Neck Injury Diagnostic Device

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***Abstract*—The paper describes a method of automating a medical study of cervical spine condition with use of MEMS inertial sensors and a magnetometer. The examination procedure aims to detect and assess the dysfunction of the cervical spine. The same exercise may be also used for rehabilitation.**

***Index Terms*—neck injury, cervical spine, diagnosis, treatment, rehabilitation, MEMS, gyroscope, accelerometer, inertial sensor, angle measurement, laser pointer**

I. INTRODUCTION

THE test was originally performed by attaching a laser pointer to the patient's head, and observing how he follows the defined shapes with a laser spot. The diagnosis is based on the scope, dynamics and precision of the motion that the examined is able to perform with his head.

In the proposed method the cursor is displayed along with the shapes required for the study using a multimedia projector. Because both, the spot position and the geometry of the displayed paths are stored in computer memory, it is possible to quickly and accurately determine their relation, detect any excesses and evaluate their features.

The measuring device is attached to the patient's head. After the start of the study, it tracks its own position with the use of integrated sensors of the linear and angular acceleration. Using information from the sensors, the computer determines the head position which is then used for calculating position of the displayed virtual laser spot.

II. THE EXAMINATION PROCESS

A. The Former Procedure

The traditional method of examination requires attaching a laser pointer to the patient's head, which is done by using fixture based on tightly fitting ear protectors. The examined sits in the front of a white screen with several color shapes drawn on it – the setup is outlined in the Figure 1. The medicine doctor observes how fast and accurately the patient follows the shapes with the spot of the laser. This method requires doctor to stay strongly focused for about ten minutes, during which he assesses the quality and time of completion of subsequent tasks.

Reduction of human engagement in the process of data acquisition should make the assessment more precise and repeatable. Estimation of the accuracy, with which the examined is able to operate the spot, evaluation of the scope of the screen that the patient is able to reach and time measurement are tasks, that are proved to be successfully performed by the computers. Moreover, the digital storage of the results will in the future facilitate tracking progress in rehabilitation and will help design new exercises tailored to the individual patient's needs.

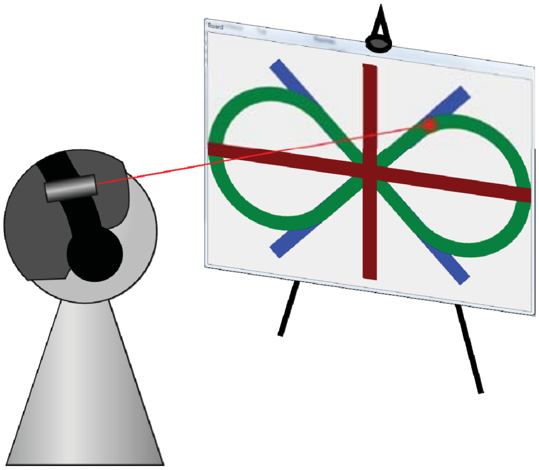

Figure 1. Former examination procedure.

B. Requirements for Automated Test

The measurement method has to fulfill several types of constraints, these are: accuracy, bandwidth and reproducibility of results. All these fields were initially discussed with medical doctors.

The measurement setup is expected to achieve the resolution of about 1 mm with patient sitting or standing about three meters away from the screen. The desired accuracy is hence similar to one achieved by a person observing the screen during the original examination procedure.

The typical man is able to perform up to about 15 cycles of tensing and relaxing of skeletal muscles per second [1]. The people training the same move on a daily basis may double or even triple this value, but such a situation may be neglected in case of the head. However, hence the movements are generally nonlinear several higher harmonics shall also be taken into account. Inclusion of first three harmonics implicates sampling rate reaching about 90 measurements per second (to fulfill Nyquist equation for three first harmonics of body part moving with 15 Hz fundamental frequency).

The device shall not indicate a drift of the pointer larger than 2 mm during a 10-minute time period of being at rest.

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C. The Proposed Measuring Method

The adopted approach is founded on the assumption, that it is possible to calculate the laser pointer location on screen basing on the limited knowledge of patient's head position – see Figure 2 for reference. The task could be easily accomplished if the head position (three coordinates) and angles (at least two) in relation to the screen would be known with appropriate accuracy. The problem could be then brought to projection of a point on a plane along a predefined line.

In practice the precise measurement of an actual head position is complicated and the applicable techniques are expensive. Therefore, the proposed system shall be able to operate without obtaining those parameters directly. The measurement of angles is more straightforward, as there are numerous sensors available, that can directly or indirectly provide the elevation and heading angle.

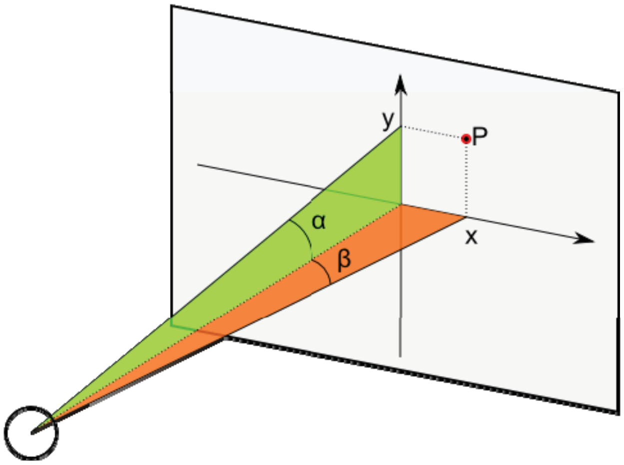


Figure 2. Spot projection on the screen.

A convenient way to measure the required angles is to fix a device with sensors to the patient's head, in the same manner as the laser pointer was originally mounted. Measurement of the elevation angle (labeled α in Figure 2) is relatively simple as it requires only determining the direction of the Earth's gravitational force vector in the coordinate system of the device and thus the head. The market available inclinometers, sensors dedicated for this measurement, are relatively expensive. Alternatively, the α angle can be determined using accelerometer accompanied with angle computation procedures implemented in the software.

The measurement of rotation in the horizontal plane (β) cannot be done analogically, as the g-force vector is constant during such a movement. Apart from the gravitational, the Earth is also a source of magnetic field, which might be used to determine the patient heading with the utilization of magnetometer. Unfortunately this field is very weak and the local induction vector depends heavily on the nearest environment. It can vary significantly even in the short term observation, for example due to operation of nearby electrical appliances. The system could never fully rely on the magnetometer readouts.

Another method of determining both angles is the measurement of angular velocities of the device using a gyroscope. Integrating these will directly lead to the angle values. This method is simple, but have several important drawbacks. Any sensor error will be integrated over time causing constant drift of the angle value. Moreover, the integration constant is not known in advance. Nevertheless, the gyroscope is more reliable than the magnetometer and it is utilized in the proof-of-concept device. Both of the problems indicated above had to be solved to take the full benefit of this sensor's features.

The drift of calculated angles can be significantly reduced by calibrating the sensor before the examination. The system can determine the constant component continuously present on gyroscope outputs and cancel it out during the actual measurement. The calibration values are expected to vary with temperature, hence the sensors are equipped with thermometers. The possibility of thermal compensation has not been explored yet.

The chosen method of calculating the integration constants is to instruct the patient to move the laser spot to the point on screen which coordinates are well known. Then, the angle values can be calculated by reversing the projection process. When the examiner indicates that the laser pointer met the designated coordinates, the software stores the determined angles as sought constants and restarts the integration process.

To obtain pointer position in screen coordinates, the pair of angles has to be projected on screen. This is usually done with use of basic the trigonometric functions and constructs. To calculate the patient's head position an approach with pointing markers of known position could be used. Preparing an initial software revision this relatively complicated procedure was substituted with much simpler solution. Assuming that the measured angles are relatively small, the y and x coordinates may be considered as directly proportional to the corresponding angles α and β. To account for possible skew of the screen in relation to the measuring device, the projection transformation should consider the influence of each angle on each planar coordinate. To simplify the device calibration, the integration constants were also composed into the projection procedure as constant offsets.

Assuming the mentioned simplifications, the projection procedure may be realized as simple matrix multiplication of the following form:

$$\begin{bmatrix} m_{xx} & m_{xy} & m_{x1} \\ m_{yx} & m_{yy} & m_{y1} \end{bmatrix} \cdot \begin{bmatrix} X_{in} \\ Y_{in} \\ 1 \end{bmatrix} = \begin{bmatrix} X_{out} \\ Y_{out} \end{bmatrix}, \quad (1)$$

where the Y_{in} and X_{in} are the α and β angles.

The described projection implementation was intended to be temporary, which should be corrected just after the application would become functional. Unexpectedly, this solution seems to be accurate enough for system evaluation purposes and initial tests on patients. There is a visible deviation between laser pointer and the simulated pointer when performing moves after which the assumption of small angles is not proper and after fast moves that can exceed the sensor full scale range. Nevertheless, when not leaving the operational area, the simulated pointer behaves as the brain would expect it to, thus the application is functional enough to guide the patient to perform a set of predefined moves.

The projection matrix from equation 1 has six elements that have to be determined during calibration. In order to unambiguously compute the *m* coefficients, a set of at least six independent equations is required. Such a set is obtained, by requesting the user to point the laser pointer at three nonlinear points on the screen. Since all the X_{in}, Y_{in}, X_{out}, Y_{out} variables are known during this process, three independent equations of the form shown above may be formulated. The resulting determined system of linear equations is then solved, in particular using the Gaussian elimination method.

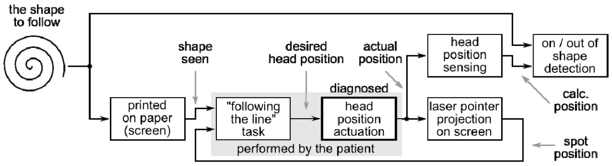
D. The Feedback Loop

The device is not accurate enough to precisely compute the laser pointer position over longer time. The improvements in algorithms (projection, more advanced tracking of device position, Kalman filtering) can eventually increase the accuracy.

This problem is not as significant as it may seem. The small offsets and drifts are not really important in this examination. In the opposite case the patient's head would have to be thoroughly aligned with the screen, his posture fixed and the laser tightly coupled mechanically to the body. The essential aspects are the dynamics, the quality of reproducing momentary movements, the detection of any lapses and measurement of their amplitudes.

A feedback loop is naturally present in this examination. In the case of traditional test procedure, the loop is formed by the patient observing the screen and trying to actuate his head to follow the shape – see Figure 3 part a) for reference. In the referenced sketch, the system is already extended by adding a measuring device and a block comparing the pointer position with the selected shape. Apart from the possible neck dysfunction, there are two main sources of deviation in such a system. Firstly, the desired shape has to be printed on screen and its accurate position relative to patient should be determined to account for every possible geometrical distortion. Secondly, any sensing device error would be superposed on the calculated pointer position, beyond the possibility of any automatic correction.

a) The case with paper printout and no multimedia projector:



b) The proposed method with multimedia projector:

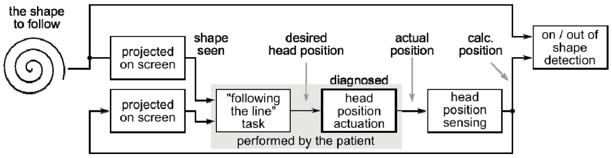


Figure 3. Two of the possible feedback loop structures.

To compensate the device inaccuracies, the sensor should be included in the feedback loop. To achieve this, its output signal has to be provided back to the patient. The proposed method, is to use the multimedia projector, which would cast the calculated pointer on screen (the real laser should not be enabled then). This approach has a very valuable advantage - the shape for patient to follow may also be displayed by the projector. During casting it will experience exactly the same geometrical distortion as the pointer spot, effectively compensating any projection shortcomings. Moreover, using projector enables for designing custom shapes for individual patient needs. Finally, hence both the shapes and the pointer position are stored in the computer memory – their relation to each other may be easily and precisely determined.

E. The Examination Setup

The complete setup is depicted in Figure 4. The actual laser is still needed for calibration purposes, but is turned off during the examination. Assuming the hospital has a presentation PC with projector it only need to invest in a device worth about $50 in components.

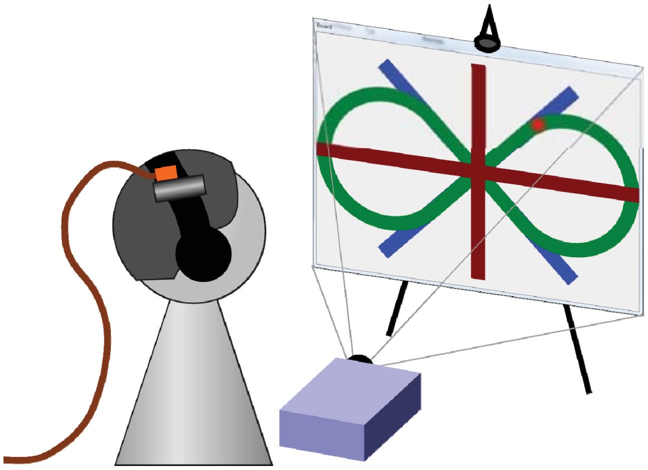


Figure 4. The proposed examination scheme.

F. System Concepts Summary

In the designed solution a small device with a gyroscope, accelerometer, magnetometer and laser pointer is fixed to the head of the examined. The sensors gather the information on the elevation, angular velocities of the device and magnetic field lines direction, hence determining the head's position. The shapes and calculated pointer are casted on the screen by means of standard multimedia projector. Before the examination, the system has to be calibrated to account for the change of examined position and location of the screen.

The computer, which coordinates the system, easily obtains the information on the actual spot position in relation to displayed shapes. Since no exhaustive computations are needed, a typical office PC performance is more than sufficient.

III. THE MEASUREMENT DEVICE

A. *Initial Considerations*

The sensors box has to be small enough to be mounted on the frame of ear protectors. It should contain the laser pointer on-board and the pointer should be enabled/disabled automatically.

The device should be as light as possible and the cabling should not limit the patient movements in any way. The wireless operation was considered but finally dropped. It would require costly radio module, define additional requirements of the computer and increase the mass due to need for battery, which would be the heaviest component. Due to high popularity and more than sufficient throughput the USB 2.0 standard was chosen for both data link and power supply.

According to the earlier considerations, the device should have the resolution of 1 mm with patient located 3 meters away from the screen. Calculation of the appropriate arctangent reveals that the angular resolution should be of about 0.00033 rad (0.02°).

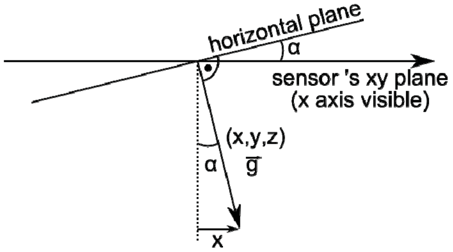


Figure 5. The g vector in sensor’s coordinates.

The system calculates the elevation angle using components of the measured acceleration vector:

$$\alpha = \arcsin\left(\frac{x}{\sqrt{x^2 + y^2 + z^2}}\right). \tag{2}$$

The meaning of the variables is explained in the Figure 5. Assuming the patient’s head is located at about the level of the screen’s center, the elevation angle should be relatively small and the linear approximation of arcsine might be used:

$$\alpha \approx \arcsin(\alpha). \tag{3}$$

Due to the linearity of the above equation, the same relation is true also for deltas:

$$\Delta\alpha \approx \arcsin(\Delta\alpha). \tag{4}$$

Moreover, assuming that during examination the patient is at rest (or at least not accelerating), the value of denominator in equation 2 should be approximately equal to g:

$$\sqrt{x^2 + y^2 + z^2} \approx g. \tag{5}$$

Basing on equations 2, 4 and 5 the following approximation can be derived:

$$g \cdot \Delta\alpha \approx \Delta x. \tag{6}$$

This leads to conclusion, that the accuracy of x measurement has to be of the order of 0.0003 g. Most acceleration sensors offer a mode of measuring accelerations in a ±2 g range (for a total of 4 g for a full scale resolution). The relative accuracy of such a sensor has to be about $8.3 \cdot 10^{-5}$, which corresponds to resolution of roughly 13.5 bit. Concluding, at last 14-bit accelerometer has to be used.

B. *The Proof-of-Concept Hardware*

To test if the proposed solution can be implemented successfully a prototype sensor board, codenamed GyroAccel, was build. The device, pictured in the Figure 6, is fitted into the case of the small flashlight. It features 8-bit accelerometer, 16-bit gyroscope (250 °/s range [2]), laser pointer and two user accessible buttons.

Figure 6. First prototype: GyroAccel v1.

The device has proven that the idea is useful for the patient examination and encouraged for further development. The main disadvantage of the first prototype is too low resolution of the accelerometer.

To accommodate for the sensor of higher resolution, second version of the board was designed and manufactured. Unfortunately, due to not careful enough study of the documentation of the new accelerometer, this version also have not reached the required level of accuracy - the actual resolution was much lower than the marketed readout register size.

The third prototype, pictured in Figure 7, was first to achieve the expected resolution. The chosen sensor offers 12-bit readout refreshed up to 800 times per second [3]. By utilizing the oversampling technique the sensor provides a 14-bit result at the satisfactory rate. The calculation of the two least significant extension bits requires acquiring 16 samples from the device, which results in the overall speed of 50 measurements per second [4]. This sensor is not required to operate at 90 samples per second, because it is mostly responsible for providing heavily low-pass filtered reference signal. The high-pass component is supplied by the gyroscope.

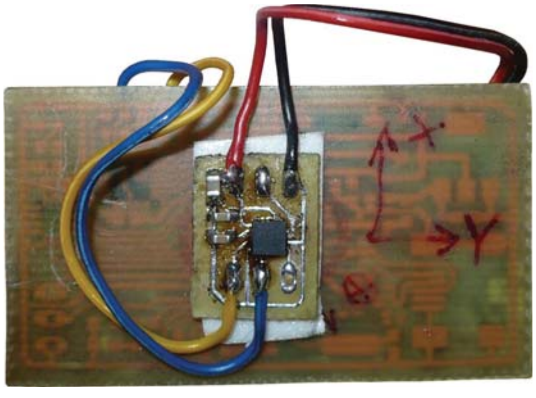


Figure 7. Third prototype, new accelerometer on top.

The schematic of the final revision, v4, is heavily based on the previous prototype. Minor improvements were made, the board have been redesigned to adopt for the new accelerometer and to fit in much smaller case, along with the complete laser pointer assembly – see the Figure 8.

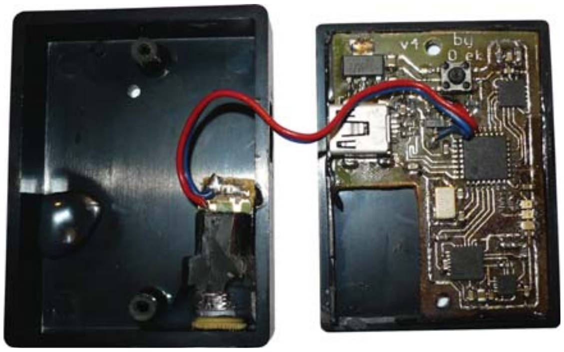


Figure 8. The final device integrated with laser pointer.

All the prototypes are developed around ATMEGA32U2 microcontroller from ATMEL. It is an affordable 8-bit core processor accompanied with 32 KiB[1] of FLASH memory, 1 KiB of RAM memory and a rich set of peripheral circuits. It has an embedded USB 2.0 Full Speed compatible controller. The microcontroller interfaces accelerometer and magnetometer with an I^{2}C compatible two wire interface and the gyroscope using four-wire SPI bus.

IV. THE DATA PROCESSING

A. *System Outline*

The hardware part of the system captures the data from the physical sensors and realizes oversampling required for obtaining valuable accelerometer readout. Packets, containing the values read from gyroscope, accelerometer and magnetometer are transferred through the USB pipe. The computer receives the data stream of the inertial sensors and passes though the calibration module. The magnetometer's data stream is also extracted, but in the current software revision is not used.

The accelerometer data are used for calculating the absolute elevation angle using arcsine. The output from gyroscope, is integrated to obtain values of rotation in vertical and horizontal plane. If no calibration would be done before, the DC component of integrated signal would lead to a drift of the calculated angles.

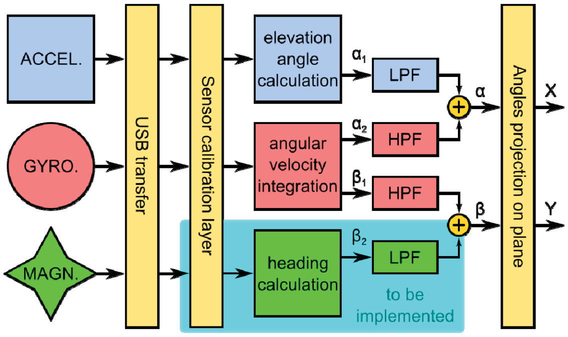


Figure 9. The data processing scheme.

The β coordinate is currently obtained directly from the integrated angle value. The α coordinate is composed of data coming from both gyroscope (accurate deltas, fast response – high-pass filtered) and accelerometer (absolute angle value, low-pass filtered). See Figure 9 for the process outline. The calculated α and β values are finally passed through the perspective correction and are used for drawing the simulated laser pointer on the screen.

B. *Microcontroller Software Design*

The economic one-sided PCB design process has put several constraints on the microcontroller I/O usage. The SPI lines had to be routed through some other pins to be able to reach the dedicated lines of built-in SPI block. Furthermore, the microcontroller does not offer a hardware support for the I^{2}C protocol, hence the software solution was adopted.

The complete USB device stack is provided by ATMEL for free, even for commercial applications. Unfortunately, the *AVR USB Series2 software library template* had had a number of errors at the time of writing the firmware. The author documented steps required to use this library both under GNU/Linux and under Windows in a dedicated website [5].

The application sets the accelerometer for the 800 Hz operation. It collects all the readouts and averages them appropriately to obtain the 14-bit result out of 12-bit samples. The gyroscope and magnetometer readouts are also acquired and complete matrix of nine 16-bit values is stored in the local FIFO. When the USB controller receives a read request form the host, the data are passed to the USB endpoint buffer and marked for transmission. The communication is done using bulk transfers [6].

The device firmware may be upgraded easily, as the microcontroller is equipped with an USB boot loader. The upgrade feature is activated after pressing a dedicated pushbutton, which is hidden inside the plastic case to avoid accidental activation.

C. *The Computer Application*

The computer application is written in the C# language with bindings to libusb library. The project was developed under Windows with the .NET Framework but should also compile under the Mono framework for Unix-like platforms.

The data arriving from the USB interface are first checked for valid packet structure. If the check fails, the algorithm skips following bytes until a valid packet is found. The data are then extracted and the sensors saturation detection is performed. Next the data are processed according to Figure 9. Finally the application presents the patient with the screen resembling the one used in the traditional form of examination – depicted in Figure 10. The trajectory of the move is recorded and every point outside the predefined shape is highlighted.

The length of the path outside the shape should be measured together with the maximum deviation to the path. Also the time required to pass between several markers is important and shall be recorded.

The doctor is presented with a simple window for controlling the calibration process and defining visibility of shapes and points of error occurrences.

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[1] KiB – kibibyte, 1024 bytes

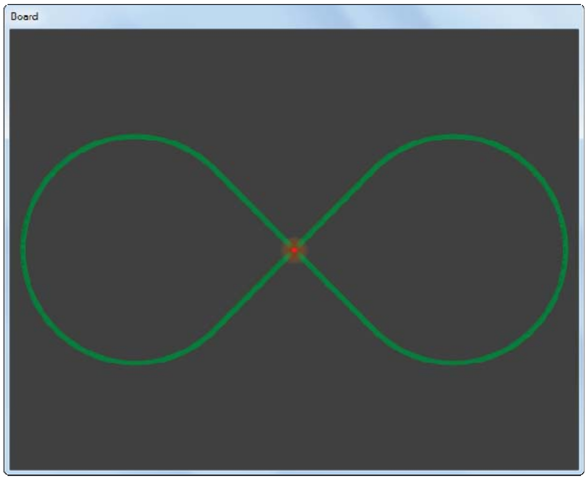

Figure 10. The application screen of examined

V. THE RESULTS

The most important objective has been achieved – the developed prototypes proved that the idea of using gyroscope and accelerometer for simulating position of the laser pointer is applicable and can be exploited for building useful medical devices. The cost of parts required for building one prototype is about $50. The worst-case price of a commercial device could be about $100, which would still render it an affordable solution for the health care services.

The prototyping process brought forward numerous issues that the engineer has to face constructing similar equipment. The most important is that there are currently no affordable MEMS accelerometers of resolution higher than 12 bits. Secondly, the simple matrix multiplication based projection may be used only if the strict simulation of the laser pointer is not required and only over relatively small range of angle values. Nevertheless, its performance may be satisfactory in some cases, mainly if the feedback is provided using simulated pointer instead of the real one.

VI. PLANS FOR THE FUTURE

Several aspects of the described solution have not been examined yet and still constitute an open field for further evaluation. The following problems still have to be explored:

- Implementation of a more realistic model for mapping angles to screen coordinates.
- Algorithms for measuring the patient performance and accuracy during the test.
- Use of the magnetometer data for calculating the absolute heading.
- Feasibility of the device for other medical examinations and measurements.
- Temperature compensation for sensor calibration values

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