Evaluation of the measurement set for recording of skull movements



**Summary**

This report describes the work done within the knowledge voucher project 10-098180 (journal number Research and Innovation Board). A measurement set consisting of two mechanical actuators has been evaluated. For this purpose, a computer program for data collection and analysis has been developed. The purpose of the setup is to measure potential skull expansions of magnitude up to 300 µm. The actuators are stable within a measurement uncertainty of about 5 µm within the maximum measuring range of about 10000 µm. The newly developed program visualizes movements of the actuators and can detect periodic fluctuations in measurement data.

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# Knowledge voucher

Within the knowledge voucher project 10-098180 (journal number Research and Innovation Board), a measuring set is developed for detecting and measuring the periodic extension of the skull of up to 300 µm, about 6-12 times per minute. The extension is noticeable, but it is not yet technically documented. Two sensitive mechanical actuators with a measuring solution of 1 µm are positioned opposite each other on each side of the skull. The development is carried out by Institute Meulengracht and the GTS Institute Danish Fundamental Metrology (DFM). Institute Meulengracht provides two moving coil actuators that can detect displacements with a measuring solution of 1 µm. The optimal measurement points on the skull are defined according to the institute's experience values.

In close collaboration with the Institute Meulengracht, DFM designs a measurement set and builds a prototype with available laboratory equipment. Dedicated stand-alone software is written for reading and analyzing measurement data for further use by the company. Finally, the DFM evaluates the measurement setup in a metrological manner. The uncertainty budget is drawn up and measurements are analyzed.

# Mechanical actuators

## Background

An actuator is an instrument that can measure the length of a displacement by means of a pinole and a built-in glass ruler, see Figure 1. The guide of the pinole only allows displacement along an axis. During the movement, an optical sensor is passed across the glass ruler, which detects the ruler's divisions and thus records the distance. In addition to a ruler for distance measurement, an actuator includes a linear motor consisting of a coil and a magnet. The motor can be used to generate a displacement of the pinole at a given distance or, as described in this report, to generate a small spring force which keeps the pinole in contact with the measuring element. Modern actuators can measure displacements well below one micrometer. The division of the glass ruler as well as the mechanical stability constitute limitations to the measuring ability. This report describes two uniform actuators, which have a resolution of 1 µm in a measuring range of 10000 µm, see the technical drawing in 5.1 actuators.

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| Figure 1 An actuator seen from the inside |
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| Schematic of an actuator. The most relevant parts are: the shaft which transmits the motion to a glass scale, an electro-optic encoder that detects the movement of the glass scale, and a magnetic coil used to generate a desired mechanical resistance. |

The actuators in this project are identified by their serial number:

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| Actuator 1 (connected COM6) | Actuator 2 (connected COM4) |
| |  |  | | --- | --- | | AVS 50-12-010-51 | | | S/N: CE52 |  | | 0907 |  | | |  |  | | --- | --- | | AVS50-12-010-51F3 | | | S/N.:CE173 | | | 24V 1110 |  | | |

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| Figure 2. Arrangement for evaluation of the actuator's measuring capacity |
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| The actuator (left) is set to measure the displacement of a displacement table (see post). From the other side is measured the relocation of an interferometer with laser light (dashed red line). |

## Evaluation of the actuators' measuring capacity

The meter is realized at the primary level at the wavelength of radiation from an iodine-stabilized helium-neon laser. By means of an optical measurement arrangement, a so-called interferometer, the displacement of the actuators can be related to the meter definition. An interferometer can use laser light to measure displacements without contact with nanometer accuracy, i.e. 1000 times finer than the actuators' measuring capacity. For this purpose, the actuators are alternately inserted into an interferometric array, see Figure 2. An actuator is placed for measurement on one side of a displacement table, a mirror mounted on the other side of the table. Thus, the same displacement of both the actuator and the interferometer is measured, which thus allows the evaluation of the actuator's measuring performance. If the offset table is not moved, the actuator will show the same constant value. Thus, the noise signal is smaller than the resolution and can be neglected.

Figure 3 shows a diagram where the actuator shear measurement is plotted against the interferometer measurement. To clarify the measurement deviations of the actuators from an ideal position, it is necessary to draw a regression line from the collected measurement data. The slope of the calculated regression line is also the mean scale coefficient. When the divisions of the glass ruler and their count correspond to the actual displacement, the scale coefficient will be equal to 1.

Metrology - in brief, prepared by Preben Howarth, Danish Fundamental Metrology (1999), DFM-98-R12 (Danish version), ISBN 978-87-988154-5-7 (English version)

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| Figure 3. Actuator 2 against interferometric distance measurement |
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| Measurement result of actuator validation setup 2. The distance as measured with the actuator is shown opposite the distance as measured with the interferometer. |

The scale coefficients (or slope of the regression line) are determined to be 1.00018 ± 0.00003 (actuator 1) and 1,00085 ± 0.00003 (actuator 2). In both cases, 0.00003 is the statistical standard uncertainty of the coefficients which is thus well determined. The small deviations from the ideal coefficient 1 lie within the angular variations of the evaluation set, (cosine contribution in the uncertainty budget, see 5.2).

The diagrams in Figure 4 show the difference (so-called residuals) between the actuator shear measurement and the interferometer measurement are shown over the entire measurement range of 10000 µm. Here the local differences between the ideal regression line and the actuator measurements are shown. Small errors up to 2 µm can be seen for both actuators. This corresponds to the actuator repeat error, see 5.1 "Encoder repeatability". The variation around the regression line has a standard deviation of 0.9 µm. Thus it can be concluded that the actuators' display of displacements lies with 95% probability within a range of 2 µm around the measured value shown. This uncertainty is sufficient to measure extensions which are expected to be between 100 µm and 200 µm.

In the total measurement range of the actuators, the expanded uncertainty U (d) at a measurement of distance d from the actuators minimum value is estimated to:

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| *U*(*d*)=, | (1) |

See the uncertainty budget in 5.2. For a typical distance measurement of an actuator of 200 µm, the expanded uncertainty is about 2 µm.

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| Figure 4. The residuals of distance measurements |
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| The differences from the ideal line, so-called residuals, of the actuator measurements in the evaluation set. It can be clearly seen that the position error is well within 2 µm deviation for the entire measurement range. |

2.3 Computer interfacing and synchronization:

## Both actuators support an RS232 communication protocol on the serial port of a standard PC. Actuator 1 is set to COM Port 6, actuator 2 is set to COM port 4. Both COM ports are operated at a speed of 19200 baud. The actuators are programmed to transmit their measuring position 20 times per minute. To this end, both actuators use their internal time norms. A difference between the two time norms of about 1% was recorded during the measurements. To prevent the synchronization of the measurements from running out of phase significantly, for example. 2 minutes, the time program of actuator 2 is selected in the computer program to synchronize measurements of both actuators. Thus, the maximum synchronization error is limited to a maximum of 1/20 second. The expanded relative uncertainty of the measured value "oscillations per minute" is estimated at 5%.

## 2.4 Measurement setup

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| The actuators are each put behind an ear with contact on a skull bone, see Figure 5. In addition to the individual displacements, the positioning of the actuators can advantageously be used to distinguish an displacement caused by a movement of the head, e.g. from left to right, where the actuators are displaced in the same direction, and a potential extension of the head, where the actuators are displaced in the opposite direction. Mathematically, the sum of the actuators' measurements describes the overall expansion motion, while the difference can be used to identify a displacement that results from a displacement of the measurement object. Since the actuators can only measure linearly in one direction and thus cannot detect forces upwards, small shoots due to an almost vertical skull movement are also recorded. The expanded measurement uncertainty Us for a composite signal, either the sum signal or the difference signal, is calculated by the following formula: | | |  |
| In the case of , i.e. both actuators measure the same distance, the equation can be simplified to, | | |
|  | (3) | |

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| Note that there may be a systematic error in a composite measurement when the actuators are not parallel to each other. An angular deviation of measuring directions of 10 ° leads e.g. to a measured displacement 2% shorter than the actual displacement.  Figure 5. Schedule measurement set "skull pulse" |
| Kranie  Actuator 1   |  |  | | --- | --- | |  | (2) |   ator 1  Actuator 2 |
| An actuator is placed on each side of the test subject's skull. In addition to the individual actuator measurements, the difference and sum of their measured values can be used to distinguish between the situations when the actuators move in the same direction or in opposite directions. |

## **3 Control Program**

3.1 Content and Installation

* The program is written in LabWindows / CVI and consists of two files:
* Puls3\_PRJ.exe (the executable program)
* Puls3\_UI.uir (the graphical user interface)

LabWindows / CVI are a scientific programming environment that allows application deployment. In order to run a program on a PC without any installed programming environment, there is a run-time engine which can be downloaded from the website: [www.ni.com](http://www.ni.com) 🡪 Support 🡪LabWindows/CVI🡪Drivers and Updates🡪LabWindows/CVI Run-Time Engine.

**In addition to having the LabWindows / CVI run-time engine installed on a PC, both of these files must be in a common (arbitrary) folder.**

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| Then the program Puls3\_PRJ.exe can be started by a normal double click.  Figure 6. User interface screen |
| O:\My Documents\7221 PULS3\Test Endelige KCM 29.08. - 30.09. 2011\Knud 30.09.2011\Knud 56 4 kst 10.bmp  **(9)**  **(8)**  **(7)**  **(6)**  **(5)**  **(4)**  **(3)**  **(2)**  **(1)** |
| The screen displays nine elements for data analysis and control of the measurement process. See the text for further details.  http://www.ni.com/lwcvi/ |

## 3.2 Program features

The program communicates with the actuators, displays and analyzes measurement data, and allows the data to be stored both as numbers and as a graphical screen of the user interface.

The user interface is shown in Figure 6. The individual elements are:

(1): Displays the current measured values from both actuators. Values are displayed both as numbers in the top line and as a scale indicator. If the value is outside of the scale's display area, a red frame is placed around the scale. The scale range can be adjusted, see (3) and (4). A green light means that there is flawless contact for data transfer between the actuators and the program, see also (2).

(2): When the actuators are connected to the PC and their power supply is turned on, communication between the actuators and the PC can be started with the "Connect" button. When the connection is faultless, the indicators light green, see (1). Then the actuator initialization routine is started by clicking "run out". When the actuators have run out and have encountered a mechanical resistance, data transfer can be started by clicking on "send data". The values are now displayed in (1). A measurement including data analysis is started at the click of "Start" and can be stopped at the click of "Stop".

(3): The dials can be adjusted with the dial. The largest area is the “max” setting, where the entire area is displayed. The other numbers indicate a symmetrical range of about 0. In Figure 6, the dial is set to 600, which corresponds to a scale range from -600 µm to +600 µm. It is recommended to use button (4) to reset the actuators.

(4): The button sets the current actuator values to 0 µm. This helps to make measurements symmetrically around 0 µm. The previously collected data as well as the charts (6), (7), (8) and (9) are deleted.

(5): The buttons start a dialog where you can save measurement data either as number rows ("Save data") or as a screen ("Save screen") with all charts. The number rows are stored in an ASCII text file and can be opened with ordinary editors such as "notepad". At the beginning of the ASCII file there is text that specifies the date and time of the measurement etc. The program can store a maximum of 1000000 measurements. At 20 measurements per second, this corresponds to 13 hours and 53 minutes of continuous measurement. When saving a screen, a line of date and time is inserted between the charts (8) and (9).

(6): The charts show the history of measured values for the last 30 seconds for each actuator.

(7): Here the sum signal of both actuators is displayed. The sum shows when the actuators move in opposite positions. Thus, an expansion movement can be visualized.

(8): Here the differential signal of both actuators is shown. The difference shows when the actuators move in the same alignment direction. Thus, a movement due to a move can be separated from a move that results from an expansion.

## (9): This diagram shows an analysis of the sum signal (7). The analysis involves finding periodic fluctuations in the sum signal. The result of the FFT analysis, see 3.3 below, is shown as yellow stripes in the diagram. Frequencies are converted to fluctuations per minute. The heights of the stripes show the oscillation width, ie. the maximum distance of a periodic oscillation of the actuator signals. At the bottom of the chart are areas where the heart rate (resting heart rate of 70x-100x per minute), breathing rhythm (15x-30x per minute) and a possible skull heart rate (6x-12x per minute) are expected. A small switch at the bottom left of the diagram can switch the scale of the y-axis between linear and logarithmic. Note that there are some previous program versions where the frequencies are shown as oscillations per second and only half the oscillation width is stated as "Amplitude".

## 3.3 Oscillation Analysis

Assuming that the measured sum signal is a mixture of periodic oscillations, the mathematical method "Fourier Transformation" can advantageously be used to find and separate the individual oscillations in the measurement signal. To perform the Fourier Transformation in real time, the so-called Fast Fourier Transformation (FFT) is used. This algorithm is fast, but limits the number of measurement points to powers of 2. A good compromise between measurement and calculation speed (20 measurement points per second) and a sufficiently large signal history (about one minute) is 1024 (= 210) data points. Thus, 1024/20 = 51.2 seconds recording of measurement data can be stored and analyzed at once. At the start of the measurement (2) it takes approx. 7 seconds until a sufficient amount of data is collected to perform an initial FFT analysis. After the first 51.2 seconds, sufficient data is available to perform the full analysis. After 51.2 seconds, new measurement points are moved in, while the oldest data point is moved out (FIFO buffer).

# 4 Measurements

## 4.1 Testing the stability of the set-up

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| An array with a static test object was selected to test the noise level of the actuators, i.e. their signal stability, see Figure 7. A skull was used to create a measurement situation without movements. The result of more than three minutes of measurement can be seen in Figure 8. Both actuators keep their measured values constant throughout the measurement period.  Figure 7. Test setup with a skull |
| O:\My Documents\7221 PULS3\Fotos\3. puls opstilling til rapport\3. puls opstilling til rapport\IMAG10.jpgO:\My Documents\7221 PULS3\Fotos\3. puls opstilling til rapport\3. puls opstilling til rapport\IMAG2.jpg |
| The actuators are seen running into the skull to test the stability of the measuring signal. |

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| Figure 8. Stability test screen |
| O:\My Documents\7221 PULS3\Fotos\3. puls opstilling til rapport\3. puls opstilling til rapport\IMAG12 Kontakt på dødt kranie.bmp |
| Over a 200 second period, no measurement activity is displayed by either actuator. The level of instrument signal noise is thus less than the measurement resolution. The actuators measure stable. |

## 4.2 Testing the setup with mechanical simulation

The set-up and program are tested using a rotation table. A glass bottle is used as a measuring object, see Figure 9. By placing the glass bottle decentrally on the axis of the rotation table, both shear and extension movements are simulated during rotation. Irregularities on the outside of the bottle further contribute to periodic oscillations during the rotation of the bottle, see Figure 10. From the measured sum signal, two significant frequencies are extracted at about 34 and 68 rpm. This shows a good agreement with the expected rotations of the rotation table respectively 33 and 66.

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| Figure 9. Test setup with rotation table |
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| A decentralized glass bottle on a rotation table is used as a test object for the set-up and the program. The actuators are not mounted in direct extension of each other. The angular deviation is about 10 degrees. However, this only affects the absolute measured distance, which becomes smaller than if the actuators were parallel and diametrically located. The periodic analysis remains untouched by this. |

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| Figure 10. Signal analysis of test setup |
| O:\My Documents\7221 PULS3\Målinger\Måling20110315.bmp |
| Measurement result of validation setup for the oscillation analysis. In the periodic analysis, a frequency close to 0.58 Hz is displayed, which corresponds to about 35 rpm. At 1.18 Hz another frequency signal is seen. This equates to about 70 revolutions, the double value. This is due to 2 elevations in the glass where the halves of the bottle are fused together during the preparation of the bottle. Note of the screenshot is from a previous version. |

## 4.3 Tests with people

The measurement set as outlined in Figure 5 was applied to 27 test subjects with a total of 158 trials. The persons are resting on a bed of a foldable piece, where a 7 cm top mattress of the brand ErgoPur is applied to cushion unwanted swings. After the first 25 tests on 3 people it was seen that i. the body's breathing movements superimposed the measurements. In order to disengage the body's movement movements from the measuring points on the skull, a plate is then mounted at the head end of the bearing. The plate forms the basis of a roller board, on which the head rests on a "knee pad" in two layers. The actuators are fixed in two racks on the roller. This maintains the relative position of the head and actuators.

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| For most measurements, the actuators are located on the wart-shaped part of the ear bone, see Figure 11. For some of the measurements, the actuators are first placed on the wart-shaped part of the ear bone, then in the middle of the ear bone.  Figure 11. Actuator set-up with test person |
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| The actuator measures movements on the wart-shaped part of the ear bone. |

Various measurements are shown below. See the captions for details.

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| Figure 12. Test person "Johannes" |
| O:\My Documents\7221 PULS3\Målinger\Test Endelige KCM 29.08. - 30.09. 2011\Johannes\jw6.bmp |
| Fluctuation of 200 µm approx. 8x per minute. Camped without a skateboard. |

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| Figure 13. Test person "Johannes" |
| O:\My Documents\7221 PULS3\Målinger\Test Endelige KCM 29.08. - 30.09. 2011\Johannes\johannesholder_vejr_med_puls.jpg |
| Small oscillations of 50 µm around 60x per minute. Camped without a skateboard. |

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| Figure 14. Test person "Johannes" |
| O:\My Documents\7221 PULS3\Målinger\Test Endelige KCM 29.08. - 30.09. 2011\Johannes\PulsJohannes.bmp |
| Small oscillations around 60x per minute and at 4x per minute. Camped with skateboards. |

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| Figure 15. Test person "Kasia" |
| O:\My Documents\7221 PULS3\Målinger\Test Endelige KCM 29.08. - 30.09. 2011\Kasia\Kasia_4.jpg |
| Small fluctuations around 18x per minute. The clay without a skateboard. |

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| Figure 16. Test person "Kai" |
| O:\My Documents\7221 PULS3\Målinger\Test Endelige KCM 29.08. - 30.09. 2011\Kai\kai 16.bmp |
| Small fluctuations around 68x per minute. Wide contribution of frequencies between 10x and 20x per minute. Camped with skateboards. |

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| Figure 17. Test person "Karl Christian" |
| O:\My Documents\7221 PULS3\Målinger\Test Endelige KCM 29.08. - 30.09. 2011\Karl Chr 26.08.2011\Karl C 58 1kst 10 vejr 20 puls 100.bmp |
| Small fluctuations around 10x per minute. In addition, fluctuations at 20x and 10x per minute. Camped with skateboards. |

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| Figure 18. Test person "Bjørn" |
| O:\My Documents\7221 PULS3\Målinger\Test Endelige KCM 29.08. - 30.09. 2011\Bjørn 16.09.2011\Bjørn 7 kst 10.bmp |
| Fluctuations at 15x per minute. Camped with skateboards. |

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| Figure 19. Test person "Bjørn" |
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| Fluctuations at 10x, 15x and about 60x per minute. Camped with skateboards. |

# 5 Appendix

## 5.1 Technical drawing



## 5.2 Uncertainty budget actuator measurement

