EVALUATION OF SENSOR TECHNOLOGIES FOR THE RULERS, A KALIMBA-LIKE DIGITAL MUSICAL INSTRUMENT

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ABSTRACT

Selecting a sensor technology for a Digital Musical Instrument (DMI) is not obvious specially because it involves a performance context. For this reason, when designing a new DMI, one should be aware of the advantages and drawback of each sensor technology and methodology. In this article, we present a discussion about the Rulers, a DMI based on seven cantilever beams fixed at one end which can be bent, vibrated, or plucked. The instrument has already two sensing versions: one based on IR sensor, another on Hall sensor. We introduce strain gages as a third option for the Rulers, sensor that are widely used in industry for measuring loads and vibration. Our goal was to compare the three sensor technologies according to their measurement function, linearity, resolution, sensitivity and hysteresis and also according to real-time application indicators as: mechanical robustness, stage light sensitivity and temperature sensitivity. Results indicate that while strain gages offer more robust and medium sensitivity solution, the requirements for their use can be an obstacle for novice designers.

1. INTRODUCTION

In the context of DMIs, stability and robustness are often discussed as ways of evaluating a device's behaviour and as a means of expressing the desired parameters and features required for performance. In most cases, these requirements differ from those expected in the laboratory environment. Often, DMIs require some adaptation after performer's practice sessions, through technical and player's evaluation. Also, stability and robustness are required qualities for learning and practice process.

The Rulers, an instrument developed in 2004 by David Birnbaum [1] [2], has undergone two versions and numerous performances, but none of these versions have produced a stable instrument. The first version was based on using Infrared (IR) sensors to measure the distance between the sensor and the cantilever beam. The second version used Hall sensors to measure the same variable. In this paper, we present a third version of The Rulers that uses strain gage (SG) sensors to measure the strain on the beam. The goal of this work is to provide more sensitivity and stability for The Rulers, as well as present a possible application of strain gages on DMIs.

Although widely used in industrial applications, strain gage sensors have not been widely employed in DMIs, possibly due to their relative complexity when compared to more popular sensors for measuring force and pressure, like Force Sensitive Resistors (FSR). This paper introduces the use of the strain gages in DMIs, and compares their performance relative to other, more popular, sensor technologies applied to The Rulers.

2. THE RULERS

The instrument was designed to induce the gesture of plucking or bending the free end of seven beams. The lengths of each of the seven aluminum cantilever are various. Therefore, each beam oscillates at a different frequency when plucked. This provides visual and passive haptic feedback to the player, otherwise the oscillations are not used for acoustic purposes. The beams' motion - created by a variety of gestures - is measured by sensors, which output signal is mapped to control a computer-based sound synthesizer. Figure 1 shows The Rulers being played.

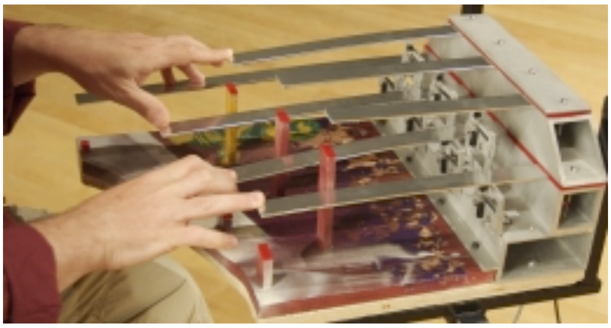

Figure 1. The Rulers

The expected and unexpected beam movements executed can be approximate by the Euler-Bernoulli beam equations [3]. These equations, considering some boundary conditions, provide information about the displacement and the strain at each point of the beam. Nevertheless, the full mathematical description of the riddle would only be possible by numerical simulation of the physical model or by making use of real-time control/monitoring of some variables in conjunction with the agreement between a good mechanical design and its implementation. The sensors placement is showed in the Figure 2.

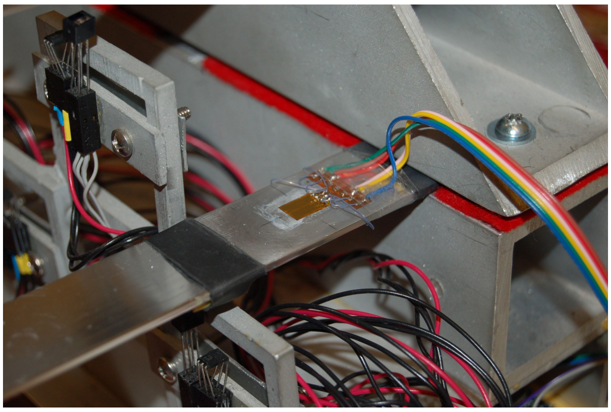

Figure 2. Sensors placement

Usually, approximating the load as a constant concentrated force and considering the fixed point as a clamp, it's possible to predict the strain at any point of the beam. Consequently, taking in consideration the area of concentrated strain and the SG's maximum relative strain rating, the optimal point for the sensor application can be determined.

2.1 Infrared Sensor Version

This version's conception is based on measuring the distance between the infrared system (IR transmitter + IR receptor) and the beam. Therefore, the displacement value at the free end is obtained from the distance between sensor and beam next to the fixed end. Even though, the relation between the displacement and the measured distance is considered linear, this can not be assured due to the mechanical construction of the instrument.

The infrared system contains a transmitter (photodiode) and a receptor (phototransistor). The former transmits infrared waves towards the direction of the beam. The beam, partially reflects the incoming wave towards the receptor's direction. The receptor will then sense a delayed and lossy wave compared with the transmitted wave.

This sensor presents a low complexity and low set up time, but, its response is not linear. This downside must be partially compensated by calibration and software corrections, otherwise the response might contain substantial errors [4]. Linearization methods can be applied both in the hardware [5] and in the software [6, 7] implementations. Also, as stage lights radiate substantial infrared waves, interference may occur in performance contexts.

2.2 Hall Sensor Version

In this version, a Hall sensor was used to measure the magnetic field strength produce by a magnet located in the bottom of the beam. The field strength generates, according to the Hall Effect, a voltage on the sensor terminals. This voltage is directly proportional to the field and actually reflects the distance between the sensor and the beam.

Accordingly to the datasheet, the output response in Volts is linear in respect to the magnetic field in Gauss [8]. Otherwise, as the configuration is unipolar (just one magnet as magnetic field generator), the relation between magnetic field and distance is quadractic, i.e., non-linear [9]. A disadvantage encountered on this method is related to the instrument's mechanical features: small translational movements affects the alignment between sensor and magnet and slope error measurements can be expected [9].

2.3 IR and Hall Sensors Solutions

As presented above, IR and Hall sensor responses are based on the distance between the sensor and the beam. The measurements are taken near the fixed end of the beam to avoid disturbing the performer's gestures. From the measurement perspective, this spot is not optimal in terms of displacement range, limiting the input quantity range for the sensors.

In addition, some approximations would be required to consider the relation between the displacement exerted at the free end and the displacement near to the fixed end as a linear ratio. There are two sources of non-linearity when measuring the beam's movements using IR and Hall sensor. The first one is the inner sensitivity of the sensors to theirs primary quantity: infrared radiation (IR sensors) or indirectly the distance sensor-magnet (Hall sensor), which are both related to the distance between the sensor and the beam next to the fixed end. The second one is the ratio between the measured quantity (distance between the sensors and the beam) and the quantity of interest (displacement applied to the free end).

Non-linear measurement functions are generally not appreciated as they demand correction, linearization and high sensitivity along the measuring interval. This non-linear transfer functions might be perceived as an unreliable relation between the performer's gestures and the sound being controlled by the measured signals, when a decent correction process is not executed.

3. STRAIN GAGE TECHNOLOGY

From physics, it's known that once there is a force applied to a certain area, there will be a resulting stress given by $\tau = F/A$, where τ is the stress, F is the force and A is the area. For each particular load pattern, two quantities stand out: strain and displacement. Strain is the relative displacement of rigid body particles, which can be described by its *engineering normal* form as: $\epsilon = \Delta L/L$, where ϵ is the engineering normal strain, L is the original length of the material and ΔL is the length variation. In contrast, displacement (δ) is a deformation that implies change in shape or position.

Materials can react to the stress elastically or plastically, depending on its own characteristics and on the load. In the elastic regime, the relation between stress and strain is linear and there is no residual displacement when the force is released. Under this condition, the linear relation between stress and strain is given by the Young Modulus or Elastic Modulus (E) given by: $E = \tau/\epsilon$.

In the current study, we will be measuring strain, through the use of strain gages. These sensors are sensitive to strain, which is maximized in the neighbourhood of the fixed end. The strain at this point can be correlated to the displacement at the free end. This ratio, for static loads, small displacements and negligible weight of the beam, can be considered quadratic in respect to the length. This comes from the fact that, regarding these boundary conditions, the displacement along the beam and the strain are respectively:

$$\delta = F * L^3/E * b * h^3 \quad (1)$$
$$\epsilon = 6 * L * F/E * b * h^2[3] \quad (2)$$

where b is the beam's width and h is the height of the beam.

3.1 Types of Strain Gages (SG)

There are a variety of models, principles of operation and measuring intervals that should be considering when selecting a certain model for each specific application. Among the electrical-type strain gages, there are the resistive SG (based on resistance changes) and the semiconductor SG (based on conductivity changes) [10]. The first one, also called metallic SG, experiences changes in its resistance when submitted to mechanical forces. The second one varies its resistance according to changes on its resistivity (piezoresistive effect), when strained. Their sensitivity, called Gage Factor (GF), is usually from 1.8 to 4.5 for metallic SG and from 40 to 200 for semiconductor SG [11]. Both sensor types are sensitive to temperature changes, especially the semiconductor one. Therefore, in real-time applications, without strict temperature control, employing semiconductor SG is not advisable, that's why a metallic SG was selected to perform this task.

3.1.1 Metallic Strain Gage Functionality

An electrical resistance of a conductor having length L, area A and resistivity ρ is:

$$R = \frac{\rho * L}{A} \quad (3)$$

If the wire experiences a longitudinal load, both its dimensions, L and A, and resistivity ρ will change at different ratios:

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dL}{L} - \frac{dA}{A} \quad (4)$$

According to [11], for an isotropic conductor, within the elastic limit, the amount of resistance variations is

$$\frac{dR}{R} = \frac{dL}{L} * [1 + 2\nu + C * (1 - 2\nu)] = GF * \frac{dL}{L} = GF * \epsilon \quad (5)$$

where ν is the Poisson coefficient, C is the Bridgmann's constant.

All sensors are sensitive to so-called secondary quantities [12]. The main secondary sensitivity for metallic strain gages is temperature variation. Temperature affects the strain gage performance in two ways. First, metal materials face dimension changes as stated by the thermal expansion coefficient.

Due to that, the strain gages are built over a foil material which thermal expansion coefficient is similar to the specimen thermal expansion coefficient. By doing that, no relative expansion between specimen and sensor is expected.

Secondly, temperature variations modify the resistance of the unstrained grid wire and the Gage Factor.

For compensating this effect, two solutions are commonly put in use: to conduct the experiments under a controlled temperature environment (what it is difficult in a stage environment); or to use *dummy* strain gages, that experience thermal strain but no mechanical strain. Thermal effects can then be compensated.

3.2 Strain Gage Application

The four steps for applying strain gages to measure strain in the instrument are: determine the bridge topology, design the conditioning circuit, apply the sensor into the specimen and perform the measurements.

3.2.1 Bridge Topology

Strain gage resistance variation, calculated by $\Delta R/R = GF * \epsilon$, are usually small enough for being measured with a reasonable resolution using voltage dividers. Due to this fact, Wheatstone bridge is employed, that consists on a balanced/unbalanced circuit.

These features are profitable for strain gage measurement as the disposition of elements defines whether they will have adding or subtracting contributions to the differential output voltage. In the current application, a *full bridge configuration for bending purposes* was used. This topology infers that there are four strain gages applied to the specimen: two of then installed on the top, two installed on the bottom.

Considering a one-way bending, two strain gages observe stretch and sense $+\epsilon$, while two observe contraction and sense $-\epsilon$. In addition, all of them experience thermal deformation, that can be considered the same (due to small dimensions) if there is no temperature gradient between top and bottom.

Finally, summing up all strain contributions, it's possible to calculated the resulting bridge output voltage as follows:

$$V_{out} = V_{pw} * GF/4 * (\epsilon_m^1 + \epsilon_{th}^1 - \epsilon_m^2 - \epsilon_t^2 + \epsilon_m^3 + \epsilon_t^3 - \epsilon_m^4 - \epsilon_t^4)$$
$$V_{out} = V_{pw} * GF * \epsilon_m \quad (6)$$

where V_{out} is the output voltage, V_{pw} is the power source voltage, GF is the Gage Factor and ϵ_x^n is the strain, where the upper indices mean the element number and the lower indices whether the strain is mechanical or thermal. The solution above takes into account the fact that all thermal strains are equal as well as all absolute values of mechanical strains are equal.

3.2.2 *Conditioning Circuit*

A conditioning circuit was designed to perform the following functions: zero the bridge, compensate lead wire resistance, amplify and adjust the scale for USB voltage patterns. These tasks are essential when dealing with small signals, like strain gage bridge output voltage. First, an analog zeroing process is executed by using two fixed resistors (tolerance 0.1%) and two trimpots (tolerance 1%). Adjusting course and fine trimpot resistors, it's possible to correct small disagreements that could be present when the sensors are unstrained.

Furthermore, lead wires resistance, specially on remote measurements, may have a great influence on the output response. For solving that, the six-wire measurement method was designed. Amplification and scaling is performed by a low-power differential operational amplifier. Note that the bridge can deliver positive and negative differential voltage outputs depending on the unbalance direction. For this reason, a voltage reference is summed up with the bridge output bringing the reference voltage output to 2.5 V (suitable for USB interfaces).

3.2.3 *Sensor Application into the Specimen*

Applying the strain gages into the specimen requires attention due to strain gage's delicate structure. Also, the installing process requires dirt-free environment and tools, as any impurity may degrade the strain gage grid and pads or affect the strain transfer from the specimen to the sensor.

Once specimen and sensor are cleansed and dried, the application point is selected. For selecting the point, there is a compromise between greater load concentration and maximum strain damage prevention. After selecting the point, signs are drawn to indicated the correct position to apply (a maximum alignment error of four degrees between top and bottom strain gages positions are acceptable).

Afterwards, the glueing process is done based on cyanoacrylate cold cure adhesive. Finally, in order to close the bridge, the pads are connected using wires with the same specifications and lengths. Ultimately, a resistance measurement test is done to verify the correct installation of the sensor.

4. EXPERIMENTAL DEVELOPMENT

The present experimental work consists on analog and digital design as presented in the Figure 3. Hardware and software were developed in order to efficiently evaluate the sensor output signals.

4.1 Measurement Chain

The measurement chain of the system is presented in the Figure 3 and described in the next sessions.

4.1.1 *Hardware*

- sensors: strain gages, Hall sensor and IR sensor;
- conditioning circuits:
  - **zero circuit:** zeroes the voltage output when the beam is unstrained, before executing measurements;

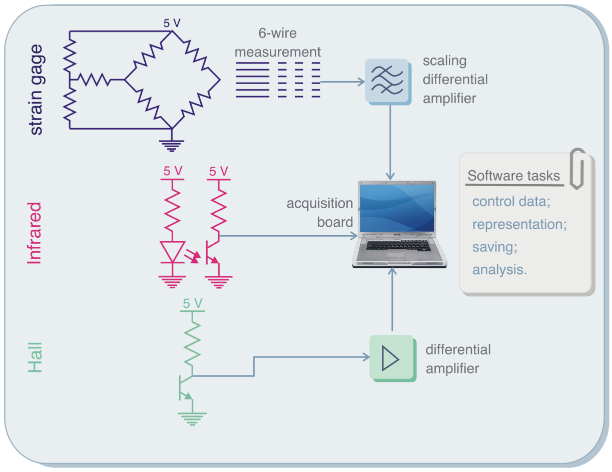

Figure 3. Measurement Chain

  - **amplification:** amplifies the Wheatstone Brigde output and Hall sensor output using differential amplifiers;
  - **scale adjustment:** adjusts the full-differential bridge output to the range (0 to 5) V, in order to be suitable for USB interfaces;
  - **lead wire compensation:** compensates voltage losses through the power source wire by measuring the power source voltage through a six-wire bridge connection.
- acquisition board analog interface from National Instruments (8 channels, 24 bits, up to 100 k samples/s). Five channels were used:
  - power source voltage;
  - sensing of power source voltage through the bridge;
  - strain gage conditioning circuit output;
  - Hall conditioning circuit output;
  - IR sensor output.

4.1.2 *Software*

A .vi code (Labview Virtual Instrument software) was implemented for processing the data from the acquisition board. The software incorporates the following blocks and functionalities:

- acquisition board settings;
- data manipulation settings (user);
- input and output data;
- simple mathematical manipulations;
- data representation (graphics): before and after manipulation;
- data saving interface.

The possibility of saving the data allows the researcher to export this data to a specialized mathematical application where one can perform more complex data manipulations.

4.2 Measurement Procedure

As soon as the hardware is setup: wiring, zeroing and gain adjusting, the measurement procedure can be started. The steps followed for each set of measurement are briefly described above:

1. perform the zeroing procedure by software;
2. bend monotonically the beam towards one direction, take measurements of position and sensor outputs at each desired point;
3. once the last measurement point is reached, slightly exceed this point before starting the bending operation toward the other direction;
4. bend monotonically the beam toward the other direction, take measurements of position and sensor outputs at each desired point;
5. once the last measurement point is reached, exceed slightly this point before starting the bending operation toward the other direction;
6. repeat four times the operations 2 to 5.

5. RESULTS

5.1 Qualitative Comparison

Table 1 presents the qualitative indicators for each sensor. Some of these indicators require discussion as follows:

QUALITATIVE COMPARISON		Sensors		
		Strain Gages	Hall Sensor	IR Sensor
desired characteristics	linearity	linear	non-linear	non-linear
	large displacement (15 to 60) mm sensitivity	medium (constant)	low (variable)	high (variable)
	small displacement (0 to 15) mm sensitivity	medium (constant)	low (variable)	low (variable)
	force sensitivity	high	none	none
	mechanical robustness	low	medium	high
undesired characteristics	stage light sensitivity	negligible	negligible	high
	temperature sensitivity	medium	negligible	negligible
	assembly difficulty	high	medium	low

Table 1. Qualitative Comparison among Sensor's Performances

force sensitivity: strain gages measure strain which is directly related to the force applied to the beam;

mechanical robustness: in this sense, mechanical robustness indicates the property of maintaining the instrument features through time and use. As strain gages are applied to moving parts, as well as their lead wires, this can imply fatigue or connection problems. In contrast, IR and Hall sensor don't have any moving parts in the sensing system. Besides, the Hall sensor was considered as having medium mechanical robustness because its operation are vulnerable to translational movements that can be performed resulting in nonalignment between Hall sensor and magnet;

assembly difficulty: it represents how difficult it is to set up data acquisition from the three sensor types. While strain gages require expertise to manipulate, to install and to have their signals conditioned, Hall sensors usually demand conditioning circuits and IR sensors' receptor can be directly digitalized.

5.2 Quantitative Comparison

The comparison results presented in this session are based on several measurements regarding the following characteristics:

- static and constant force;
- positive and negative displacements in relation to the steady-state position;
- the displacement dynamic cycle is a triangle waveform.

5.2.1 Measurement Function

This function is obtained by using both ascending and descending displacements. This function represents the output sensitivity to the input, where the input is the displacement (δ) and the output is the voltage signal value (V). This equations provide information about linearity, resolution and hysteresis.

When loading the data into a mathematical software, a graphical representation helps to estimate what is the best approximation for the function: linear, quadratic, exponential, sine waves summation or others. This procedure was done and yielded the best approximation curve for each sensor type, regarding the R-squared factor (R_{sqrt}).

- **Strain Gage** — linear — $R_{sqrt} = 0.9987$
  $V_{SG} = 0.01524 * \delta + 2.507$;
- **Hall Sensor** — quadratic — $R_{sqrt} = 0.9670$
  $V_{HL} = -2.840{*}10^{-5}{*}\delta^2 - 2.131{*}10^{-3}{*}\delta + 0.2001$;
- **Infrared** — quadratic — $R_{sqrt} = 0.9918$
  $V_{IR} = -4.937{*}10^{-4}{*}\delta^2 + 1.505{*}10^{-2}{*}\delta + 4.538$.

Some remarks about the low R_{sqrt} for the Hall sensor approximation are necessary. As it will be explained in Session 5.2.5, this sensor yields great hysteresis, i.e., it is possible to observe multiple parallel curves shifted from each other in relation to the δ axis. Therefore, although the Hall sensor has a better approximation considering each half-cycle separately (monotonic bending increasing), due to its hysteresis, the approximation tends to an average between the shifted curves. The best approximation curves for each sensor output are presented in the Figure 4.

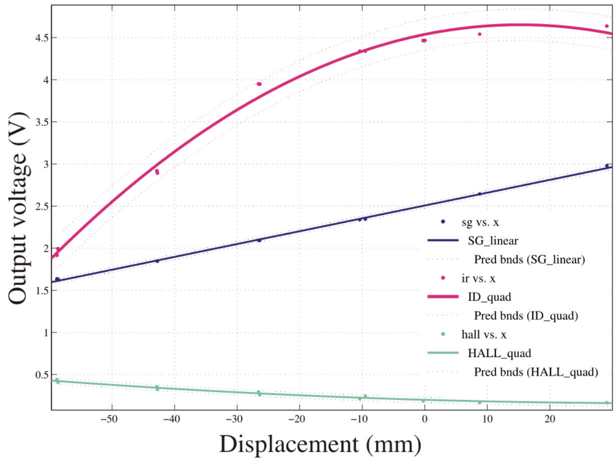

Figure 4. Best curve fitting for each sensor output

Both IR and Hall output response are non-monotonic, i.e., their output don't maintain a given order. Therefore, there is an ambiguity concerning displacements within the approximate ranges [0 to 30] mm for the IR sensor, and [-60 to -15] mm, for the Hall sensor, approximately (observe Figure 5). Unfortunately, this undesired condition is hard to compensate.

5.2.2 Linearity

A linear sensor output response is commonly desired for simplicity. A non-constant sensitivity along the measurement range requires a lookup table giving input and correspondent output values in order to obtain a verification curve. Unfortunately, usually it's hard to obtain a suitable control of the input to read as many points as necessary to obtain a reasonable error/uncertainty scenario.

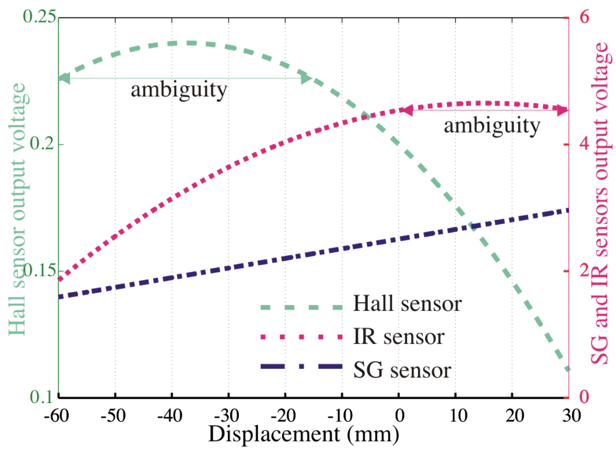

Figure 5. Quadratic Non-monotonic response of IR and Hall sensors

Fortunately, the measurement functions, once obtained by verification or calibration (better solution), can be loaded in the firmware (microcontroller) or in the real-time sound controller software.

As the actual measurements are taken in the analog domain where no correction is applied, it's possible to observe that, for the IR sensor, the output is noticeably less sensitive next to the steady-state position, as show in the Figure 5.

5.2.3 Sensitivity

As a consequence of the measurement functions, it's possible to calculate the sensitivity for each sensor technology. Figure 6 presents the sensitivity for the three sensor types, i.e. the amount of variation observed in the output (in V) when a unitary variation of displacement (in mm) is performed. As it is expected, the IR and the Hall sensor have a non-constant sensitivity across the measurement range.

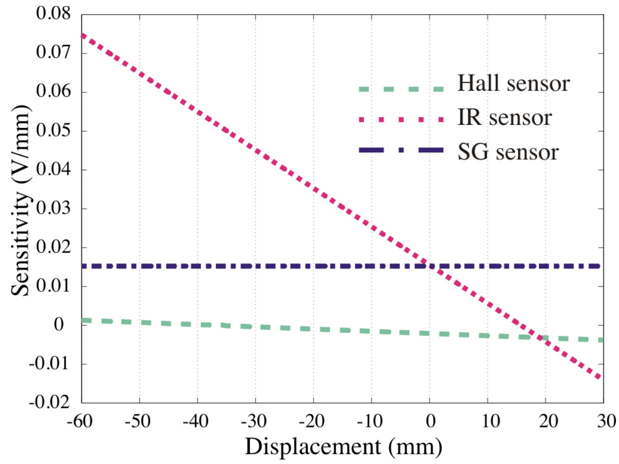

Figure 6. Strain Gage, IR and Hall sensor sensitivities across the measurement range

It's observable that depending on the beginning point for the displacement, the sensitivity varies for the IR and the Hall sensor, while the strain gage has a constant response across the measurement range. The IR presents a good performance concerning its sensitivity, especially within the range (-50 to 0) mm. Comparing the three sensitivities, the Hall sensor presents a poor sensitivity as its value is non-constant and it's the lowest one among the three sensor responses.

5.2.4 Resolution

The resolution indicates the "smallest change in a quantity being measured that causes a perceptible change in the corresponding indication" [13]. The following calculation is made based on the fact that the DMI will be connected to portable acquisition device whose analog to digital converter is, in general, not greater than ten bits resolution. High value for the resolution, i.e. a poor resolution means low value for the sensitivity. For example, the IR's low sensitivity within the interval (2 to 30) mm causes the IR sensor to have a worse resolution than the SG in this range. Figure 7 shows the resolution considering a 10-bit ADC computer interface. In order to better present this comparison, the lower graphic in the Figure 7 is a scaled version of the upper one, where just resolutions lower than 5 mm are shown.

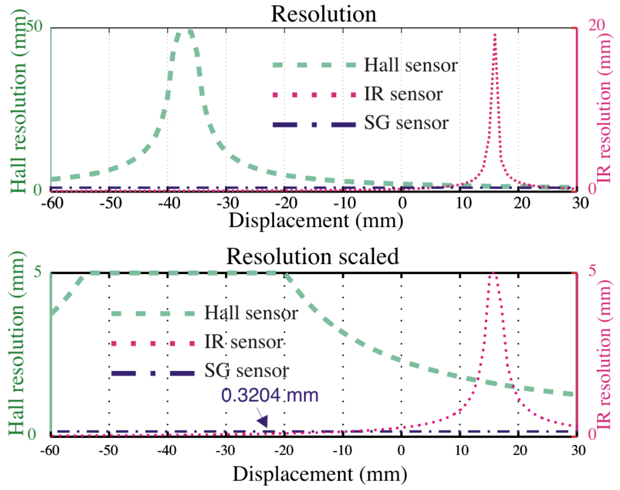

Figure 7. Strain Gage, IR and Hall sensor resolutions across the measurement range

5.2.5 *Hysteresis*

There are two hysteresis phenomena on this instrument. The first one is due to its mechanical conception causing the beam not to come back exactly to the same place when the force is relieved. This might be related to the poor affix at the fixed end and/or to the plastification of the beam's material. This problem is untreatable in this version of the instrument, demanding a new mechanical version with a clamped fixed end.

Below is represented the maximum hysteresis value ($\Delta\delta_{hist}$) for each sensor:

- **Strain Gage:** $\Delta\delta_{hist}$ = 1.01 mm ;
- **Hall Sensor:** $\Delta\delta_{hist}$ = 16.86 mm ;
- **Infrared:** $\Delta\delta_{hist}$ = 4.64 mm ;

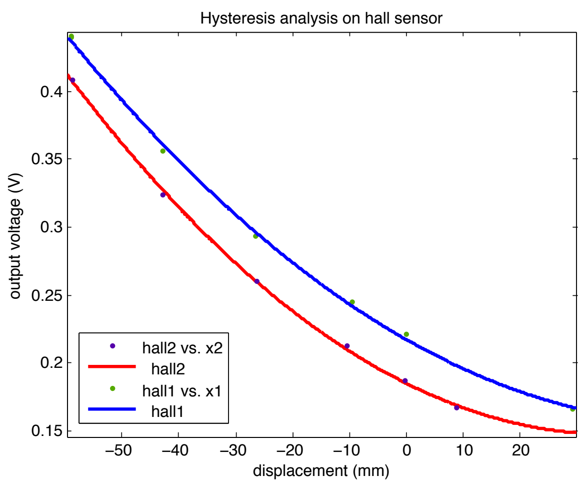

Figure 8. Hall Sensor Hysteresis Effect

The second one comes from hysteresis on the sensor operation. Different from the other sensor types, the Hall sensor presented a considerable hysteresis shift on its values (Figure 8). For calculating the maximum hysteresis value, the first and the last measurement points were disregarded.

6. DISCUSSION

After unveiling the characteristics of the three types of sensors and after comparing them,various parameters can be useful for sensor selection: responsiveness, robustness, price, availability, usability/complexity, compatibility to real-time and performance circumstances.

Concerning responsiveness, the main metrological indicator are the sensitivity and linearity. The IR sensor presents the best sensitivity over 75% of the measurement range, although this value is non-constant and decays drastically for small displacements. This implies that small performed vibrations and the damped oscillation of plucked movements are hardly sensed by the system resulting in poor possibilities of composing and playing under these conditions. The strain gage has a medium constant sensitivity over the measurement range, i.e its output is linear, while the Hall sensor has a small quadratic sensitivity. In terms of mapping sensor signals to control music, the non-linearity of Hall and IR sensor is a drawback as it requires algorithms to correct the output response and the ambiguity.

Referring to robustness, we have reports about the two first versions, based on IR and Hall sensors, given by technicians, composers and performers. When using Hall sensors, the mechanical design permits some translational movements that compromise the alignment between the magnet and sensor, changing the sensitivity. With IR sensors, they mention a strong interference of stage light on the response up to the point that it was necessary to cover the sensor area with a black fabric to diminish the problem. In the case of strain gages, we don't have substantial performance experience yet, but we can expect that some problems relating to connections and moving parts can occur and sensor and lead wires that are installed directed on the beam are subject to fatigue.

As IR and Hall sensors are more used on low-technology applications, they tend to have low price and good availability. Furthermore, they are straightforward to setup. The strain gages, however, present a high initial cost with accessories, tools and chemical products but the sensor itself is not expensive once one has all the materials for the application. The strain gages availability may also be an issue since they are sold directly by the manufacturer.

In terms of usability and complexity, strain gages are the most difficult to use, requiring some skills and special material to apply them to the instrument. The other two sensors, disseminate over both industrial and DIY contexts, are relatively easy to handle with. However, one should consider that for improving the performance of these sensors, some complex techniques of correction for linearity and ambiguity are required. Finally, these sensor should be carefully selected for a determined distance range.

7. CONCLUSIONS

As the hypothesis estimate and the qualifying test preview, strain gage sensors have a linear response that makes them an interesting sensing option for The Rulers. On the other hand, for large displacements the infrared sensor has a better sensitivity, but this behavior is undermined by its small sensitivity for small displacements and by its non-monotonic response. Finally, the drawbacks that exclude the Hall sensor as an optimal solution are its high hysteresis, wide ambiguity interval (non-monotonic) and low sensitivity, although they can be useful for measuring other distance ranges and for detecting movement directions. Ultimately, the selection should be done according to the composer and performer needs. After the comprehension of important characteristics of each sensor, this selection is easier and more conscious about the features, advantages and limitations of the selected method.

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8. REFERENCES

[1] S. Ferguson and M. M. Wanderley, "The McGill Digital Orchestra: An Interdisciplinary Project on Digital Musical Instruments," *Journal of Interdisciplinary Music Studies*, vol. 4, pp. 17–35, 2010.

[2] J. Malloch, D. Birnbaum, E. Sinyor, and M. M. Wanderley, "Toward a New Conceptual Framework for Digital Musical Instruments," *Proc. of the 9th Int. Conference on Digital Audio Effects (DAFx-06)*, 2006.

[3] A. S. Kobayashi, *Handbook on Experimental Mechanics*. John Wiley & Sons, 1993.

[4] J. Dias Pereira, P. Silva Girao, and O. Postolache, "Fitting Transducer Characteristics to Measured Data," *Instrumentation Measurement Magazine, IEEE*, vol. 4, no. 4, pp. 26 –39, Dec. 2001.

[5] D. Patranabis, S. Ghosh, and C. Bakshi, "Linearizing transducer characteristics," *Instrumentation and Measurement, IEEE Transactions on*, vol. 37, no. 1, pp. 66 –69, Mar. 1988.

[6] H. Erdem, "Implementation of Software-based Sensor Linearization Algorithms on Low-cost Microcontrollers," *ISA Transactions*, 2010.

[7] S. Khan, A. Alam, S. Ahmmad, I. Tijani, M. Hasan, L. Adetunji, S. Abdulazeez, S. Zaini, S. Othman, and S. Khan, "On the Issues of Linearizing a Sensor Characteristic Over a Wider Response Range," in *Computer and Communication Engineering, 2008. ICCCE 2008. International Conference on*, May 2008, pp. 72 –76.

[8] *Datasheet SS49E/SS59ET Series: Economical Linear Position Sensor*, Honeywell.

[9] "Hall Effect Sensing and Application," Honeywell, Application Note.

[10] E. R. Miranda and M. M. Wanderley, *New Digital Musical Instruments:Control and Interaction Beyond the Keyboard*. A-R Editions, 2006, iSBN 0-89579-585-X.

[11] R. Pallas-Areny and J. G. Webster, *Sensor and Signal Conditioning*, 2nd ed. NY, USA: John Wiley & Sons, 2001.

[12] P. Stein, "The Unified Approach to the Engineering of Measurement Systems for Test and Evaluation - a Brief Survey," in *Instrumentation and Measurement Technology Conference, 1996. IMTC-96. Conference Proceedings. 'Quality Measurements: The Indispensable Bridge between Theory and Reality'., IEEE*, vol. 1, 1996, pp. K1 –28 vol.1.

[13] *Vocabulary of Basic and General Terms in Metrology (VIM)*, Joint Committee for Guides in Metrology (JCGM) Std., Rev. 3rd, 2008.