The Device for Diagnosis and Treatment of the Cervical Spine

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Abstract

This paper presents an innovative method of automating a medical study, which is commonly used to assess the dysfunction of the cervical spine and for its rehabilitation. The diagnosis is based on determining the scope and dynamics of the motion that the patient is able to perform with his head.

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. The system is also equipped with the magnetometer, which may help find the device's absolute orientation in space. Using information from the sensors, the computer determines the angle of elevation of the head and angle of its rotation around the vertical axis.

The test was earlier performed by attaching a laser pointer to the patient's head, and observing how he follows the defined shapes with the laser spot. 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 how far from the defined shape is the pointer located.

1. The Idea

1.1 The Elementary Form of Examination

The traditional method of examination requires attaching a laser pointer to the patient's head, which is done by using headphone-like type of fixture. The examined sits in the front of the white screen with several color shapes drawn on it. The whole setup is sketched 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 computer. 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.

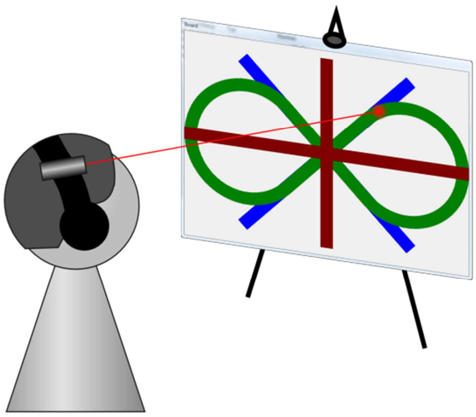

Figure 1. Former examination procedure

1.2 The Expensive Measurement Technique

The medics would like the measurement setup to achieve the resolution of about 1 mm with patient sitting about three meters away from the screen. The scientists and engineers have been thinking on the best method for performing such an examinations earlier and found a promising solution. The screen should be observed with the camera, a dedicated computer program would then analyze the spot movement in the real-time and perform appropriate computations - see Figure 2 for the setup illustration.

This idea is straightforward and its realization should be simple. Nevertheless the closer investigation reveals several important drawbacks. To achieve the 1 mm precision on the screen of size about 180 cm times 120 cm, the camera has to offer the resolution of at last 1800 x 1200 pixels (slightly more than 2 million pixels). In the real world the camera will not be positioned directly in the front of the screen, hence a suitable margin is required.

Assuming only a 20% margin, the number of pixels increases by 44% to about 3 million.

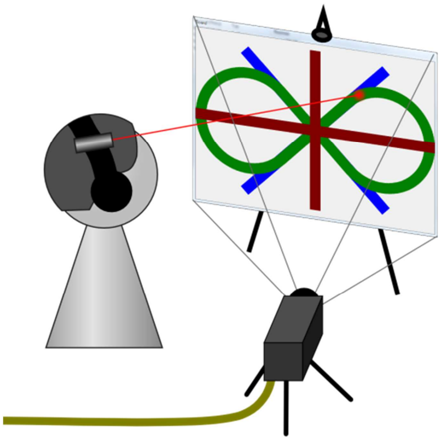

Figure 2. The camera-based system

The typical man is able to perform up to 10..15 cycles per second of tensing and relaxing of skeletal muscles [1]. The professional tap dancers are able to achieve up to 38 taps per second for a very short periods of time [2]. The base frequency of the human head movement does not reach such a high values, but hence the movements are in general nonlinear a higher harmonics also have to be passed through the system. This leads to the frame rate reaching about 90 frames per second (to fulfill Nyquist equation for three first harmonics of body part moving with 15 Hz fundamental frequency).

Not only the requirements for the camera are demanding (3 million pixels @ 90 FPS), but also the computer processing this data stream should offer a considerable processing power. Every 11 ms it have to receive a full video frame, apply perspective correction, probably some color space manipulation, then recognize the spot position and determine its location in relation to shapes drawn on the screen. The huge performance required from such a system translates into its high cost.

1.3 The More Cost-Effective Approach

The main problem of the solution with the camera is the necessity to determine the cursor and shapes positions only by observing the screen. Any architecture able to do so will require a precise image sensor and processing engine of high performance.

To offer a device affordable by health services, the engineer has to answer the question, if the system could know the pointer location without acquiring the image of the screen. It is perfectly be possible, for instance, if the head position could be measured with the appropriate accuracy, the system could calculate where should the laser beam hit. The most of methods for acquiring absolute position of patient body are very expensive (e.g. motion capture) or just impractical in the case of human being.

Assuming the patient position relative to the screen is fixed and known, the laser spot location can be determined using only two angles: the angle between the up direction of the head and the vertical axis and the rotation around the vertical axis. The Figure 9 can provide useful hints on this idea.

The most convenient way to measure the required angles is to fix a box with some sensors to the patient's head in the same fashion as the laser pointer was mounted. Measurement of the angle in the vertical plane is relatively simple, it requires only determining the direction of the Earth's gravity force vector in the coordinate system of the device and thus the head. This may be done using an accelerometer in the form of an integrated circuit.

The measurement of rotation in the horizontal plane cannot be done analogically, as the g-force vector is constant during such a movement. The most intuitive solution would be to use a kind of compass device or more formally: a magnetometer. The magnetic field of the Earth is very weak one, and the local induction vector depends heavily on the local environment. It can vary significantly even in the short term observation, for example due to operation of a nearby electrical appliances. The system could never rely fully on the magnetometer readouts. There seems to be no other kind of field or parameter that could be measured easily to obtain the actual heading (direction a person is facing, considered in the horizontal plane).

If the initial position of the device would be known, the heading could be calculated by integration of the angular velocity. The angular velocity may be measured easily by using a gyroscope. Such sensors are now available also in the form of a small integrated circuit.

By integrating the angular velocity, the system may calculate how the heading has changed during the considered time period, but it cannot determine the absolute angle. If the horizontal position of the laser spot would be known for some instant of time, the system could choose such an integration constant for the real and computed spot positions to meet. Such a calibration may be performed easily by instructing the patient to point the laser towards some designated location on the screen which position would be known for the system. Extending this idea to a three-point calibration scheme enables for an effective perspective correction.

The final concern is how the computer can know the shapes on the screen with the sufficient accuracy and if the calculated pointer will follow the real pointer precisely enough. The acceptable solution may be obtained by reformulating the problem. If the computer would know the shapes with an arbitrary resolution, it could cast them on the screen using a standard multimedia projector (available in most hospitals). If the shapes would be drawn by an application, this program could also draw a calculated pointer position – effectively eliminating the need for the use of laser, after the calibration.

1.4 The Proposed Solution

In the designed system a small device with a gyroscope, accelerometer and laser pointer is fixed to the head of the examined. The sensors gather the information on the elevation and angular velocities of the device – and of the head. The shapes and calculated position of the pointer are casted on the screen by means of standard multimedia projector. See Figure 3 for the sketch of a complete setup. Before the examination, the system has to be calibrated to account for the change of examined position and initial rotation in the horizontal plane.

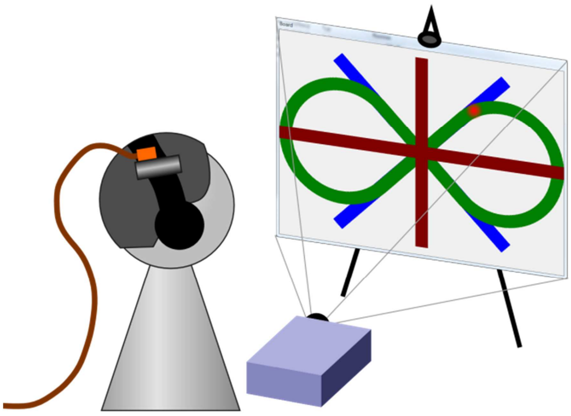

Figure 3. The proposed measuring technique

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. Assuming the hospital has a presentation PC with projector it only need to buy a device worth about $50.

2. The Measurement Device

2.1 Initial Considerations

The sensors box has to be small enough to be mounted on the headphones frame. 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 is usually heavy. Due to high popularity and larger than required throughput the USB 2.0 standard was chosen.

2.2 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 4, is fitted into the case of the small flashlight. It features 8-bit accelerometer, 16-bit gyroscope (250 °/s range [3]), laser pointer and two user accessible buttons.

The first prototype proved that the idea was right, and that this project can be now developed further. Its main disadvantage is that the 8-bit resolution of the accelerometer is too low for practical use.

Figure 4. First prototype: GyroAccel v1

2.3 Estimation of a Required Resolution

According to the earlier considerations, the device should have the resolution of 1 mm with patient sitting 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°).

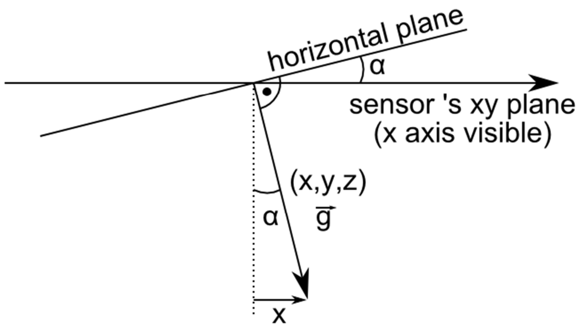

Figure 5. The g vector in sensor's coordinates

The system calculates the elevation angle using components of the measured acceleration vector with a simple equation:

$$\alpha = \arcsin\left(\frac{x}{\sqrt{x^2+y^2+z^2}}\right). \quad (1)$$

The meaning of the variables is explained by the Figure 5. As the patient's head is located at about the level of the screen's center, the elevation angle is usually relatively small and the linear approximation of arcsine may be used:

$$\alpha \approx \arcsin(\alpha). \quad (2)$$

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

$$\Delta\alpha \approx \arcsin(\Delta\alpha). \quad (3)$$

Moreover, assuming that during examination the patient is at rest (or at least not accelerating), the value of denominator in equation 1 should be approximately equal to g:

$$\sqrt{x^2 + y^2 + z^2} \approx \mathrm{g}. \quad (4)$$

Basing on equations 1, 3 and 4 the following approximation may be easily derived:

$$g \cdot \Delta\alpha \approx \Delta x. \quad (5)$$

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 4g 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.

2.2 The Second and the Third Prototype

To accommodate for the accelerometer of higher resolution, second version of the board was designed and manufactured – see Figure 6. The closer evaluation of the documentation of this advertised as a 16-bit sensor has shown, that it offers only 12-bit readout. Furthermore, which was not in the manual, the value read has at most 9 meaningful bits – the higher 3 bits were varying randomly even if the device was completely still. The test was performed with the board clamped to a huge mass (~5 kg) standing on the shock-absorbing feet.

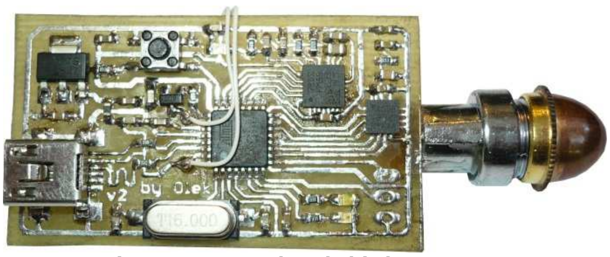

Figure 6. Second and third prototype

The third prototype is based on the same PCB, only a small overlay board was added. The board housing new accelerometer was glued on the opposite side and connected using several wires. The supplemented sensor offers 12-bit readout refreshed even 800 times per second [4]. Using the oversampling technique the sensor can provide 14-bit result at the satisfactory rate. The calculation of the two least significant bits requires taking 16 samples from the device, which results in the overall speed of 50 measurements per second.

The prototypes since version v2 are also equipped with the magnetometer. Although the use of the geomagnetic field as the main reference for heading was earlier discouraged, it may still be useful as an auxiliary reference.

2.3 The Finished Sensing Device

The schematic of the final revision, v4, is heavily based on the previous prototype. Minor mistakes were fixed and 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 7 for size estimation.

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^2C compatible two wire interface and the gyroscope using four-wire SPI bus.

Figure 7. The final device compared to a 1 zł coin

3. The Data Processing

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, of a higher accuracy, 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.

[1] KiB – kibibyte, 1024 bytes

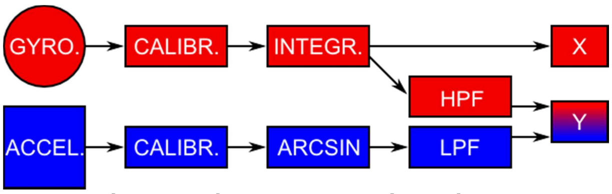

Figure 8. The Data Processing Scheme

The X coordinate is obtained directly from the integrated angle value. The Y coordinate is composed of data coming from both gyroscope (accurate deltas, fast response – high-pass filtered) and accelerometer (absolute angle value, possibly noisy – low-pass filtered). See Figure 8 for the process outline. The calculated x and y values are finally passed through the perspective correction and are used for drawing the simulated laser pointer on the screen.

3.1 Low Level Software

The 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 locations. Furthermore, the economic microcontroller does not offer a hardware support for the I²C protocol, hence the software solution was developed.

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. After every 16 samples, the gyroscope and magnetometer are also read and complete matrix of nine 16-bit values is stored in the local FIFO. When the USB controller announces arrival of the IN packet, the data are stored in 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.

3.2 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 acceleration vector is decomposed to the absolute value and the unitary direction vector. At the same stage, the DC offset from the gyroscope is compensated. The compensation is done by subtracting a vector calculated before start of the examination of a value obtained by low-pass filtering of the input signal during device being at rest.

In the following stage the elevation angle is computed using arcsine (ref. equation 1). Both angles are also obtained from the gyroscope data by means of integration of the angular velocities. Then the values of elevation from both sources are filtered and composed into one value by a weighted average.

Finally the angles are multiplied by a kind of the projection matrix and the spot position in the window coordinates is obtained. This method of projection assumes that the x and y components of the spot position are directly proportional to the α and β angles – see Figure 9 for reference.

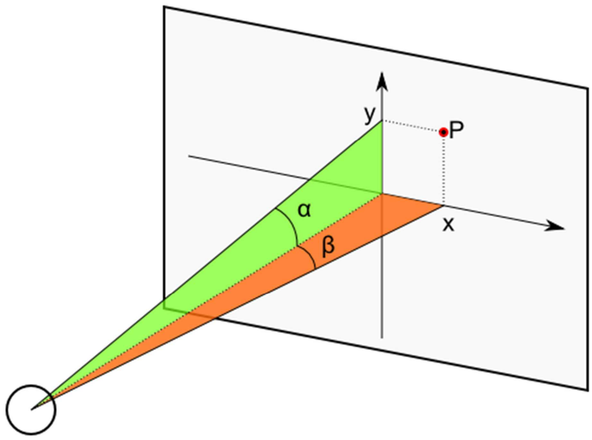

Figure 9. Spot projection on the screen

The described method of projection may be considered accurate only for small values of angle. This implementation was intended to be a temporary one, which should be corrected just after the application would become functional. Unexpectedly, this solution is accurate enough in most of the practical cases. There is a visible deviation between laser pointer and the simulated pointer when operating far from the screen center. Nevertheless the simulated pointer behaves as the brain would expect it to, thus the application is good enough to guide the patient to perform the predefined moves.

The correction to this algorithm is still one of the most important improvements to the application that are already foreseen.

The mentioned earlier three-point calibration calculates the projection matrix converting the x and y components from the sensor coordinate system to the window-relative coordinates. The projection matrix has 6 elements that have to be determined during this process – every of the two output coordinates depends on both input coordinates and a specific offset:

$$\begin{bmatrix} m_{xx} & m_{xy} & m_{x1} \\ m_{yx} & m_{yy} & m_{y1} \end{bmatrix} \cdot \begin{bmatrix} X_{in} \\ Y_{in} \\ 1 \end{bmatrix} = \begin{bmatrix} X_{out} \\ Y_{out} \end{bmatrix}. \quad (6)$$

In order to compute the *m* coefficients, a set of at least 6 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 equations of the form shown above may be formulated. The resulting determined system of linear equations is solved using the Gaussian elimination method.

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.

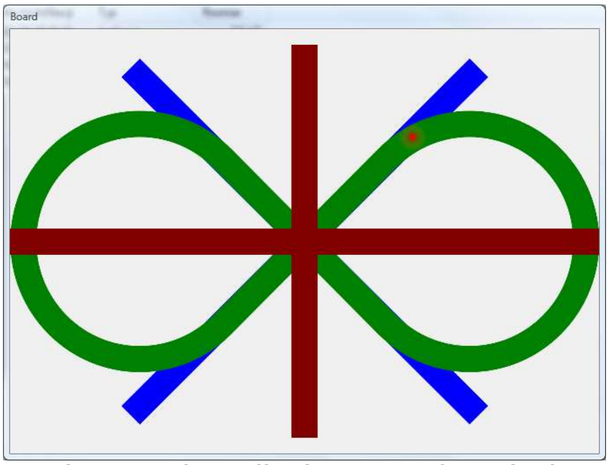

Figure 10. The application screen of examined

The length of the path outside the shape should be measured along with the maximum deviation to the path. Also the time required to pass between several markers is important and shall be recorded. The appropriate algorithms for the measurements are now being developed.

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

4. 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.

Moreover, the process of building the prototypes brought forward several problems that the engineer has to face constructing similar equipment.

There are currently no cheap accelerometers of 16-bit accuracy on the market. The resolution higher than 12 bits may be obtained only at the expense of sampling speed – using the oversampling technique. If the vertical drift is acceptable, the pointer can be simulated only using the gyroscope output.

The algorithms have to account for sensor DC offset cancelation to avoid drift of output values when using integrating stages. In such a case the noise from the sensor can cause the 'random walk' of output values, which should be also suppressed.

The use of a simple mapping the angles to the position on the screen by means of a perspective matrix may be used only if the strict simulation of the laser pointer is not required. Nevertheless, its performance may be satisfactory, even over larger angles, if the feedback is provided using simulated pointer instead of the real one.

5. The 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.
- The optimal weights for combining data from both paths into the elevation angle.
- Use of the Kalman filter for processing the data from sensors.
- Use of the magnetometer data for calculating the absolute heading.
- Feasibility of the device for other medical examinations and measurements.

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