Design of Low Cost Force Sensor System for Human Machine Interaction – Force Feedback Joystick

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Abstract—**The paper describes a low cost force sensor system ready to be evaluated in force-feedback joystick designed for a medical haptics application. It is based on low-cost parts from home appliance scale with strain gauge technology, and of-the-shelf IC instrumentation amplifier. The development process, electronic circuitry and designed software are presented. Experimental results give a good ground to believe that this approach can provide sufficient quality in further development of human-machine interaction algorithms.**

Index Terms—**Force feedback joystick, low cost design, strain gauges, software aided design.**

I. Introduction

FORCE feedback joysticks are well established as haptic interfaces [1]. Many studies have shown that force feedback can boost performance in various applications of remote control, steering, haptic tasks [1, 3], telepresence, etc. The fact that they are still not accepted when it comes to medical applications opens an issue of their redesign towards price cut, better algorithms, and better integrated drive electronics. In this paper we present a low-cost force sensor system based on strain gauges mounted on thin metal feet, integrated in a force feedback joystick that has a standard mechanical design. We discussed purposefulness of such approach in developing a low-cost laboratory setup for development, validation and verification in order to check if the solution meets specifications. Such system then can be used for further developments in haptic algorithms.

II. Global Overview of the Joystick

During development, the master device which process data and drives joystick is supposed to be PC. In order to cut the initial costs and increase flexibility in interfacing towards PC, Humusoft acquisition card MF624 was chosen. It supports integration into LabView, Matlab and Simulink. Global overview of the joystick system is shown in Fig. 1.

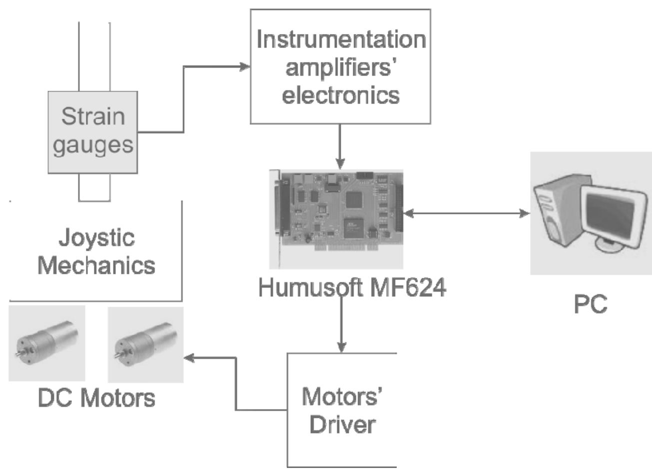

Fig. 1. Overview of the force feedback joystick system.

Mechanics is based on 2 dof gimbal mechanism [4].

Force feedback joystick is powered by two DC motors, producing 2 dofs at the handle. Due to kinematic properties of mechanism, the handle movements are produced by coupled movement of the two motor axes. That means that there must be defined correct kinematic transformation between the two sets of angles, internal, and external. Drivers for motors are currently being developed.

Four strain gauges of single low cost 20$ kitchen scale are used. Each strain gauge is already attached to piece of metal plate of T shape. Joystick handle consists of three distinct pieces, as shown in Fig. 2. The root of the handle is connected to the joystick mechanism. Upper part of two T plates is attached at the upper part of root of handle on opposite sides. Plates are aligned parallel to one another with strain gauges facing out. In that way bending of metal plates in one direction will produce opposite resistance changes of gauges and thus increase in overall sensitivity. Lower part of T plates is attached to short middle part of handle. Another pair of T plates is attached in similar manner but rotated 90° relative to the first pair of plates. In that way each pair of sensors will be used to measure bending force applied at handle for perpendicular axis. These axes will be called X and Y axis of

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joystick for further reference. The lower part of second pair of plates is attached to lower part of third part of the handle. This part is held in hand. In order to decrease torsion on handle, rotating cylinder is placed over this part of handle. Cylinder is coupled with handle via bearings.

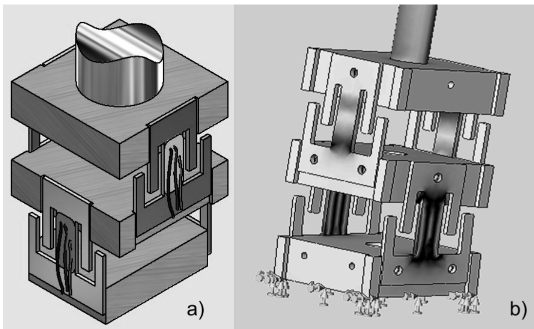

Fig. 2. Sensor plates' configuration on handle (a), with FEM analysis of stress under the force applied at the handle (b).

III. Electronics of the Sensor System

A. Sensors

Strain gauge used here is a strip resistor, where positive or negative change in length of strip resistor results in increase or decrease of its resistance. Similarly, change in width will produce the same effect but with opposite changes in resistance. Widening of strip causes resistance to decrease and vice versa. When attached to surface of object that can bend or stretch strip resistance will vary accordingly with deformation. If deformation is cause of some force applied to object then this force can be measured indirectly via change in resistance. Strip is usually pre-shaped in a specific way to increase its sensitivity. Usually it is zigzagged. Some shapes are better for particular applications than the others.

Temperature drift affect both, the object and the gauge. If the plate expands due to temperature it will stretch gauge and false readings could occur. Intrinsic resistance of strip is also temperature dependent. Therefore, special care has to be taken, possibly in two ways. Material of gauge can be chosen so that temperature deformation of object and intrinsic resistance temperature change cancel each other out. This is called Self-Temperature-Compensation or STC and is somewhat harder to achieve. The easier way is to use Wheatstone bridge. If two or all four resistors are under same temperature effect then differential result is almost unaffected.

Due to the fact the strain gauges came cheap, there is no datasheet available for them. Furthermore strain gauge on one metal plate is sealed with white glue and cannot be seen. Three connecting wires are only coming out of white goo. Cross resistance between each line was measured with multimeter. Resistance was approximately 500 Ω between two pairs and 1 kΩ between third pair. Therefore conclusion is that two 500 Ω resistors are connected in series and wires are attached to their common point and ends.

Since both resistors are from the same side of the metal plate it is highly likely that one resistor is used just for temperature compensation. That means that its resistance maintains unchanged with bending of plate. However, resistance does change due to temperature. Used alongside in Wheatstone bridge it will compensate temperature changes of resistance of the first resistor.

Another possibility is that the resistance of the second resistor changes with bending but in opposite direction than that of first one and thus increases sensitivity.

Changes in resistance due to bending are almost impossible to detect with multimeter. Hence, configuration of resistors was left unknown. Never the less application circuit of both configurations is the same, half bridge configuration. Since pair of T plates are placed in parallel, on each side of handle, to increase overall sensitivity then a full bridge strain gauge configuration is formed. This is shown in Fig. 3.

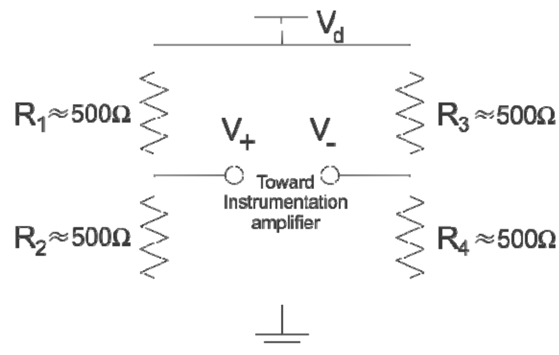

Fig. 3. Full bridge configuration of strain gauges of a pair of parallel plates.

Middle point voltages marked with V_+ and V_- are feed further to instrumentation amplifier. Differential voltage is expressed through equation (1):

$$V_+ - V_- = \frac{R_2 R_3 - R_1 R_4}{(R_1 + R_2)(R_3 + R_4)} V_d$$
$$V_+ = \frac{R_2}{R_1 + R_2} V_d \qquad V_- = \frac{R_4}{R_3 + R_4} V_d . \tag{1}$$

As previously mentioned, resistor values are almost equal, $R_1 = R_2 = R_3 = R_4 = R = 500\ \Omega$. Maximal difference between resistors is less than 1Ω. Later on with fine tune offset calibration it was estimated at about 0.1-0.2 Ω.

In the case that one resistor is for force sensing and the other is just for temperature compensation the resistor values R_1 to R_4 are given with set I) in (2).

$$\begin{array}{ll} \text{I)}\ R_1 = R - \Delta R + \delta & \text{II)}\ R_1 = R - \Delta R + \delta \\ R_2 = R + \delta & R_2 = R + \Delta R + \delta \\ R_3 = R + \Delta R + \delta & R_3 = R + \Delta R + \delta \\ R_4 = R + \delta & R_4 = R - \Delta R + \delta \end{array} . \tag{2}$$

ΔR represents change of resistance due to physical deformation of the resistor. It is assumed that change of R_1 and R_3 is approximately equal in amount, but different in sign of course. Influence of temperature is represented with δ and it is also assumed that it is same for all resistors, what is fairly truthful. If values from I-(2) are substituted in (1) then the differential voltage becomes:

$$V_+ - V_- = \frac{\frac{\Delta R}{2R\left(1+\frac{\delta}{2R}\right)}}{1-\left(\frac{\Delta R}{2R+2\delta}\right)^2} V_d \,. \tag{3}$$

Since $\Delta R/(2R)<10^{-3}$ then $(\Delta R/(2R))^2<10^{-6}$. This means that denominator in equation (3) is almost 1. Consequently the differential voltage is defined with:

$$V_+ - V_- = \frac{\Delta R}{2R\left(1+\frac{\delta}{2R}\right)} V_d \,. \tag{4}$$

In the case that both resistors are used for sensing purposes then resistor values R_1 to R_4 are given with set II) in (2). By substituting these in (1) one gets the expression (4). Therefore, (4) represents the differential voltage for the second case of resistors configuration. This proves previous claim that no datasheet is necessary for kitchen scale strain gauge sensors to be used, as it results in same application circuit.

Most of the strain gauges are made of constantan (Ni 45%, Cu 55%, usually) alloy [2]. This material is relatively cheap and has several good qualities [2, 5]:

- Fairly good sensitivity or gauge factor of 2±0.1.
- Low, negative temperature coefficient of approx. 10 ppm/°C at about 20 ºC.
- Self-temperature compensation is easily achieved.
- Non-linearity of less than 10^{-3} for $\Delta\ell/\ell < 10^{-3}$.

Having in mind that device will be used for medical purposes where room temperature range will be 25±15 ºC. Therefore, temperature change δ will be at most 0.015% of resistance value R, or 0.075Ω. Since $\delta/2R$ is less than 10^{-4} the nominator in (4) can be rounded up to $2R$.

Mismatch in resistor values do affect gain and offset but linearity is affected with just 10^{-4}.

B. Electronic

Schematic diagram of sensor's system electronic is shown in Fig. 4. Supply voltage for strain gauge is 5 V. This voltage was chosen for two reasons. It is low enough not to cause heating of resistors and big enough to give moderate differential voltage. Instrumentation amplifier used for amplification of differential voltage has CMRR of min 100dB allowing single supply voltage to be used for strain gauge.

It was estimated that differential voltage is in range of much less than 1mV. The target voltage is ±9 V since full voltage input range for Humusoft ADC is ±10 V. Desired gain was first estimated to be close to 10000. Further experiments showed that the desired gain should be 1776 for X-axis gauges and 1826 for Y-axis gauges. Difference in gains is due to slight difference in levers for these two sets of sensors. Used instrumentation amplifier AD620 has nicely programmable gain G selection with one resistor Rg, with dependency given with (5). Since single standard resistors were used to set gains, precise desired gains could not and did not need to be achieved. However, PCB was designed so that two parallel resistors, RgpX and RgX for X axis amplifier, and RgpY and RgY for Y axis amplifier, can be used for more accurate gain selection. That is why RgX and RgY have no values in Fig. 4. Standard resistance that achieves closest gains to desired ones is 27 **Ω**. The gain is then 1830.

$$G = \frac{49.4k\Omega}{R_g} + 1 \tag{5}$$

Advantage of using integrated instrumentation amplifier, like AD620, over a discreet one that consists of three operational amplifiers, is save in time and money.

During the testing it was noticed that there is high noise on ±12 V output power supply lines of Humusoft MF624 acquisition card. Variations in voltages of about 100 mV in average also would occur whenever acquisition process was started. Since the same voltage supplies AD620 and gain has to be high, there were a lot of variations in output signal of amplifier even if no stress was applied on sensors. Therefore, additional voltage regulators for ±10 V had to be used. Although voltage regulators did the job there was still a lot of noise coming out from environment. It was introduced through the long cable connecting acquisition card and sensors electronics board. Noise level was at about 5 to 10 mV even after moderate digital signal processing. Digital filter is supposed to be of moderate processing length since it is to be implemented later on in microcontroller, and since moderate latency is acquired. Therefore, cables were replaced with shielded audio ones and kept at minimum of about 1.5 m in length. That lowered the noise level down to 15 mV in average before digital filtering and below 1mV after digital filtering.

Since there were slight mismatch in resistors that lead to almost 2 V of amplified signal offset, additional offset regulating resistors had to be inserted in series with gauge's one. It was deduced from experiments that one strain gauge has slightly higher mismatch with other strain gauges. It could be possible that during phase of holes drilling by electrical discharge machining in metal T plates, it was strained or damaged by heat. Other possibility is that it was just production variation. No matter the reason, resistor had to be placed to lower the offset for one axis. Since mismatch is only about 0.1 to 0.2 **Ω** multi turn trimmer of 10 **Ω** were used. As it can be seen in Fig. 4, two trimmers per sensor set were used for two reasons. Firstly, with small turns, big jumps in trimmer resistance occurs when near zero resistance is desired at trimmers. Even in 25 turns trimmer. By adding extra offset with second 15 turn trimmer, of about 0.3-0.5 **Ω**, a more precise offset cancelation was achieved. Trimmer with lower numbers of turns are cheaper and could be used for this trimmer. Second reason is that flexibility is made due to no special attention to strain gauge placement is needed. Also this is the reason for placing the other pair of trimmers for the second axis' gauges. Besides, the second pair of trimmers was used to lower small offset of 0.5 V in amplified voltage for second axis. It was not really necessary and could have been removed after the software calibration.

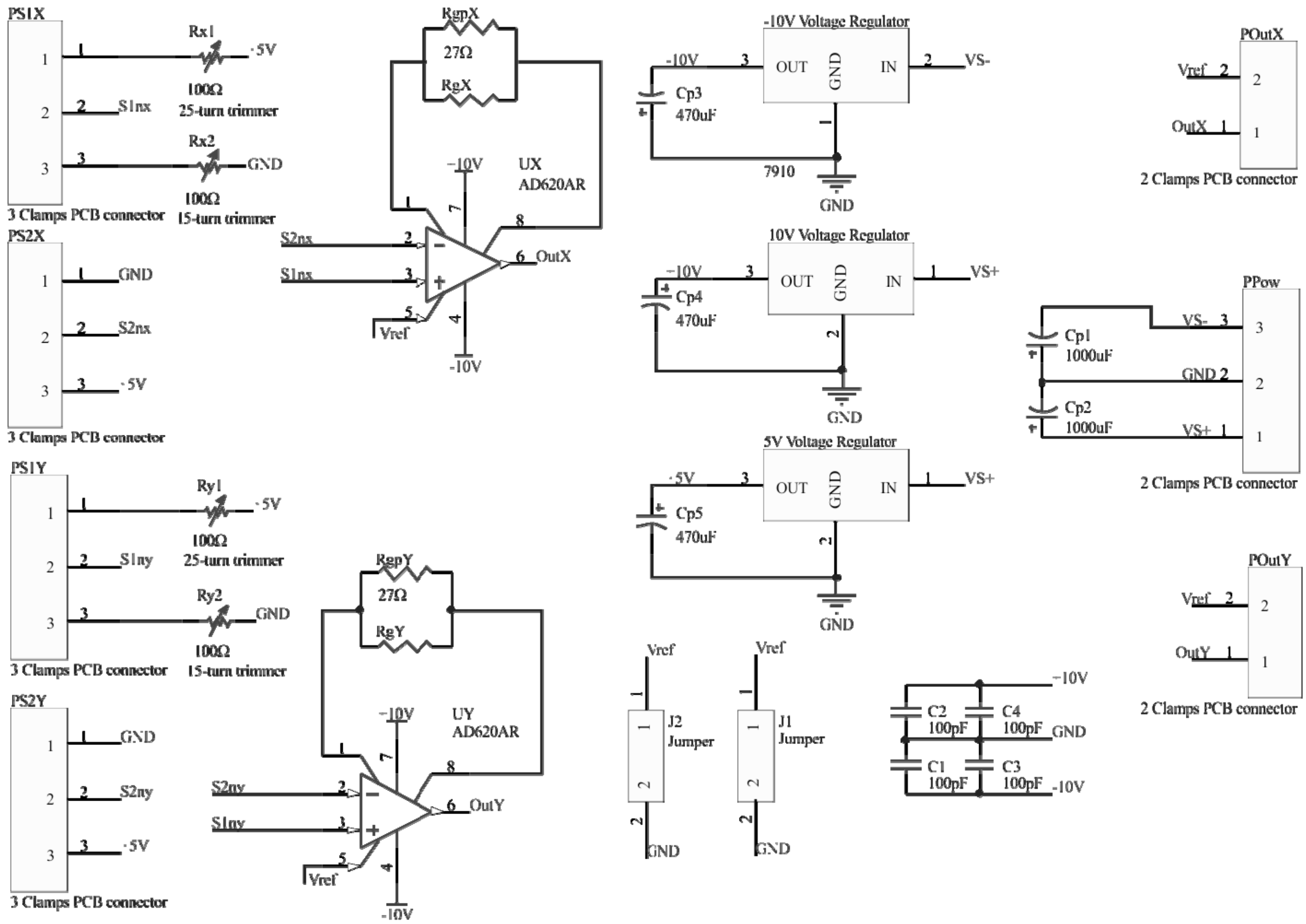

Fig. 4. Schematic diagram of sensor's system electronic.

I. Measurement

A. Setup

Matlab and Simulink software are used to collect data from Humusoft card. Simulink and Real Time Windows Target were chosen for data collection and processing, and control for force feedback joystick because they offer a flexible framework, easy programming, and C code generation for later uses. Besides, Matlab Virtual Reality Toolbox is planned to generate data for later simulation and testing of force feedback joystick.

Digital filter processing is needed to remove intrinsic resistor noise and EMI. Since both of these noises were unknown until completion of electronic and tasting, GUI based digital filter processing and implementation tool was designed in Matlab. Main task of this tool was to:

- acquire various length of data and truncate initial values,
- show graphically acquired data and its spectrum,
- design filter block for Simulink model and test it by filtering acquired data,
- view graphically filtered data and its spectrum,
- implement designed filter block into Simulink model for calibration, and control.

For calibration purpose a GUI based tool was designed that:

- acquire data for both axes,
- truncate variations induced by filter; initial conditions are all zeros which will create sort of step input data,
- finds mean value for truncated filtered data and maximal deviation,
- stores data for force of various intensity and direction applied on handle in table, that can be saved in excel document,
- it presents results for various force measurements in a concise and informative manner.

Since no precise force reference was available, the testing and calibration method was then based on gravity force and known weights. Handle was screwed tight at the end of horizontal threaded rod, as shown in Fig. 5 and 6. Arrow pointer, made from bended sheet of metal, was put on to rod and fastened with two nuts. The rod was placed through hole of vertical wooden plate. It was fastened with nut from handle side of wood and with butterfly nut from the other side. By using butterfly nut, for easy loosening and tightening, rod can be easily rotated horizontally. From the front side of the wooden plate, as marked in Fig. 5, a radial scale was attached. Scale has lines radiating from the rod's hole. Solid lines mark 10° increment. Dotted lines mark 5° increments in between of solid ones. In this way the pointer rod can be rotated at 5° and 10° increments with estimated precision of ±1°. Vertical wooden plate is attached firmly to horizontal one that has counter weight at opposite end. Since no upper part of handle had been made yet a screw was screwed at the most upper T plate holder. Weight was hanged via string to this screw. Aware of change of lever and thus the moment, weight was increased proportionally. The desired maximal weight to be measured was 2 kg at the center of handle. Equivalent to this is approximately 4 kg at the screw.

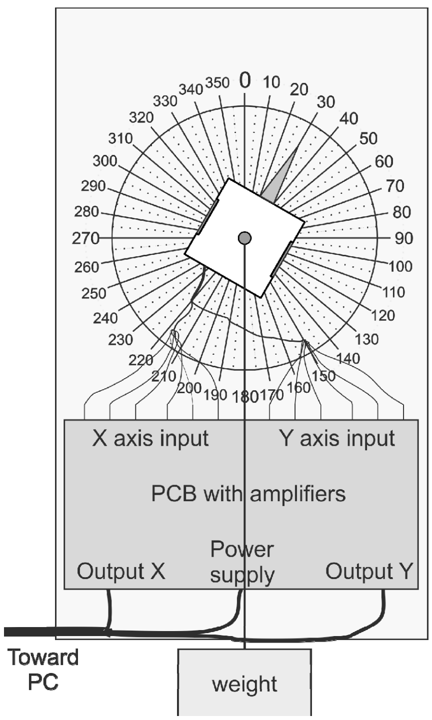

Fig. 5. Testing and calibration setup's front view.

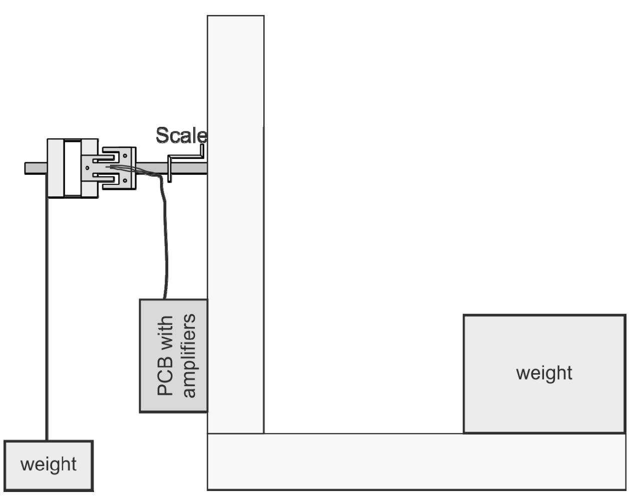

Fig. 6. Testing and calibration setup's side view.

The sling was made as short as possible. Unfortunately, even small oscillations were detected. Long settling times were required especially for heavier mass. Settling time for maximal mass of 4 kg was about 5 min in average when careful rotation was done. So the data set for calibration was planned with awareness of long waiting time. Nice linearity was already observed in the phase of electronics testing. Having that in mind it was estimated that only 4 distinct weights were good enough both for calibration and testing. Although nice sinusoidal characteristic for angular change in force was noticed angle in increments of 10° were chosen in order to achieve better visual effect of plotted data, and accuracy as well.

B. *Result*

Graphical representation of some of the measured data is given in Figs 7 and 8. The linearity of data is almost perfect for a set of masses at constant angle. Angle is measured between vertical axis and the scale's arrow in clockwise direction. For example, 0° is equivalent to maximal force on Y axis and no force on X axis. Sensor's voltage for both axes, for reference angle of 0 degrees and weight set of 0, 0.5, 1 and 4 kg, are shown in Fig. 7. This data set is characteristic. It clearly shows that angle offset exist for X axis. The same applies for Y axis.

Also, nice sinusoidal result can be seen for constant mass and angles varying from 0° to 350°. One set of sinusoids for weight of 1 kg is shown in Fig. 8. A plain sinusoid was fitted in X axis sinusoid from Fig. 8. Difference between measured data and fitted sinusoid is shown in Fig. 9. Since majority of values from Fig. 9 are below zero it can be deduced that beside angle offset there is a DC offset as well. Same procedure proves existence of small Y axis offset.

C. *Sources of errors*

Further data analysis is on the way. Even now we know some apparent source of errors that can be removed if measuring setup is enhanced. For instance some slight bending of rod was detected when heavier masses were applied. This will cause nonlinearity in mass-voltage characteristic. This error can be removed if vertical wooden plate is replaced with metal one with tighter hole, and if the rod length is shorten. Also the vertical plate was not ideally parallel with vector of gravity force and sometimes it moved a little because it was not firmly fixed. So with little more time and money accuracy of system can be enhanced. However for now we assume that hand tremor will produce more noise than the current level of accuracy. Much in the same way the pendulum had affected the measurements.

To sum up, most of our error sources can be removed, although it is not currently needed, since we achieved what we desired.

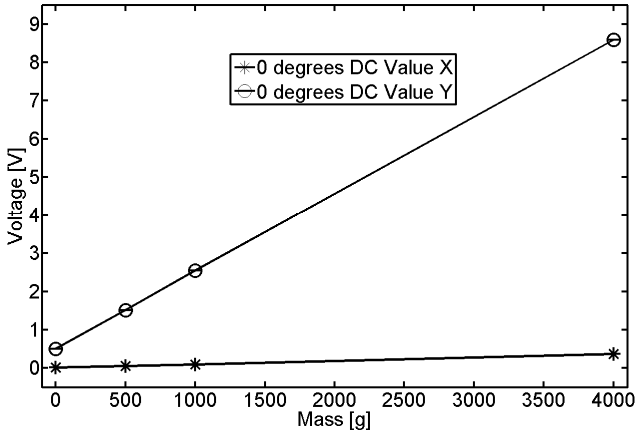

Fig. 7. Sensor's voltage for 0 deg and 0, 0.5, 1 and 4 kg of weight.

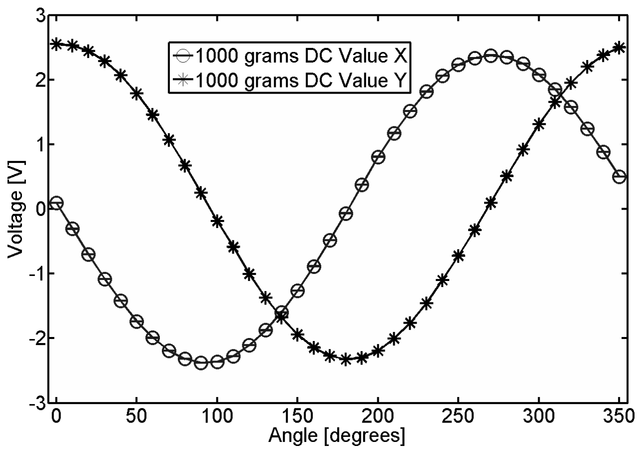

Fig. 8. Sensor's voltage for 0° to 350° and 1 kg of weight.

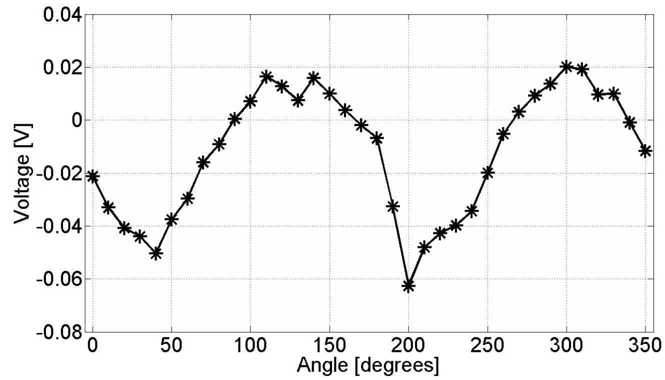

Fig. 9. Difference between measured X axis data from Fig. 8 and plain sinusoid fitted into it.

II. CONCLUSION

Design of inexpensive force sensors system to be used in feedback joystick for medical applications is discussed in the paper. We showed that it is possible to make a force sensing system out of a low-cost kitchen scale strain gauges. Visual representation of measured data showed that notable linearity is acquired. For constant force direction change from 0° to 350° sinusoidal voltage dependency occurs. Further data analysis is currently on the way. Calibration models are being further improved. Although we obtained promising results it was not our intention to replace high quality sensors available on the market, like ATI automation's f/t sensors. They are able to measure force and torque in 3 axes with great precision but due to the silicon strain gauge technology, they cost a fortune. Solid precision sensors for measuring force in 2 axes are acceptable starting solution in force feedback joystick for remote simple medical procedures that require only rotation of the tool.

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