

Hall Effect Sensor-Based Linear Transducer

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PERCRO

Simultaneous Presence, Telepresence and Virtual Presence

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Abstract

This paper presents a new type of transducer based on Hall Effect sensors. This transducer is actually used at PERCRO as a small low cost, low displacement friction system for tracking hand position. A description of several displacement sensors as well as the Hall Effect has been reported. The mathematical model has been tested by means of an experimental apparatus. The optimal parameters have been determined on the apparatus and used for the realisation of a prototypal sensor.

1 Introduction

Several applications both in scientific research and industrial environments make use of position sensors. Linearity, resolution, sensitivity and repeatability are the most important features that a position sensor must possess with respect to the particular application. In Robotics applications the position sensors are very important since the control of the joints requires the knowledge of the joint vector (the components of the relative position or relative angular position) of each link with respect to another, in order to achieve a desired Cartesian position in the workspace.

Several Position Transducer have been found in the scientific and technical Literature. A general description of these devices is drawn from [1], [2], [3] and [4].

Potentiometers are currently used in several applications where easy and fast implementations are required. They are the simplest resistive transducers. They can convert the mechanical input, namely the physical position of its wiper terminal, into an electrical signal by the simple principle of a potential divider. The main advantages of these devices are the low cost and the small size. The main drawbacks are firstly its analogue nature, the need for additional hardware (usually an A/D Converter), secondly the contact between the wiper and the resistive element that reduces the life of the device and thirdly the thermal drift of the transducer.

Optical encoders (absolute and incremental) are required in more precise and sophisticated applications.

They transform the mechanical input quantity, namely the physical angular position of their shaft, into an electrical output quantity on the basis of the principle of light absorption of an optical sensor. Their main advantages are the high accuracy and the virtual absence of mechanical wear because of the non-contact nature of the transducer. The drawbacks are their poor angular resolution and the absence of an absolute "zero" position for the incremental type, the need for additional hardware to acquire the transducer signals, the shottypy loud and the non-derivability of the transducer.

Ultrasonic devices measure the time delay between the transmission of a pulse and the receipt of a reflecting pulse. The main advantage of this transducer is the absence of mechanical contacting parts. The main drawback is the need to compensate the input signal because the different velocity of the sound in different materials due to the temperature variations and their chemical differences.

A Hall effect sensor is essentially a transducer that responds with an output voltage proportional to the local magnetic field. The main advantage are a low cost and a small size with the device integrated on the same chip with the necessary circuitry. The main drawbacks are the analogue nature of the transducer and the need for a magnetic field created by either electromagnets or permanent magnets.

Hall Effect Sensor (HES) technologies are well developed and ready for applications; different catalogues, suchs [4], can be used for accessing the last up to date development. Any may realization of the transducer is bound to the application framework. For example the measure of the rotational position of the fingers abduction-adduction of the Glad-In-Art glove [5] is made using a HES-based rotational transducer analyzed in [6]. Another application is the HES study in the design of the Utah-MIT dexterous hand [7] where the position sensors are located directly on the rotation axis of each interphalangeal joint of the fingers. Finally in the EXOS Inc. hand exoskeleton [8], HES sensors are used to measure the angular positions of each phalanx.

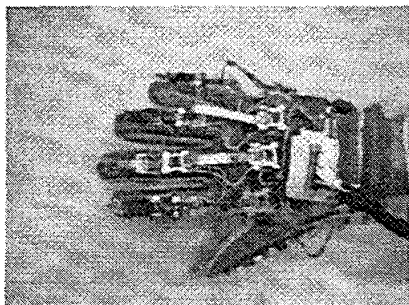


Figure 1: The Glad-in-Art Glove

In robotics applications, telerobotics as well as interaction in the VE, in which an economical aspect is predominant, the use of the Hall Effect Sensor (indicated with HES) is very interesting. In the following the utilisation of these sensors in a sensorised glove is presented. This glove is a mechanical device that identifies the position of the fingers in the 3D space.

2 The Hall Effect Sensor

The Hall Sensor is a transducer that will respond with an output voltage to a variation of the applied magnetic field. The Hall effect was discovered by E. H. Hall in 1879. Even if during his first experiments Hall used thin foils of conductive materials, the Hall effect gives better results with semiconductor elements [9]. The basic electrical circuit that represents the Hall effect is depicted in figure 2.

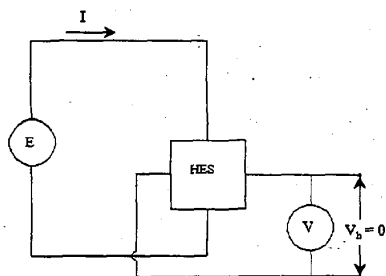


Figure 2: The Hall Effect Sensor with no magnetic field applied

Applying a constant voltage E through a semiconductor sheet, a constant bias current I is forced to flow in. If no magnetic field is present, the voltage measured across the width of the sheet V_h will be zero.

If the semiconductor sheet is placed in a magnetic field B perpendicular to the sheet itself, the voltage across the width of the semiconductor sheet will be proportional to the strength of the magnetic field as shown

in figure 3.

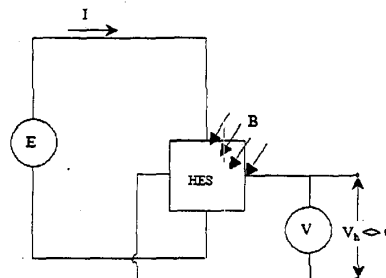


Figure 3: The Hall Effect Sensor with magnetic field applied

The effect can be computed with the following equation [9]

$$V_h = \frac{R_h(I \times B)}{t} \quad (1)$$

where V_h is the Hall voltage in Volts, R_h is the Hall coefficient expressed in cm^3/C , I is the current perpendicular to B in Ampere, B is the flux density perpendicular to I in Gauss, t is the semiconductor thickness in cm.

The voltage difference across two sides of the semiconductor element is directly proportional to the component of the magnetic field perpendicular to the path of the current flow inside the element. For this reason it is possible to assume that the Hall element is sensitive to the direction and magnitude of the magnetic field. These two parameters can vary the design configurations of the Hall sensor.

The source of magnetic field capable of activating the Hall element can be created by either electromagnets and or permanent magnets.

The described element is the base of the Hall Effect Sensor. Semiconductor material sheet can be, as example, silicon or indium-antimide. To obtain a real transducer other components are necessary: a stable voltage regulator and a temperature-compensated amplifier in order to increase sensitivity to magnetic flux and to reduce sensitivity to temperature variations and mechanical stress.

Two possible kinds of Hall Effect Sensor are commonly used for:

- *digital sensors*, in which the output has only two states depending on the value of magnetic field; hysteresis can be presented.
- *analog sensors*, in which the output is a continuous function, that relates the magnetic field on the

sensor with the output voltage. When exceeding a limit value of magnetic field the output voltage is independent by the position: saturation occurs.

HES sensors can be combined with magnet in different ways. The main methods are:

- **head-on:** the magnet is centered over the point of maximum sensitivity of the sensor and is moved to or from the sensing area;
- **slide-by:** the magnet passes the sensing surface at a fixed distance;
- **vane:** the magnet and the sensor are at a fixed distance and a ferrous metal vane slides through the gap between magnet and sensor.

Furthermore several combinations of number of magnets can be utilized in order to realize the position measure. For example:

- **unipolar head-on:** one magnet is centered over the point of maximum sensitivity of the sensor that is moved to or from the magnet (figure 4);

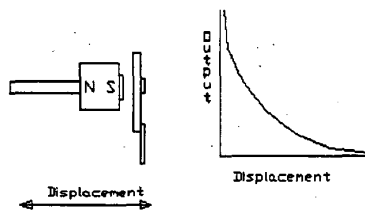


Figure 4: Unipolar head-on sensing

- **bipolar slide-by:** two magnets pass the sensing face of one sensor at a fixed distance as show in figure 5;

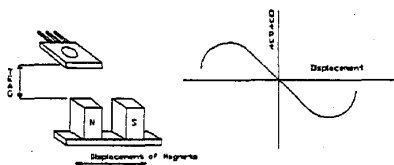


Figure 5: Bipolar slide-by

When the desired solution combination of sensor, number and position of magnets has been decided, the

determination of the hysteresis or saturation zone becomes fundamental.

It is possible to verify that in the case of *bipolar slide-by* a large amount of "linear zone" can be achieved using the combinations of magnets. For the design of a position sensor the *bipolar slide-by* has been chosen as basic solution for the position sensor.

3 Design of the Linear Transducer

In the following the description of the steps necessary to obtain the final solution are reported. Firstly the *unipolar slide-by* is analyzed in order to obtain the saturation of the sensor and consequently the maximum output voltage achieved. An experimental analysis has been conducted because the various parameters cannot be simply optimized in closed form. Secondly a *bipolar slide-by* study is made in order to find the maximum linear zone.

3.1 Unipolar slide-by

Using a permanent magnet positioned at a distance defined as the *Total-Effective Air-Gap (TEAG)*, from the HES and free to move along a line (s) representing the Displacement, as depicted in figure 5, the output voltage V is a curve that can be approximated (figure 6) with a Gaussian Curve [6] with equation

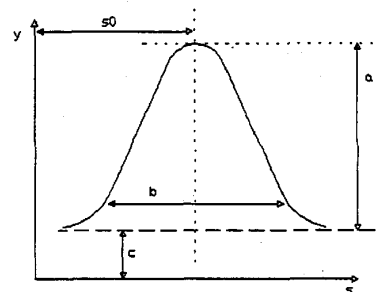


Figure 6: Gaussian Curve Parameters

$$V(s) = c + a e^{-(s-s_0)^2 / b} \quad (2)$$

where c is the Voltage offset, a is the amplification factor, b is the form factor and s_0 is the displacement offset.

For each *TEAG* it is necessary to record the output tension value V at the related position using an experimental apparatus because the parameters of equation 1 are unknown.

The mainly components of the apparatus are a mechanical equipment, in which HES and the magnet take place, including a linear slide that provides the relative



Figure 7: General view of the Experimental Apparatus

motion between the two elements (see figure 8), an electrical power supply for the HES with a constant voltage of V_0 and a multimeter to read the output voltage V .

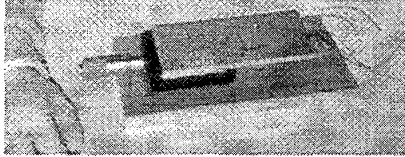


Figure 8: Realized Mechanical Equipment

This *TEAG* is important to be correctly defined because if it is too small the HES saturates (i.e. its output is not depending on the position of the magnet); on the other hand if it is too large the maximum tension value is low. In order to find the optimal *TEAG* several experimental tests have been conducted moving the linear slide with a constant step of Δ in a range of L repeated two times. The "zero" position of the segment L is defined when the sensor is placed over the magnet. The position error is related to the s_0 value. To vary the *TEAG* a series of harmonic listen of fixed thickness τ has been utilized. To measure the *TEAG* of each test a set of Johansson Blocks has been utilized. For each test a table with the numerical bound tension-displacement is given. The first table with the minor *TEAG* and without saturation has been chosen as the optimal experimental set of points. From this set the parameters of the approximating Gaussian curve has been drawn using an error-based optimization procedure. The absolute error chosen for the optimization is the Square Medium Error (SME) defined as:

$$SME = \sum_{i=1}^N ((V_i - V(s_i))^2 \quad (3)$$

where V_i is the tension value of the experimental probe at step i , s_i is the associate displacement and $V(s_i)$ is the Gaussian equation value calculated at s_i .

It is necessary to define a Relative Percentile Error (RPE) as:

$$RPE = \frac{SME}{(\max_i(V_i))^2} \quad (4)$$

where $\max_i(V_i)$ is the maximum value of the experimental voltage data, in order to compare the results of the optimization.

A numerical optimization recursive study has been conducted by varying the four parameters a , b , c and s_0 in order to find the curve that minimizes the *RPE* w.r.t. the set of experimental data. This study has been conducted by realizing a software module in C language.

3.2 Bipolar slide-by

The same magnet with opposite polarity has an approximating Gaussian Curve:

$$V(s) = c - a e^{-(s-s_1)^2 b} \quad (5)$$

The magnetic field resulting by the utilization of two magnets with opposite polarity is given by the sum of the respective Gaussian curves because the sovraposizione effect principle can be applied to the magnetic field magnitude. Mathematically, two magnets at distance ξ give the following equation, which is the representation of the emisymmetric curve depicted in figure 9:

$$V'(s', \xi) = a (e^{-(s' - \xi/2)^2 b} - e^{-(s' + \xi/2)^2 b}) \quad (6)$$

where $s' = s - s_0 + \xi/2$ and $V' = V - c$.

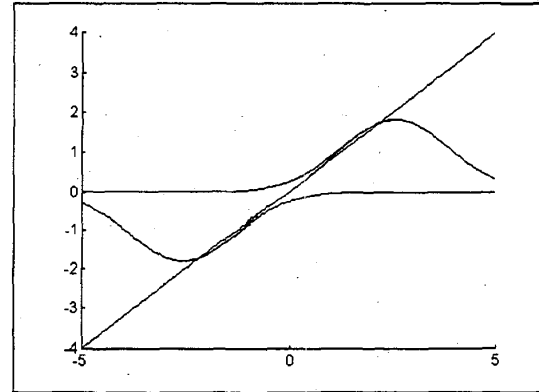


Figure 9: Representation of V'

Yet it is necessary to find the value of ξ that maximizes the linear part ϵ between the two magnets, with obviously $\epsilon/2 \in [0, \xi/2]$ w.r.t. the Percentual Linearity Error (PLE) defined as:

$$PLE = \frac{|V_2(s') - V_1(s')|}{\max_{s' \in (0, \xi/2)} V_2(s')} 100 \quad (7)$$

where $V_2(s')$ is the curve of equation 6 and

$$V_1(s') = q s' \quad (8)$$

is the equation of line, target of the search, with angular coefficient q calculated as

$$q = \frac{V'(\Delta) - V'(-\Delta)}{2\Delta} \quad (9)$$

To find the value of ξ that maximizes ϵ , a recursive analysis is made in the field $[0, \xi/2]$ with the *PLE* assigned to a percentual value representing the desired linearity error. This procedure has been implemented by using a Matlab software.

4 Results

In the following, the equation and the software tools reported in the previous paragraph are utilised to find the parameters of a practice example. The overall scheme is depicted in figure 10.

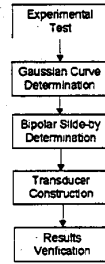


Figure 10: Steps of the Procedure

4.1 Experimental Test

The utilised sensor of the experimental apparatus is the Allegro *UGN 7032 U* [4] and the magnet CIBAS *REN 35 3×3* [10]. The starting parameters, that define the environment in which the experimental probes have been conducted, are numerically depicted in table 1. The meaning of the symbols is reported in a previous section.

Parameter		Value
V_0	V	5
Δ	mm	0.1
L	mm	10
τ	mm	0.1
<i>PLE</i>	$\%$	5

Table 1: Experimental Parameters

The experimental tests have been conducted with $TEAG = 0.6 \div 1.5 \text{ mm}$ and step τ . The optimal experimental set of point is reported in table 2 related to an optimal $TEAG = 0.9 \text{ mm}$.

$\Delta \text{ (mm)}$	Measure 1 (V)	Measure 2 (V)
...	...	...
-0.1	4.220	4.232
0.0	4.238	4.245
0.1	4.249	4.252
...	...	...

Table 2: Experimental Results

4.2 Gaussian Curve Determination

The results of the *C* software utilised to find the coefficients of the Gaussian curve in the Unipolar Slide-by case are $a = 1.817V$, $b = 0.2931/mm^2$, $c = 2.522V$, $s_0 = 0.329mm$ and $RPE = 1.56\%$. The graphical representation of the experimental points and the related Gaussian curve are depicted in figure 11.

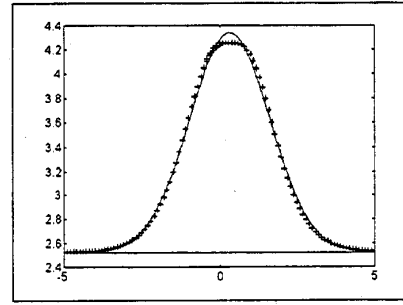


Figure 11: Experimental Data and Gaussian Curve

4.3 Bipolar Slide-by Determination

The results of the Matlab software utilised to find the optimum Bipolar Slide-by curve are $q = 0.796V/mm$, $\xi = 5.120mm$ and $\epsilon = 4.817mm$.

4.4 Verification of the results

Starting from the basic dimensions of the Bipolar Slide-by curve obtained in the previous paragraph a displacement transducer has been realized for a sensorised glove. It is composed by a fixed part on which the HES takes place and a mobile part where the two magnets are fixed. A transmission allows the relative motion of the magnets with respect to the sensor. An image of the sensorised glove is depicted in figure 12. The mechanical measure range of the sensor is $l_m = 15.3mm$ and the lectures range is $l_l = 5.1mm$.

Using the experimental apparatus depicted in figure 8 with small modify it is possible to collect the data reported in table 3. l_{max} and l_{min} are the distances from the mobile support of the magnet to the frame of the transducer. V_{max} and V_{min} are the maxima and minima tension measured in the transducer.



Figure 12: The sensorised glove

The effective $\xi = l_{max} - l_{min}$ is 5.1 mm and the measured $TEAG$ is $TEAG \approx 1.1mm$ due to the tolerance chains of the various elements of the transducer. With this value a lower V_{max} and a lower linear lecture range are expected. The results of the realised sensor are depicted in figure 13. The drawn values are of the similar magnitudo of the spermental data.

Parameter		Value
V_{min}	V	1.029
l_{min}	mm	4.40
V_{max}	V	4.157
l_{max}	mm	9.50
ϵ	mm	4.60

Table 3: Verify parameters

5 Conclusions

In this paper the analysis of a Hall Effect Based Position Transducer has been made. Firstly the description of the displacement sensor has been explained, secondly the description of the Hall Effect has been reported, thirdly an experimental apparatus has been realized in order to find the optimal parameters of the transducer and finally the value of the parameters of a realized sensor are provided. The Hall Effect sensors described have been utilized for the design of a new type of sensorised glove, based on an innovative kinematics arrangement, and used for VE applications. It is expected that the favorable relationship between performances achieved by such a type of sensor and issues selected to the effective costs for this implementation will open new opportunities for exploration especially for VE applications.

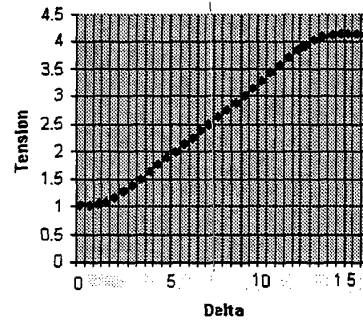


Figure 13: Voltages vs displacements for the realised displacement transducer

References

- [1] S. R. Ruocco, "Robot Sensors And Transducers" *Wiley and Sons*, 1985
- [2] D. A. Bradley et.al., "Mechatronics" *Chapman & Hall*, 1993
- [3] G. G. Lisini, "Servomeccanismi" *Edizioni SEU*, 1994
- [4] AA.VV., "Integrate and Discrete Semiconductors" *Allegro Microsystem Inc.*, 1995
- [5] AA.VV., "Glad In Art EU TIDE Project 512", 1990.
- [6] D. M. De Micheli and M. Bergamasco, "Characterization of a Hall Sensor-Based Angular Transducer" *ARTS Lab Internal Report 89-03*, 1989
- [7] S. Jacobsen et. al., "Design of the Utah-MIT dexterous hand" *Center of Engineering Design, University of Utah*, 1986
- [8] AA.VV., "Product Literature" *EXOS Inc., Burlington*, 1990
- [9] T. Wood, "The Hall Effect Sensor", 1986
- [10] AA.VV., "Magneti Permanenti e Attrezzature Magnetiche" *CIBAS s.r.l.*, 1992