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PROGRESS OF THE TU ILMENAU DUAL AXIS TILTMETER WITH NANORAD RESOLUTION

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Abstract – The progress of our tiltmeter, which bases on force compensating weigh cells (EMFC) is discussed in this paper. Currently a resolution of ~ 1 nrad at a range of ± 9 mrad, a linearity of < $0.25\cdot10^{-3}$ and a cross error of the axes of < ± 22 ppm is achieved. Long term measurements of earth tide related tilts demonstrate the ability to resolve tilts with very small frequencies (1 – 2 d^{-1}).

Prospectively it will be applied to measure and control tilting of measurement basements and tables.

Keywords: tiltmeter, inclinometer, electromagnetic force compensation, nanorad

1. INTRODUCTION

A tiltmeter measures the inclination between the acceleration of gravity and the normal to the earth’s surface.

In the field of force and mass metrology even small changes of the inclination of measurement setups could generate significant measurement deviations. Depending on the mechanical design of the balance lateral components of the weight force resulting from the tilting can be sources for measurement deviations. For instance, the torsion balance described in [1] is almost as sensitive for tilting as for force measurements.

The contribution of tilting to the measurement uncertainty can be reduced if tilt is controlled or monitored and its influence is corrected or compensated. In current research traceable force measurements in the piconewton range are described [2-5]. Nesterov for instance measured the force of 47 pN that is induced by the light pressure of a 7 mW laser beam acting on a mirror [4]. A tilting of the used “Nanonewton Force Facility” of just 1 nrad would generate a measurement deviation of 40 pN. Thus, a measurement of tilting with a resolution of < 1 nrad is included in the “Nanonewton Force Facility” to compensate and correct the influence of tilting.

In the field of contactless flow measurement techniques, the setup described by Diethold et al. and Vasilyan et al. [6, 7] is used to determine horizontal Lorentz forces in the µN-Range. Here a 10 nrad tilt of the setup causes a measurement deviation of 0.1 µN.

Above all, high precision measurements of tilting are long-established in geophysics and geodesy where observations of local tilting are carried out and used for earthquake research for example [8].

Local tilting bases on several natural phenomena such as wind-blown vegetation, precipitation, body waves or surface waves (seismic waves), atmospheric pressure changes deforming the ground or thermoelastic deformations and pore pressure changes as well as joint deformation related to groundwater motion [8, 9]. Besides these, earth tides are the best known effect. Depending on the location and direction of measurement, they cause tilting of the Earth´s crust in the 100 nrad amplitude range with semidiurnal (~12 h) and diurnal periods (~24 h) [8, 9]. Deformations of the founding or the floor of buildings caused by moving persons or machinery were observed to be in the µrad range and are additional sources of tilting of a laboratory or a measurement setup.

In conclusion, it is obvious that local tilt measurements in the nanoradian range are not only needed in the scope of geophysics but also in various fields of metrology such as force and mass measurements.

The aim of the presented investigation is to develop a tiltmeter/ inclinometer with a reasonable resolution of ~ 1 nrad at a, compared to the state of the art, expanded measurement range of up to ~ ± 9 mrad (1°) and low measurement uncertainty contributions such as nonlinearity, cross sensitivity or temperature drift. This would extend the field of application of such highly resolving tiltmeters. Only one device would be needed to cover both: measurements of very small and large changes of inclination with a resolution of ~ 1 nrad. Furthermore, calibrations of tiltmeters with different measurement ranges could be carried out with one setup.

2. STATE OF THE ART

Several principles for the measurement of tilt/ inclination are known. The most common ones apply pendulums, gas bubbles (level) or liquid surfaces as a reference [8].

Borehole tiltmeters established in the field of geophysics offer a resolution of 1-5 nrad at a measurement range of 50 - 200 µrad [8, 9, 10]. The Askania borehole tiltmeter was developed in the late 1960s and was later manufactured by BODENSEEWERKE GEOSYTEM GmbH. It still represents the state of the art in the field of geophysics. Basically it consists of a 0.6 m pendulum, a capacitive deflection measurement and a force feedback applied by Helmholtz coils [8]. Unfortunately it is not produced anymore.

The tilt measurement included in “Nanonewton Force Facility” works on the pendulum principle as well [2-4]. The inclination dependent deflection of a pendulum is measured with an interferometer and is compensated by an applied feedback force that is generated electrostatically. The applied capacitor voltage is then a measure for the force and thus for the inclination. A resolution of < 1 nrad is given.

A capacitive sensing of a pendulum is also used within the Lippmann tiltmeters [11], achieving a resolution of ~ 1 nrad at a range of ~ ± 2 µrad.

Sensing gas bubbles is applied in tiltmeters of Leica Geosystems AG and Applied Geomechanics Inc. (AGI) [12]. The Leica Nivel 210 inclinometer made by Leica Geosystems AG features a resolution of 1 µrad and a measurement range of ± 3 mrad [13].

In summary it can be stated, that a resolution of ~ 1 nrad represents the state of the art in the field of tilt or inclination measurements. However, the measurement range of the high resolving devices is very limited.

All have in common that a cross sensitivity of the axes (see Sec. 3.2) is not given in the datasheet. The Askania Borehole tiltmeters for instance show cross errors of up to 7 % [14].

Furthermore, the uncertainty limiting temperature drift of the devices can be in the range of some µrad. Leica gives ~ 5 µrad/K [13], AGI gives ± 3 µrad [12] and the Lippmann tiltmeters have been tested with up to ± 5 µrad [15].

3. MEASURMENT SETUP

The setup was presented in detail in [16] and will be shortly introduced here.

As well as the state of the art devices, our chosen principle of measurement bases on a pendulum. The pendulum is realized by the mechanics of a commercial electromagnetic force compensation (EMFC) weigh cell made by SARTORIUS WEIGHING TECHNOLOGY GmbH. The weigh cells base on standard parts [17] but were optimized for our purposes. In contrast to their designated use, the weigh cells are not mounted horizontally but in a vertical (hanging) position as shown in Fig.1.

Fig. 1: Dual axial tiltmeter realized by mounting two EMFC weigh cell in a hanging position

The hanging weigh cell consists of a pendulum which is designed as a monolithic parallel spring guidance made of aluminum, a weight m attached to this pendulum as well as a transmission lever system, an optical position sensor and a voice coil. The position sensor is realized by a fixed LED and a fixed differential photo diode. An aperture mounted to the transmission lever is placed between the two diodes. Thus, the illumination of the two sensitive areas of the photo diode changes when the lever moves. The tiltmeter comprises two orthogonal axes, see Fig. 1. The measurements can be carried out in two different modes.

In the Pendulum Mode the tilt related pendulum deflection is measured with the position sensor of the EMFC weigh cell [16].

In the Balance Mode the tilt proportional lateral force F of the weight force $F_G = m \cdot g$ acts on the weigh cell and is measured. In this case the system is used as a hanging balance and the pendulum deflection is controlled to zero by generating a counterforce with the voice coils. The electric current applied to the voice coils to produce the counterforce is then proportional to the tilt [16].

All the results depicted in the following were determined using the Balance Mode.

3. RESULTS

3.1. Calibration and Linearity

In the Balance Mode, the lateral Force F is measured by recording the displayed mass values $m_{Balance}$ of the used standard balance electronics. Hence, the relation of tilt φ and displayed mass will be expressed by the sensitivity S of the system:

$$\varphi = S \cdot m_{Balance} \quad (1)$$

A tilt calibration table (tilttable) was developed (see Fig. 2) to calibrate the tiltmeters sensitivity S and was calibrated with a calibrated autocollimator [18]. It offers a calibration range of ± 18 mrad at resolution of < 1 µrad. Backlash and linearity deviation were observed to be < 2 µrad (k = 2).

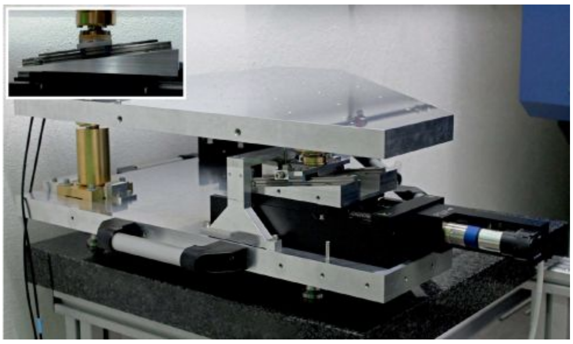

Fig. 2: Tilt calibration table (tilttable)

The characteristic curve of one tiltmeter axis is shown in Fig. 3 whereas the corresponding sensitivity results in $S = 1.77 \cdot 10^{-3}$ rad/g at a measurement range of ± 9 mrad. The linearity deviation was computed based on the fit residuals and is as low as < ± 2 µrad (conforms to < $0.25 \cdot 10^{-3}$ of rel. linearity deviation) in the whole range, see Fig 3 (lower section). The computed linearity deviation is within the measurement uncertainty which mainly results from the calibration uncertainty of the tilttable linearity [18]. Thus, the linearity deviation of the tiltmeter can be expected to be even lower than the proven ± 2 µrad. For the second axes the same values have been achieved.

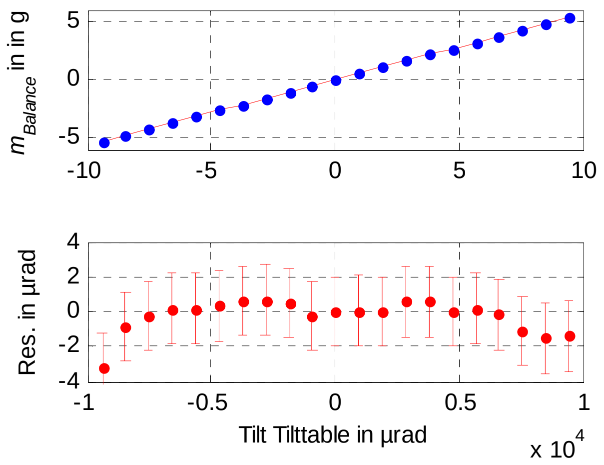

Fig. 3: Characteristic curve and linearity deviation of the tiltmeter

3.2. Cross error of the axis

A not corrected cross-error of the tiltmeter axes is a fundamental contribution to the measurement uncertainty of tilt measurements. In the datasheets of all the introduced tiltmeters [8-13] this contribution is not mentioned. It mainly results from an angular misalignment of the two axes among themselves ($\delta \neq 90°$) and its axes regarding to the axes to measure (α, β), see Fig. 4. For the user it is desirable to align the tiltmeter with respect to the edges of its housing. Thus, the axes of the tiltmeter must be aligned to the axes of its housing and the resulting misalignment (α, β) should be calibrated to reduce measurement uncertainties.

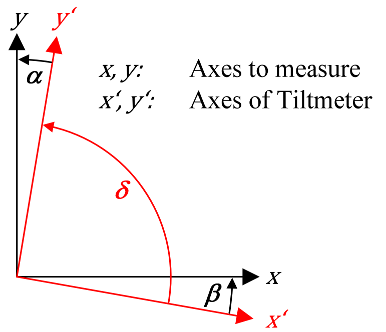

Fig. 4: Alignment errors during a tilt measurement

The cross-sensitivity and the cross-tilt were investigated using the tilttable as well. The cross-error of the tilttable axes was proven to be < 1 µrad in a Range of ± 10 mrad ($k = 2$) [18]. The determination of the angles (α, β, δ) bases on the mathematical rotation of coordinate systems expressed by the following equations:

$$x^* = y \cdot \sin\beta + x \cdot \cos\beta \qquad (2)$$

$$y^* = y \cdot \cos\alpha - x \cdot \sin\alpha \qquad (3)$$

For the determination of the cross-sensitivity and cross-error the tiltmeter was placed on the tilttable and its housing edges were adjusted with respect to the axes of the tilttable. The x-axis of the table was coincident with Channel 2 (CH2) of the tiltmeter in this case. Then the tilt about the x-axis of the tilttable was changed and the displayed tilts of CH1 and CH2 of the tiltmeter were recorded, see Fig. 5 (red curve). The corresponding cross-sensitivity can be given as $S_{xy}(\mathrm{CH1}) = 1.126 \cdot 10^{-3}$ rad/rad which corresponds to an angle $\alpha = -0.0723°$ (see Equ. 2, whereas $y^* \triangleq$ CH1, $x \triangleq$ CH2). The same procedure was applied to determine $S_{xy}(\mathrm{CH2}) = -1.46 \cdot 10^{-3}$ rad/rad ($\triangleq \beta = -0.0838°$). Thus, the angle δ between the tiltmeter axes results to $\delta = 89.9885°$.

Based on the angles α and β and the Equations 2 and 3, the measured tilts can be corrected mutually. By applying this procedure the cross-tilt can be reduced to $< 2 \cdot 10^{-7}$ rad in the whole measurement range of $\pm 9 \cdot 10^{-3}$ rad, cf. Fig. 5 (blue curve). This corresponds to a relative cross-error of ± 22 ppm. Considering the uncertainty of the tilttables own cross-Error of $< 1 \cdot 10^{-6}$ rad ($k = 2$) [18], the relative cross-Error must be given with < ± 22 ppm ± 111 ppm ($k = 2$).

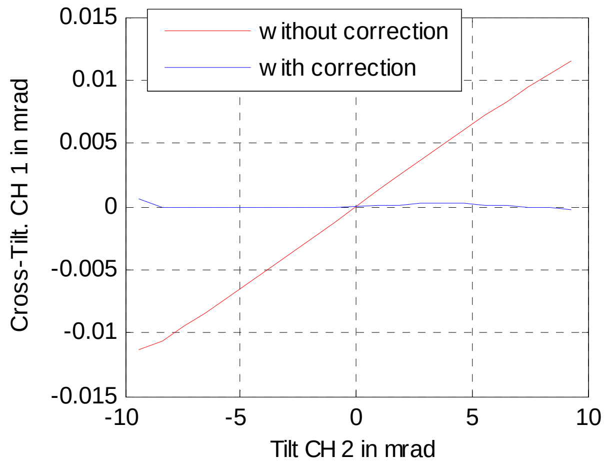

Fig. 5: cross-tilt with and without a correction based on the angles α and β

3.3. Noise and resolution

To investigate the resolution of the device, especially in short term measurements, the tilt signal was measured for 60 min with a sample frequency of Fs = 17 Hz. For those and the following long term measurements the tiltmeter was brought to the Geodynamic Observatory Moxa (50° 39' N, 11° 37'E) [19] which is operated by the Institute of Geosciences of the Friedrich-Schiller-University Jena (Germany). There, the device was placed on a concrete block, which is directly attached to the ground and mechanically decoupled from the laboratory building.

The peak - peak amplitude of the measured signal (Fs = 17 Hz) was between 60 - 80 nrad and the standard deviation can be given with σ = 17 nrad. The corresponding FFT of the CH1 Signal is shown in Figure 6 (blue). A dominant peak at frequencies between 0.1 - 0.5 Hz is obvious. This is a typical signal resulting from a tilt and a horizontal acceleration due to microseisms: surface waves generated at sea with frequencies between 0.05 - 0.5 Hz [8]. This signal is permanently existing and is therefore often used for functional tests of tiltmeters in this frequency range [15]. The amplitudes are depending on the distance to the oceans and the damping of the ground and were measured with 50 - 200 nrad (peak - peak) by geophysicists in south east Germany [15]. In the FFT they observed a frequency depending peak between 0.1 - 0.5 Hz which is in good agreement with our results. Thus, it can be outlined, that our tiltmeter is properly working with nanorad resolution in this frequency range.

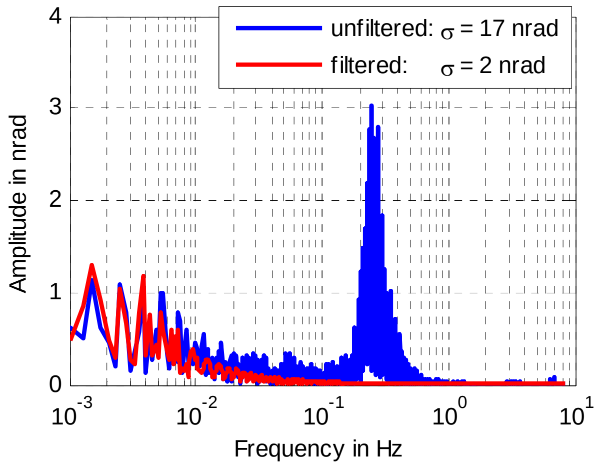

Fig. 6: FFT of a 60 minutes measurement of CH1

To suppress the microseisms a mean value filter with a filter length of 60 s was applied to the signal resulting in a standard deviation of σ = 2 nrad. The corresponding FFT with remaining peaks of ~ 1 nrad is shown in Fig. 6 (red). Sources for noise in frequency range of $1 \cdot 10^{-3}$ - $50 \cdot 10^{-3}$ Hz are given as atmospheric pressure changes (eg. wind turbulences) that are deforming the ground [8].

Anyway, especially in this frequency band it is very hard to distinguish the sources for the measured noise. They can be ground noise or instrumental noise [8].

Therefore, the instrumental noise and useful resolution of the tiltmeter is estimated with ~ 1 nrad.

3.4. Long term stability and long periodic noise

The investigations on the long term stability were carried out on the concrete block in the Observatory Moxa as well. The tiltmeter is operating in a specially designed vacuum chamber to reduce possible influences of humidity on the instrument. Prior to that the temperature drift was estimated in Ilmenau. Thereto a water tempered box was put above the tiltmeter which was placed on a stable measurement foundation. Changing the temperature of the tiltmeter resulted in a temperature drift of TK = -0.54 nrad/K for both axes. This temperature drift is roughly 10 times less than the drift given for the state of the art devices, cf. Section 2.

A 106 day measurement of the East West tilt (EW tilt) in Moxa is shown in Fig. 7 including a 5 day extract to depict the periodic influence of the earth tides clearly. Besides the earth tides other influences are obvious.

The long term drift might be due to an annual period which will be investigated closer after one complete year of measurement.

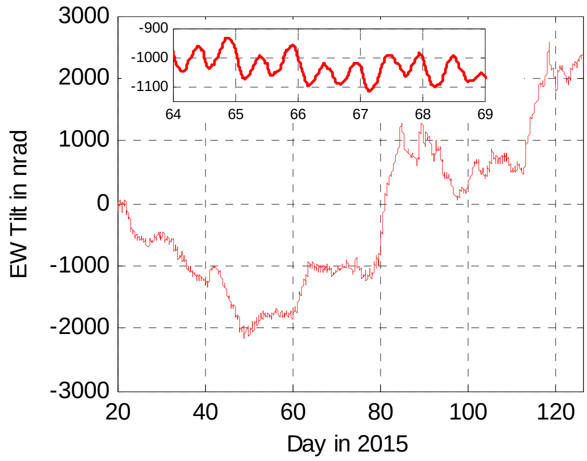

Fig. 7: Long term measurement of EW tilt

Other signal changes such as on day 30, 40, 60 and 90 seem to be well correlated with the ground water level which is generally known as one source of tilting [8] and was especially predicted for the measurement site Moxa [20]. The influences of ground water on our measurements are expected to be within the frequency range 0 d^{-1} - 1 d^{-1}. The change from day 80 – 85 is well correlated to the temperature of the concrete block and might be due to its thermal deformation.

The earth tides embody an appropriate test signal to investigate long periodic noise characteristics of a tiltmeter [15]. The chosen procedure to evaluate the noise bases on the procedure presented in [15]: The EW tilt was filtered with a highpass (cut off frequency 2d^{-1}). The corresponding FFT is depicted in Fig 8 (red). Additionally the expected tidal horizontal displacement of an ideal and homogenous solid earth was computed with the software from [21] and converted to tilt with the factor $7.692 \cdot 10^{-5}$ m described in [22], see Fig. 8 (blue). It applies as a good estimation of the expected tilt but local inhomogeneities and the influence of the oceans are not taken into account. The earth tide related diurnal (O1, P1, S1, K1) and semidiurnal harmonics (M2,

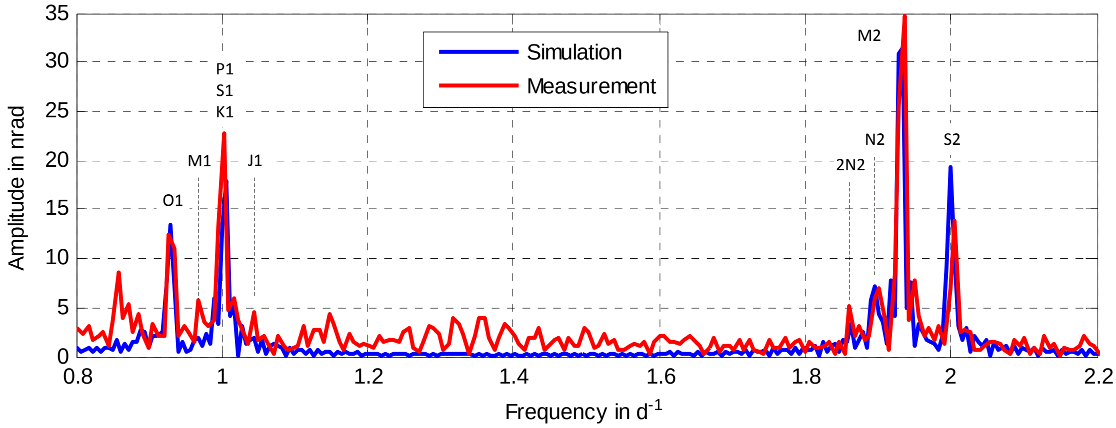

Fig. 8: FFT of a 106 day measurement of EW tilt

S2) are clearly resolved from the noise and well coincident with the simulated ones. The smaller amplitude harmonics (M1, J1, 2N2, N2) also seem to be distinguished from the noise.

In [15] the contributions between 1.2 d^{-1} and 1.8 d^{-1} have been taken into account to classify the noise of the measurement. In this frequency range our mean noise can be given as 1.7 nrad rms. The source for this tilting, either instrumental or ground noise is not clear at this point of time. In investigations of Klügel it was supposed, that this noise might be partly dependent on the depth of the measurement location under the ground [15]. They achieved 3.1 nrad in a depth of 6 m using an AGI-722 Borehole tiltmeter, 0.5 nrad in a depth of 10 m using a Lippmann and 0.24 nrad in a 30 m borehole with an Askania tiltmeter. Our device is not installed below the ground level but somewhat in the beginning of a tunnel that goes horizontally into a hill.

Those considerations indicate that our presented tiltmeter is suitable to observe even very long periodic harmonics with nanorad resolution. Investigations on the noise contributions will be an object of further discussions with the geophysicists in the future. The annual long term stability will be observed after one complete year of measurement in January 2016.

4. TILT CONTROL OF A MEASUREMENT BASEMENT

An application of the tiltmeter besides the geophysics is the improvement of tilt sensitive measurements such as high sensitive force measurements [2-4, 6, 7].

One possibility is to measure the tilt of the tilt sensitive measurement setup and then mathematically correct its measurement result. Hence, the tilt sensitivity of the measurement to correct must be known precisely. This can be seen as a disadvantage of this method.

In contrast to this, the tilt of the tilt sensitive measurement setup, the measurement table or the basement respectively can be servo controlled. First tests on this have been carried out in Ilmenau by servo controlling one axis of a 3 ton granite stone on which high precise force and mass measurements are carried out. As actuator a piezo stack was placed under the stone. In this simple first test we achieved a tilt stability of the controlled stone of < 1 nrad rms in 9 hours.

Due to this promising first result the servo control of the tilt of measurement tables or basements will be subject of further research at TU Ilmenau.

5. CONCLUSIONS

We have proposed a novel design for tiltmeters basing on commercial weigh cells. The tiltmeters can be operated in two different modes. Results achieved with the Balance Mode have been presented in this paper.

Due to permanent natural noise sources it is very challenging to separate the ground noise from instrumental noise of the tiltmeter. Based on analysis of the FFT in different frequency ranges the useful resolution can be given with ~ 1 nrad. Thus, our tiltmeters reach the state of the art resolution of ~ 1 nrad at a remarkable extended measurement range of up to ± 9 mrad. The relative linearity deviation is as low as $< 0.25 \cdot 10^{-3}$ ($k = 2$). We also investigated the cross-sensitivity of the tiltmeter axes, a parameter which is usually not indicated in datasheets but is important to reach low measurement uncertainties. Here we observed a relative cross-error of < ± 22 ppm ± 111 ppm ($k = 2$). The uncertainty results from the uncertainty of the used tilt calibration table.

Furthermore long term measurements proved, that the tiltmeters are capable for the measurements of small fundamental signals such as the earth tide related tilting of the earth crust. To consider local annual tilt changes of the measurement site a possible long term drift of the instrument will be further observed after one complete year of measurement.

In the future the device will be used to control the tilt of measurement tables and basements at TU Ilmenau. First test have shown that we can control the tilt of heavy measurement basements (3 tons) with a standard deviation of < 1 nrad in a range of some µrads.

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