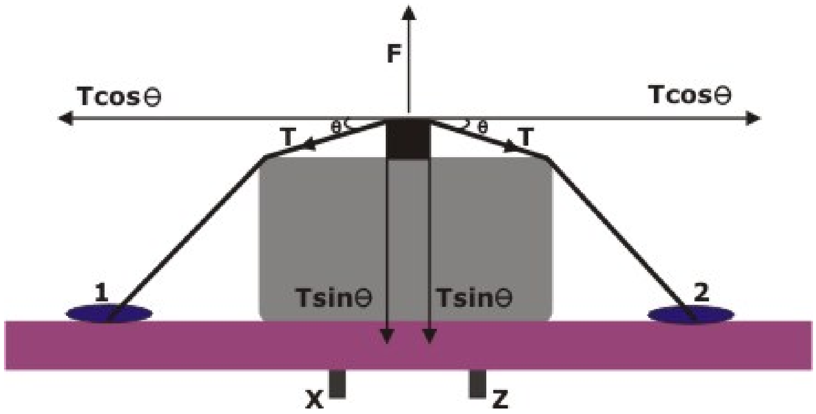


Fig. 3. Force components in SMA wire based micro switch.

"Equal Arm Beam Balance method" for force measurement is used to calculate the force required to press the tip of micro switch. From experiment, the value of the force comes out to be 0.498N. Using the thermo-elastic formulation by Liang and Rogers [14] T_i can also be computed based on the stress generated by the SMA wire which is given by:

$$\begin{aligned} \sigma &= \Theta(T - T_m) + \sigma_0 \quad T \le A_s \\ \sigma &= \Theta(T - A_s) + \Omega(\xi - \xi_0) + \sigma_{A_s} \quad A_s \le T \le A_f \end{aligned}, \tag{2}$$

where, Θ is the modified thermo-elastic modulus, Ω is the modified transformation co-efficient, ξ denotes the fraction of martensite present at any instant, A_s – the Austenite beginning and A_f the Austenite end temperature respectively.

It may be noted that the optimum length of SMA wire used in this proposed model of micro switch is considered as 30mm after several trial and errors. The details of the SMA wire are provided in Table 1.

Table 1. Specifications of the SMA wire used in the Micro Switch.

SN	Parameters	Values	SN	Parameters	Values
1.	Input Voltage	1.0 V	5	Estimated force to press the switch	Eqv. to 50 gm force
2.	Input Current	260 mA	6	Operating Frequency	Up to 6Hz
3.	Diameter	.003 inch	7	SMA wire phase transformation temperature	80 ^{0}C start of Phase Transformation
4.	Active length	30.0 mm	8	Modulus of Elasticity of SMA	80 GPa (Austenite) 35 GPa (Martensite)

2.3. Experimental Setup

A schematic diagram of the SMA based micro-switch with driver circuit is shown in Fig. 4. The SMA wire is connected at the drain terminal of the FET (IRF-540) which allows sufficient current to flow through it. When a high pulse is applied at the input of the gate, the FET turns ON and current starts flowing through the SMA wire. This current flow causes resistive heating which results in phase transformation of SMA wire and the wire retracts producing blocking force. This action triggers the tip of the micro switch, causing the switch to close the circuit connected to it.

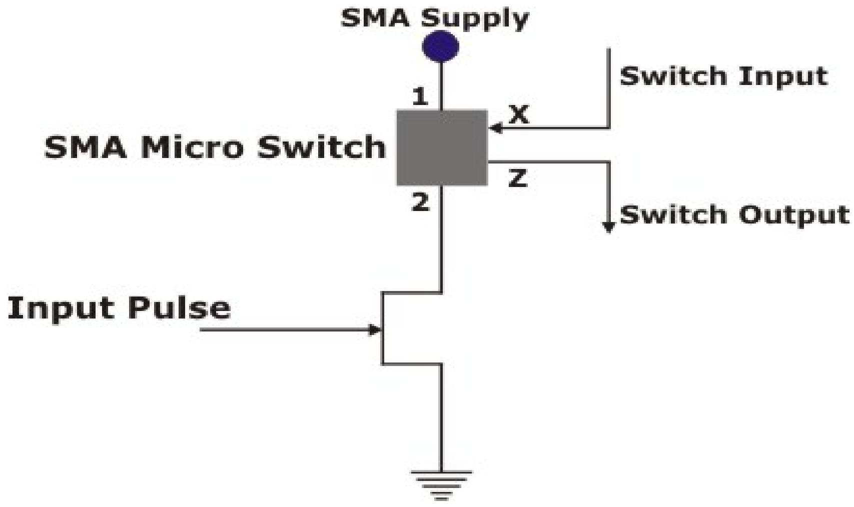


Fig. 4. SMA Based micro switch with driver.

An input pulse of 6Hz is supplied to the SMA wire through the driver circuit to obtain the response from the micro-switch. In the following sub-section, we will discuss about the output response of the switch at length.

2.4. Phase Lag Analysis of the SMA Based Micro-Switch

The response time of SMA based micro-switch is important for analysis as it affects the performance of the new angle encoder. To obtain the time response, square pulse is provided to the SMA based micro-switch and dependency of the actuation time is analyzed with variation of other parameters such as input voltage and performance of switch with respect to time. During the ON time of pulse, the SMA wire starts to contract which results in triggering of the switch and during the OFF time, the wire gets cooled and deactivate the micro-switch.

The response of SMA wire is captured in the form of square pulse output. Because of the phase transformation in SMA wire, there is a time lag between supplied input pulse and activation of the micro-switch by the SMA wire. This activation of the micro-switch results closing of the circuit which gives pulse at the output of the switch. The phase delay is captured using Pico-scope ADC 212 and is shown in Fig. 5.

In order to quantify the exact time delay, the input pulse is supplied to SMA wire and output pulse obtained from the micro-switch is given to an X-OR gate. The output of the X-OR gate goes high only when there is a difference between the inputs and remain low for the same level of inputs.

Due to the phase transformation of SMA wire, a time lag appears between applied input pulse and output of micro switch which results at a high output for the corresponding interval in the X-OR gate. The same is explained in Fig**.** 6.

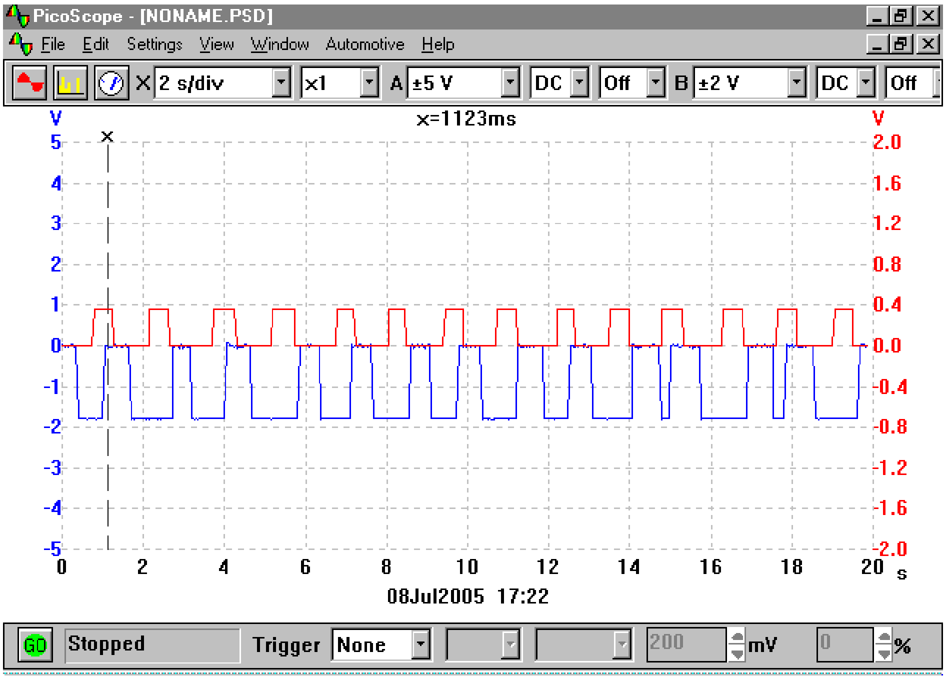


Fig. 5. Phase lag in SMA micro-switches. Pulse in red color indicates the input to the SMA wire and the blue color pulse indicates out put from the switch.

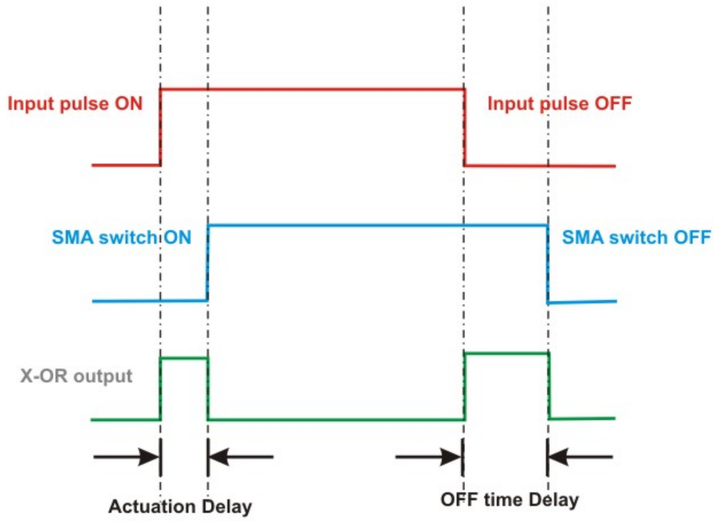


Fig. 6. Input and output response with X-OR gate.

The X-OR output has been used to accurately determine the ON and OFF time delay variations of the SMA switch. The corresponding plot with supplied input is shown in Fig. 7. The Red pulse in the graph represents the input to the SMA switch, whereas the blue pulse is the X-OR gate output. It is assumed that the gate delay is negligible compared to the ON-OFF time delay of the switch.

2.4.1. Effect of Voltage and Current on Activation - Deactivation Time Delay

The activation-deactivation time response of SMA micro switch with the variation in input voltage and corresponding change in different parameters are given in Table 2. In this experiment, the SMA wire length and diameter are kept constant. The frequency of actuation of the micro-switch is kept close to 1 Hz frequency – maximum possible with the chosen wire diameter under natural cooling condition. It is assumed that the surrounding temperature remains constant throughout the process.

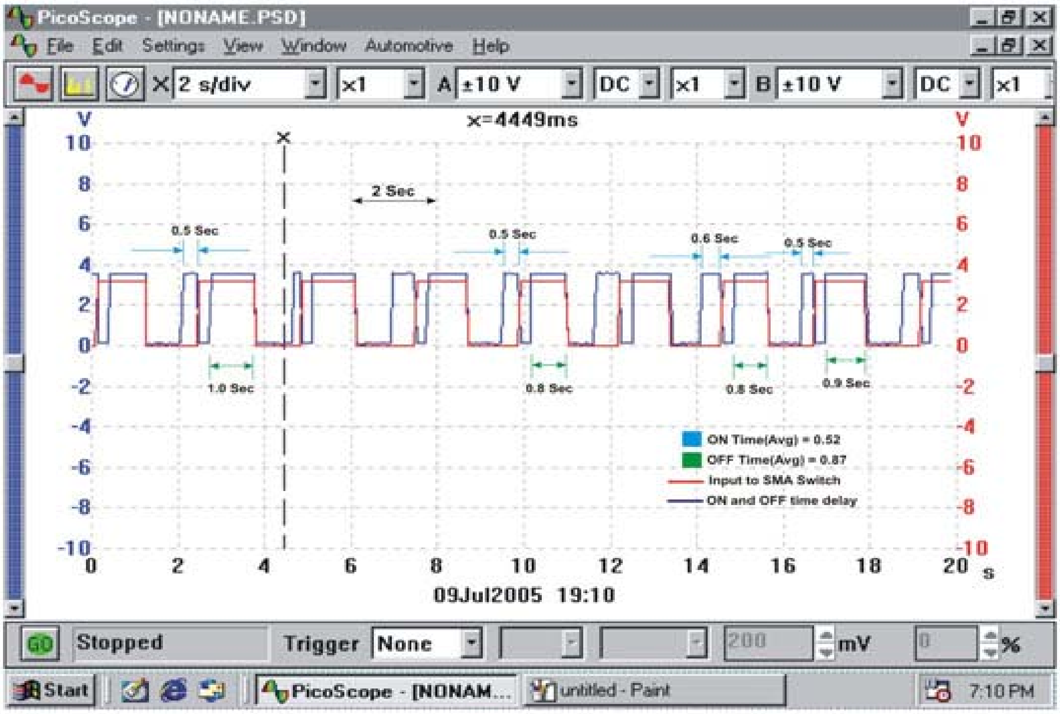


Fig. 7. X-OR output for applied input and X-or gate output.

Table 2. Effect of voltage and current on the activation-deactivation time delay.

SNo.	Voltage (V)	Current (A)	Activation Time delay (ms)	Deactivation Time delay (ms)	Frequency (Hz)
1.	0.8	0.22	600	300	0.91
2.	0.9	0.24	300	300	1.25
3.	1.0	0.26	200	320	1.38
4.	1.1	0.29	200	500	1.1
5.	1.2	0.33	150	600	1.05
6.	1.3	0.36	150	700	0.95

Fig.8 shows the effect of input voltage on various parameters of the SMA micro-switch.

From Fig. 8.a, it is clear that the activation time delay reduces as voltage increases. The possible reason is that as input voltage increases, the current flow through the SMA wire also increases and so the power dissipation. The increased rate of heat dissipation reduces phase transformation delay and activation time. Fig. 8.b shows the effect of voltage on deactivation time. Deactivation time also increases with the increase in voltage. It is because at higher voltage the electrical resistance of SMA is more and the SMA wire takes more time for phase transformation from austenite to martensite state. Fig. 8c shows the total time delay in the micro-switch due to the combined effect of activation and deactivation delay.

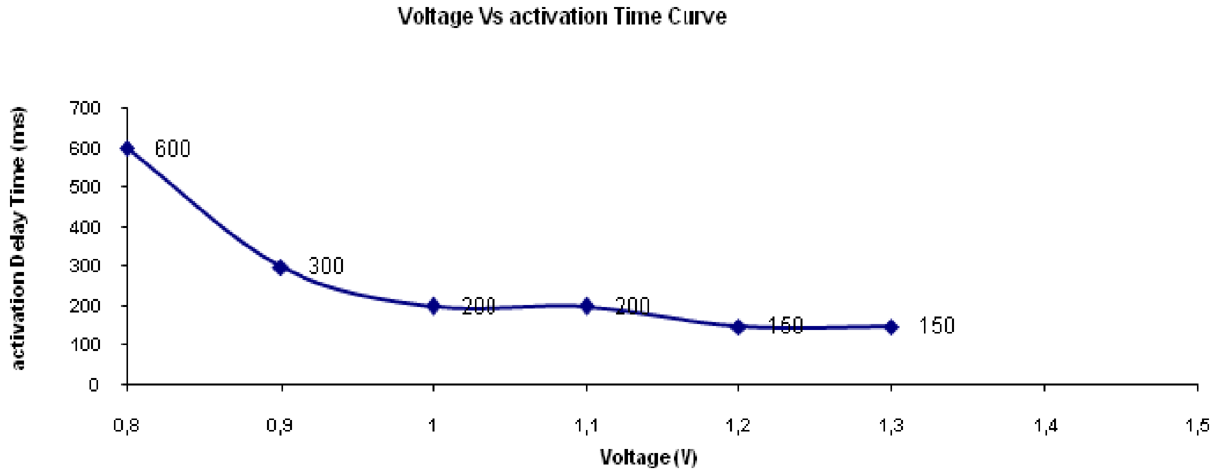


Fig. 8 (a). Effect of Voltage on activation time Delay.

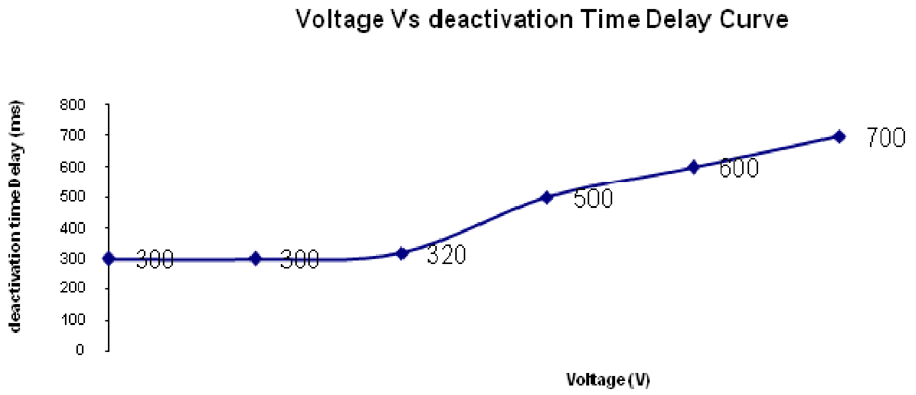


Fig. 8 (b). Effect of Voltage on deactivation time Delay.

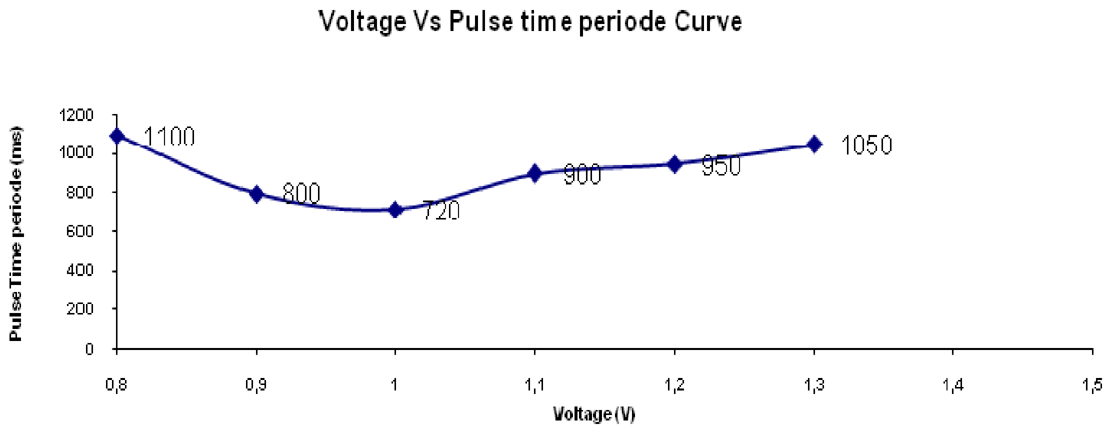


Fig. 8 (c). Effect of Voltage on total time Delay.

3. Development of SMA Based Angle Encoder

In this section, we will provide a brief description of development of SMA based angle encoder. A simple proof of the concept prototype has been developed in the laboratory, the performance of which has been compared with a standard optical encoder.

3.1. Design Aspects of SMA Based Angle Encoder

The SMA based angle sensor consists of a stationary index plate, SMA micro switches and a rotating link. The stationary circular index plate contains conductive contact strips placed radially with angular difference of 1 degree. All these conductive strips are connected together having a common electrical contact. A rotating link is attached to the shaft. This link has two contact points which generate pulses having phase shift of 90^0 same as in incremental shaft encoder [14]. These contact points provide continuity with conductive strips on the index plate. Two SMA wire operated micro-switches are placed beneath the index plate. Every time when the shaft rotates, pointed ends of the rotating link gets in contact with the individual conductive strip on the index plate, then the SMA wire gets fired and activate the micro-switch. The activation of the switch is taken in the form of pulses which are then processed to obtain direction, angle and velocity of rotating shaft. Fig. 9 shows the schematic diagram of the SMA based angle sensor.

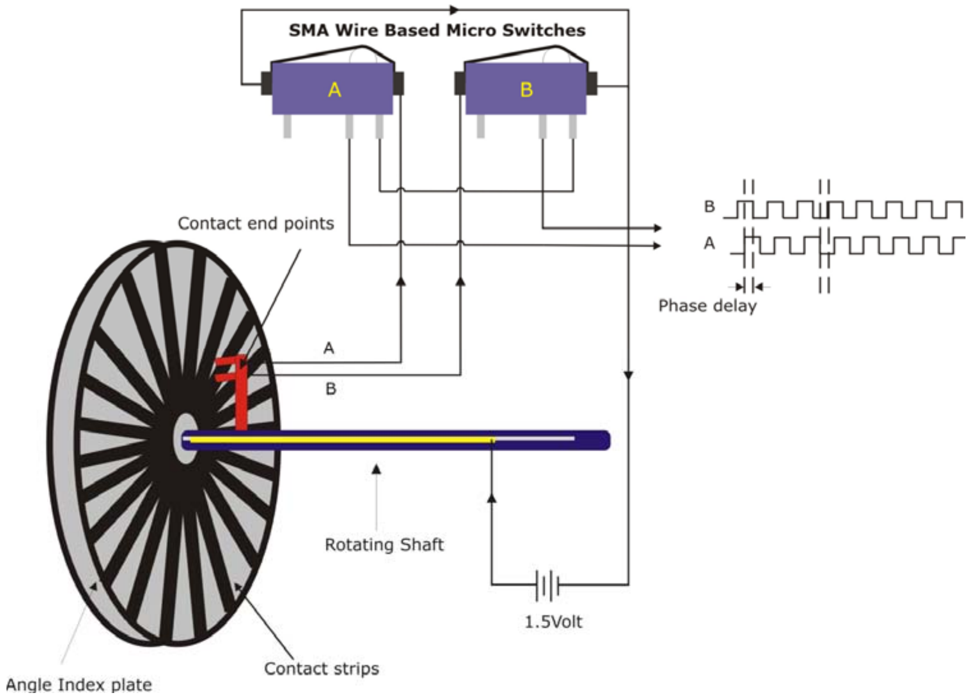
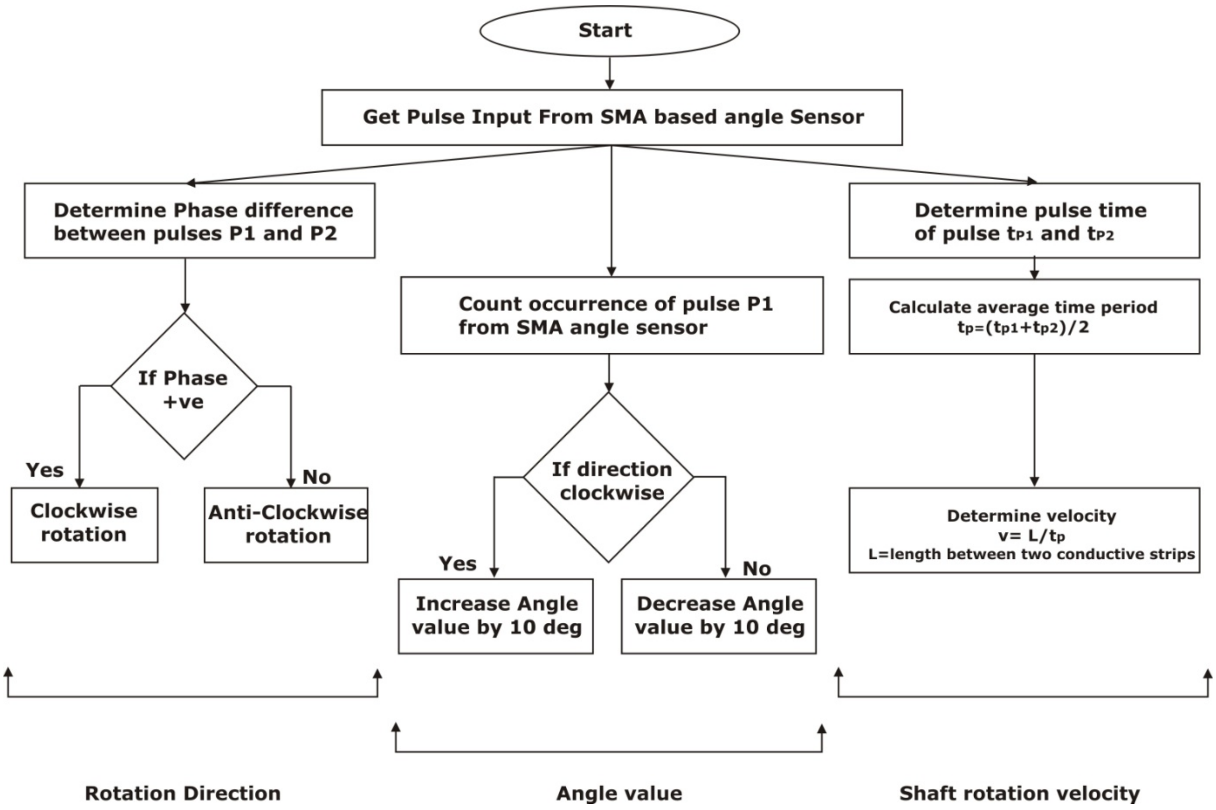


Fig. 9. Schematic diagram of the SMA Based angle sensor.

3.2. Working of SMA Angle Encoder

A P89c51RD2 microcontroller based system is developed to extract direction, angle and velocity from the SMA based angle encoder. When the shaft rotates, contact points on the rotating link come in contact with the conductive stripes on the index plate and this result in generating pulses from SMA based micro-switches. Number of pulses obtained from the angle encoder gives the total angular distance traveled by the shaft. In order to obtain angular displacement or angle value, direction of shaft rotation is needed. This is evaluated by determining the phase delay between two input pulses from the angle encoder. For a given shaft RPM, the frequency and time delay of these generated pulses remain constant and varies with variation in shaft angular velocity. The angular velocity can be obtained by measuring the time period of pulses and then calibrated, in order to get accurate results. A Flow chart below is provided to obtain the direction, angle and velocity from these pulses.



Response from the SMA based angle encoder are compared with incremental optical shaft encoder. LabView7.1 is used as platform to create a virtual instrument which is then interfaced with optical encoder and microcontroller using PCI-7344 motion control card along with MID-7604 drive to compare the results obtained from SMA based angle encoder and optical encoder. Fig. 10 shows the front panel of the virtual instrument used to compare performance of SMA angle encoder and optical shaft encoder.

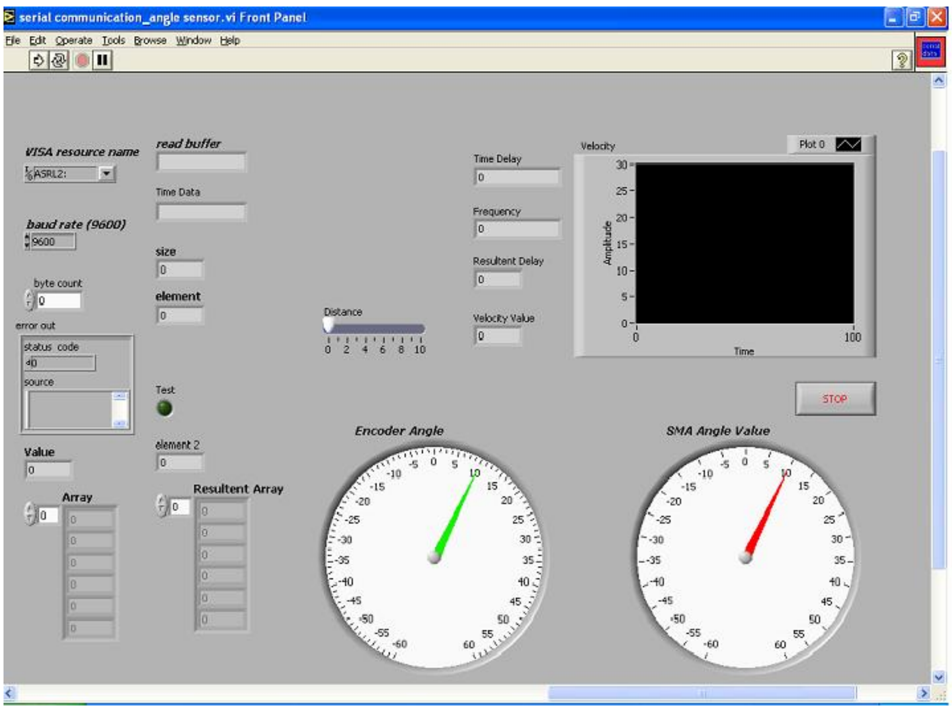


Fig. 10. Front panel of the Virtual instrument.

3.3. Index Plate Calculations

The dimensions of the index plate are taken in such a way that 1^0 of shaft rotation is equivalent to 1mm angular distance as shown in Fig. 11.

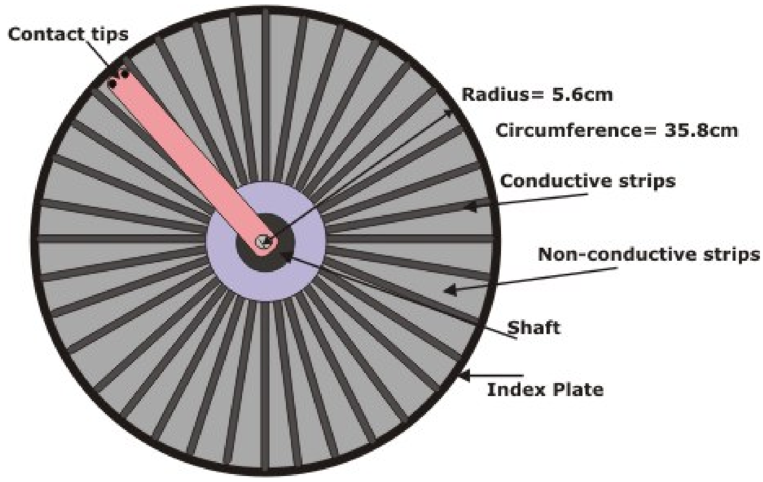


Fig. 11. Top view of the angle sensor.

For each degree of rotation, the shaft takes *t* amount of time, where *t* is given by

$$t = \frac{60 \times 1000}{360 \times \kappa} \text{ ms}, \tag{3}$$

where *k* is the shaft RPM and *t* is the time in millisecond.

In order to get proper pulse from the angle sensor for a given maximum RPM and applied voltage, widths of the conductive and non conductive strips are taken such that the SMA switch gets sufficient time to activate and deactivate during contact point rotation over the index plate.

For maximum RPM and applied voltage, the conductive strip width is calculated as

$$\text{Conductive Strip width} = (\mathbf{T}_{activation\_delay}/t)$$
$$\text{Non-Conductive Strip width} = (\mathbf{T}_{deactivation\_delay}/t),$$

where $\mathbf{T}_{activation\_delay}$ is the activation-time delay for SMA switch, $\mathbf{T}_{deactivation\_delay}$ is the deactivation-time delay for the SMA switch.

$\mathbf{T}_{activation\_delay}$ and $\mathbf{T}_{deactivation\_delay}$ for a few typical cases are given in Table 2.

Error of the system can be calculated as follows:
Max Error= ±Conductive strip width/2
Resolution of the angle sensor depends also on the non-conductive strip width. Accordingly,
Resolution =Non-Conductive strip width + Conductive strip width
For different values of RPM and voltage, error and resolution are given in Table 3.

Table 3. Performance of SMA based Angle Encoder at different RPM and supply Voltage.

SNo.	RPM	Input voltage=1 V		Input voltage=.9 V		Input voltage=1.1 V		Input Voltage=1.2 V	
		Error in deg	**Resolution in deg**	**Error in deg**	**Resolution in deg**	**Error in deg**	**Resolution in deg**	**Error in deg**	**Resolution in deg**
1	1	0.06^{0}	0.192^{0}	0.09^{0}	0.18^{0}	0.06^{0}	0.03^{0}	0.05^{0}	0.04^{0}
2	2	0.12^{0}	0.038^{0}	0.18^{0}	0.36^{0}	0.12^{0}	0.06^{0}	0.09^{0}	0.07^{0}
3	3	0.18^{0}	0.057^{0}	0.03^{0}	0.54^{0}	0.18^{0}	0.09^{0}	0.13^{0}	0.11^{0}
4	4	0.24^{0}	0.076^{0}	0.04^{0}	0.72^{0}	0.24^{0}	0.12^{0}	0.18^{0}	0.14^{0}
5	5	0.30^{0}	0.096^{0}	0.04^{0}	0.90^{0}	0.30^{0}	0.15^{0}	0.22^{0}	0.18^{0}
6	6	0.36^{0}	0.115^{0}	0.05^{0}	0.108^{0}	0.36^{0}	0.18^{0}	0.27^{0}	0.21^{0}
7	7	0.42^{0}	0.134^{0}	0.06^{0}	0.126^{0}	0.42^{0}	0.21^{0}	0.35^{0}	0.25^{0}
8	8	0.48^{0}	0.153^{0}	0.07^{0}	0.144^{0}	0.48^{0}	0.24^{0}	0.36^{0}	0.28^{0}
9	9	0.54^{0}	0.172^{0}	0.08^{0}	0.162^{0}	0.54^{0}	0.27^{0}	0.40^{0}	0.32^{0}
		On Time=200 ms Off Time=320 ms		On Time=300 ms Off Time=300 ms		On Time=200 ms Off Time=500 ms		On Time=150 ms Off Time=600 ms	

3.4. Robustness of the Angle Encoder in Noisy Environment

In this section we have compared the performance of the SMA based angle encoder with a standard optical encoder in a vibrating field. Both the sensors are placed on a vibrator platform and the platform was excited at a frequency of 50 Hz. The shaft was rotated at a low RPM close to 1Hz. Fig. 12 (a) shows the mechanical noise due to vibration at the input of SMA switch and Fig. 12(b) shows the output of the SMA switch which indicates that the switch itself acts as a pulse shaping circuit and remove the unwanted mechanical noise.

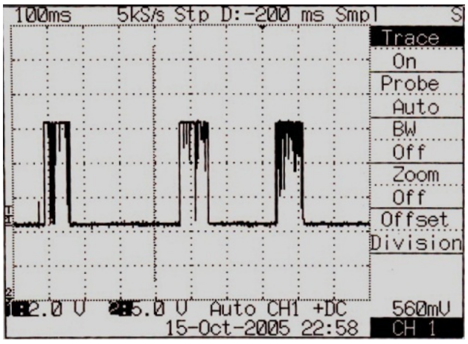


Fig. 12(a). noise due to mechanical contact at the input of SMA switch.

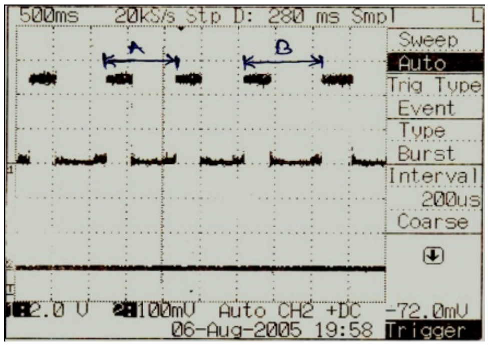


Fig. 12(b). Output of the SMA based angle encoder sensor.

Fig. 13 shows qualitatively the corresponding noisy output of the optical encoder subjected to the same vibrational environment while measuring rotation of the same shaft.

As mentioned earlier, the SMA switch has its own activation and deactivation time delay, hence high frequency noise due to vibration does not create any problem in SMA based angle encoder; whereas, in case of optical encoder, the effect of vibration appears at the output and generate unwanted signal that corrupts the angle information. Another reason of reduction of this noise in SMA angle encoder is that, the mean square value of the pulse is utilized to heat the SMA wire, which then activates the SMA switch. This mean square value does not contain high frequency signal which may corrupt the angle information and provides robustness to the SMA based angle encoder in vibrational environment.

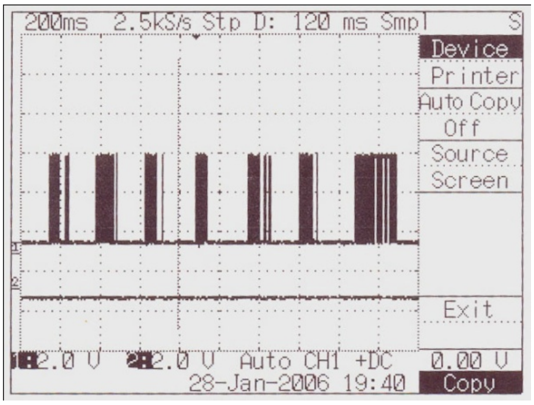


Fig. 13. Output response of the standard optical encoder subjected to the same vibration.

3.5. Effect of Temperature on SMA Angle Encoder at Different Temperature

For the SMA, properties like resistivity, modulus of elasticity and atomic structure vary with temperature. It is found that the resistivity increases as the temperature increases and this occurs continuously up to 45^0C. Now, at constant applied voltage as the temperature increases, current flow through the SMA wire decreases. This affects the phase transformation resulting in time delay in the SMA wire based micro-switch. Response of the SMA angle encoder at various temperatures is given in Fig. 14 which clearly shows the reduction of activation time at high temperature.

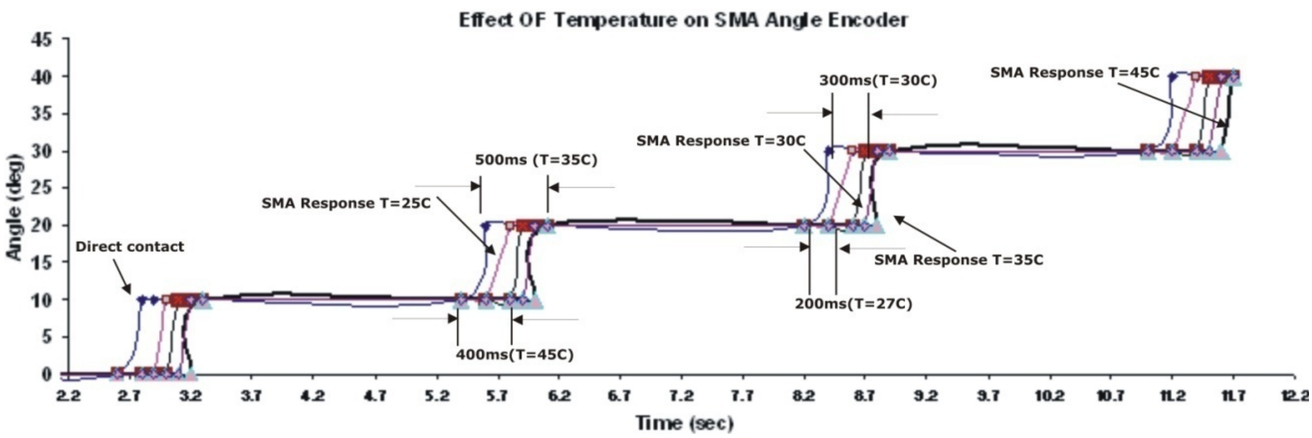


Fig. 14. Effect of temperature on the performance of SMA angle encoder.

Table 5 shows the performance of the developed SMA based angle sensor along with the specifications at a glance.

Table 5. Performance of the SMA based Angle Sensor at a glance.

SNo.	Parameter	SMA based angle sensor
1	Shaft diameter	6 mm
4	Power supply	1 V±5 %
5	Power consumption	1 V/.26 A=.26 W
6	Max pulse frequency	6 Hz
7	Phase shift	45^0.
8	Max Error	0.18^0 at 1V with 6 RPM

4. Conclusion

In this paper, a working prototype along with a novel approach to encode the direction, angle and velocity of rotating shaft using SMA wire actuated micro-switches are presented. The switches act like relays with the SMA wires fixed on it. The angle sensing approach includes a novel control scheme. The control System is implemented using the microcontroller P89c51RD2 and graphical user interface is provided using LabVIEW7.1. The experiments conducted has confirmed the ability of the SMA wire based system to sense the direction, angle and velocity of a rotating shaft. Currently the SMA based angle encoder efficiently works at low RPM. The results are carefully compared with conventional optical incremental encoder and calibrated accordingly. The results indicate that SMA based angle encoder efficiently works and gives accurate results in vibration condition. The time delay of SMA switch due to phase transformations in SMA wire has to be overcome in future to make the angle encoder more robust. Also, future work will be devoted in making the system suitable for encoding the angles at high velocity with minimum errors and better angular resolution.

Acknowledgements

The authors highly appreciate the suggestions of Dr. B. R. Vidyashankar, India Science Lab., GM, at various stages of this research.

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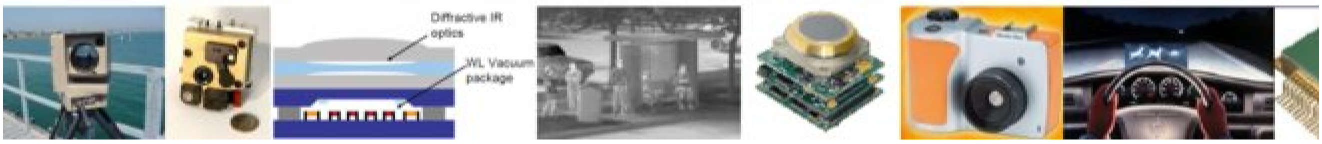
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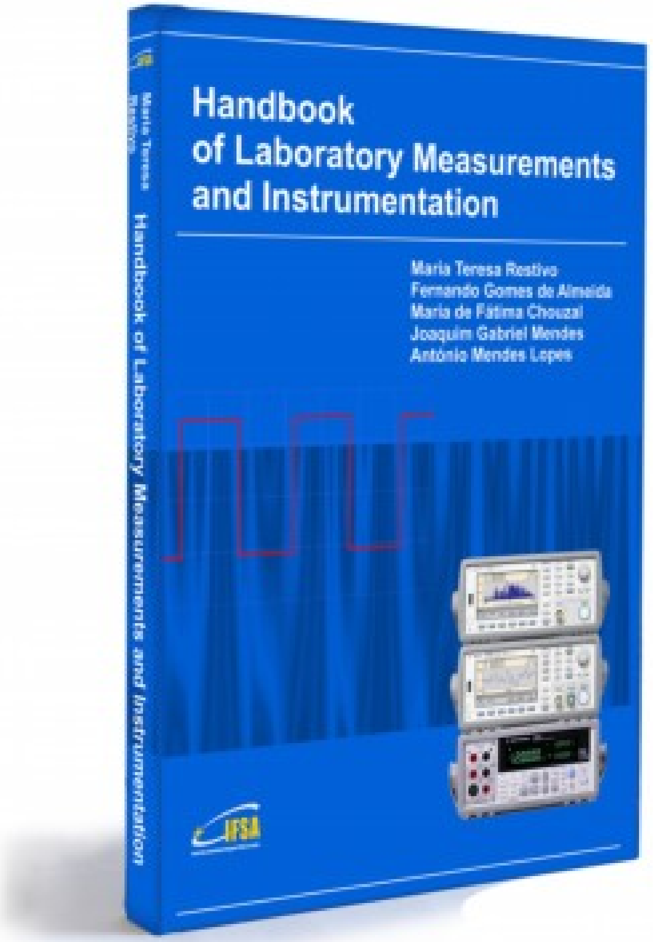

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