Research Article

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Accuracy and functional assessment of an original low-cost fibre-based inclinometer designed for structural monitoring

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Abstract: Safe exploitation of a building requires constant monitoring of both the object itself as well as its surrounding through the monitoring system. These tasks find particular applications when operating large construction projects, especially in urbanised areas. Besides the warning function and undertaking reactions, the monitoring system allows for recording changes in object geometries to assess their stability. To conduct monitoring, various sensors and instruments that work within the applied measuring systems can be used. As an example, one can mention precise inclinometers ('electronic bubbles') allowing for accurate determination of inclination angles. The paper discusses the precision and functional aspect of the original inclinometer developed and improved by the authors. The working principle of the device is based on optical fibres, light projection and its detection on a CCD camera objective. The presented issue is a low-cost solution offering high measurement accuracy, which may be used in structural monitoring of objects located in the impact zone of a deep excavation or other nearby ongoing investments.

Keywords: deformation monitoring precise inclinometers, displacements, surveying control networks

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1 Introduction

The problem of deformation monitoring has been the subject of research and implementation activities in the World for many years. It is worth noting that the crucial elements of each monitoring system are warnings and alerts. Such action requires providing continuous or quasi-continuous (continuous for some time) measurements. It is useful here to utilise and integrate different surveying technologies, i.e., metrological or physical monitoring [14,16,20,28].

For several years, we have been observing dynamic economic development in Poland, which transfers into numerous ongoing investments. The development of infrastructure concerns both roads, bridges, as well as residential or office buildings. The main Polish cities are mainly involved in construction works, including investment and business centres. The specificity of their location (in particular, geological and geotechnical conditions) makes it necessary to apply various solutions in the field of geodetic deformation monitoring. An example may be the construction of the second metro line in Warsaw, the Warsaw Southern Highway Bypass, or the extension of the Grunwaldzki Square in Wrocław, Poland (Figure 1).

In the vicinity of the existing building of the Faculty of Environmental Engineering and Geodesy (Wrocław University of Environmental and Life Sciences) situated in the mentioned Grunwaldzki Square, a construction project was begun, which required a deep excavation. Therefore, it was necessary to start the deformation monitoring – initially mainly vertical displacement surveys. Regarding that, a unique control network called 'Plac Grunwaldzki' was established with numerous benchmarks for precise levelling. Soon, apart from the study of vertical soil movements, it has become necessary to monitor structural deformations of existing buildings. This problem motivated the authors to develop an appropriate device – a new solution competitive to the instruments existing on the market in terms of accuracy, price, as well as maximally resistant to adverse

Figure 1: The location of Grunwaldzki Square in Wrocław, Poland, with the recent most extensive investments (own elaboration).

external factors (like vibrations caused by pneumatic hammers and pile drivers). The device has been developed and constructed using the advantages of optical fibres, which – for testing purposes – were mounted on the supporting wall. This project is a modification of the already existing structure, which both working principle and application are presented in ref. [6]. These instruments had been designed and tested mainly for geodynamic and geoengineering studies. In such applications, there exist some unique factors determining the measuring conditions. Above all, such instruments' constructions need to be more robust because they are dedicated to be used in long-term surveying cycles, especially in mountains, on slopes, or near landslides. Using such devices to study the displacements of surveying networks of engineering structures is also shown in ref. [7].

In the presented solution, the authors have modified the instrument's core design in terms of studying its stability (mainly damping). Instead of round weight pendulum equipped with supporting wings, as it is presented in ref. [6], based on own observations and empirical tests, the authors decided to use a hexagonal weight. Such a new solution is easier to implement and provides more stable damping. What is more, the authors resigned from underneath placed mirrors perpendicularly transferring light rays to camera lances. Instead of that, they chose the principle of a direct light projection on CCD camera. The newest version uses also different materials – first of all, a round polymer housing as well as it utilizes a modified way of fixing the pendulum. Generally, the new construction is based on low-cost, broadly available components.

The functional aspect of our newest solution encompasses single-core optical fibre placed in a unique inclinometer tube. As the light emitter, a luminescent diode is used. The light ray is then transmitted through a hanging fibre line projecting light onto a CCD sensor placed directly underneath the emitter (white unpolarised light ray issuing directly from fibre-optic cable). Thus, the emitted light is observed continuously within the field of view of the CCD camera, which prevents from possible systematic errors that may appear during the transmission of the beam employing mirrors. Such as simplification of the solution transforms into a lower cost of production (all components used are readily available), and hence, opens up vast possibilities of using the device in various structural monitoring projects. The material presented encompasses preliminary studies of an own construction which – contrary to complex professional solutions offered by different manufacturers worldwide should be treated as completion of existing, large-scale solutions and not as their replacement.

2 Fibre-optic measuring instruments

Among the physical measurement technologies used in Structural Health Monitoring (SHM), an important place is taken by increasingly popular optical fibers. Their use refers to the study of both phenomena occurring on an object (temperature changes, vibrations, pulses) as well as different properties of the structure itself (deformations and displacements). In this area, a rich literature is available describing various structural solutions or discussing specific use cases [2,19,26]. Besides the use of ready-made technological solutions, specialists in the field of metrological and physical instrumentation continuously conduct researches on developing new or improving existing projects.

Works on designing devices dedicated to investigating changes in inclination angles of geotechnical objects (mainly slopes) as well as engineering structures have been conducted for many years in various construction and research teams [4,8,10,11,22]. For example, the use of fibre optics for the construction of inclinometers was presented in ref. [18]. The relative accuracy of the device obtained during laboratory tests depended on the size of the displacements studied and equalled from 3% to 14% (relative to the length of the test section). Such a solution relates more to classical inclinometers detecting movements of ground layers and can successfully be applied more in geotechnics rather than in SHM. In work [24], the authors presented the concept of Fiber Bragg Grating (FBG)-based inclinometer – the so-called FBG sensor embedded in a short segment of an optical fibre, which was used in the monitoring of slopes' movements. The applied computational algorithm allowed for estimating the deflection of the device by transforming the measured strain from the displacement response. The cantilevered beam used in laboratory tests was previously subjected to numerical modelling in order to assess the reliability of the results obtained in practice. After the tests, the authors stated that their developed inclinometer made it possible to determine the values of deflections with an average relative error of 5%, which is satisfactory and acceptable in deformation monitoring. Another innovative solution is proposed in the paper [23]. The developed device used the advantages of Fabry–Perot (F–P) interferometer [25]. The instrument consists of a bracket placed in the housing equipped with suspended test mass. Due to the ongoing displacement, the whole set reduces its distance to the optical fibre placed in front of it. The average measurement accuracy that the authors obtained during device testing was 0.03 mm within the measurement range of ±1.048°. According to the authors, their inclinometer is resistant to vibrations and various disturbances, which dedicatees it, in particular, for construction works applications. Such principle is close to our motivation; however, we aimed to construct a clinometric device based on widely available elements giving high accuracies on the same level.

In another research paper [1], the authors described a fibre-optical sensor based on the fibre-taper-modal Michelson interferometer. The authors presented the design utilizing a fibre combination characteristic for the Michelson interferometer [9,21,27]. After the tests, the angle of the measured deflection reached the accuracy of 14 mrad, which can be useful in geotechnical monitoring. Nevertheless, the measurement accuracies required for SHM are usually one order higher than the aforementioned [13].

Developed inclinometers can successfully be implemented into combined measuring systems used for structural monitoring purposes. In publication [12], the authors propose utilizing a precise, self-designed, laser-beam-based inclinometer in the automated monitoring of building structures localised in unstable areas – mostly influenced by mining labours. The described system uses laser emitter placed in the bottom floor (basement) of a building and projecting light ray towards the structure's ceiling. Then, the laser spot is detected by a CCD array of a dedicated camera. The emitter is equipped with a compensator which suppresses potential vibrations and shocks. Such laser gauge provides users with high relative accuracies. Mean errors of measuring displacements towards *XY*-axes of a local reference frame was estimated as ±2 mm. The system concept, however, refers rather to high-rise buildings or mining shafts where users have to face the problems of measuring tall, linear items.

Besides, directional measurements performed by various instruments, among others the inclinometers, can be assessed and optimized by using algorithms or data processing approaches, for example utilizing entropy [15].

All inclinometers are subject to accuracy validation and calibration. Detailed procedures for such approaches are presented in ref. [3,17,28].

Each described instrument allows for determining the angle of deflection of the tested element to which it is attached using a light beam transferred through optical fibres. The studies carried out by the authors of this article also fit into the mainstream work on fibre-optic technologies in applications of engineering geodesy. A summary of these achievements can be found, among others, in the monograph [5].

3 Inclinometer's design

The scheme of the developed inclinometer is shown in Figure 2a and its working principle is explained in Figure 2b.

The device was tested in the instrumental laboratory of the Institute of Geodesy and Geoinformatics, Wrocław University of Environmental and Life Sciences.

On the bracket (1) a kind of pendulum is hung – i.e. fibre-optic cable (2) with a copper hexagonal weight (3). The beam of light emitted from the face of the optical fibre (4) passes through the lens (5) and falls on the CCD sensor of the digital camera (6) which resolution is 5 MPx. Then, the image is recorded at a frequency of 30 frames per second. The whole set is surrounded by a polymer housing (7), which is attached to the tested object using clamps. As a pendulum, we used a copper weight suspended on an optical fibre with a diameter of 1 mm and a length of 1,050 mm. It passes through the centre of the pendulum. Then, a CCD camera observes the image of the glowing end of the optical fibre core mounted directly under the pendulum at a length of 20 mm. The optimal weight and the distance to the camera lens were determined experimentally. The working principle of the device relays on conducting a continuous measurement of the pendulum movements, whose changes in the position in space are related to the displacement of a building structure (Figure 1b). A complete set for mounting the inclinometer is shown in Figure 3.

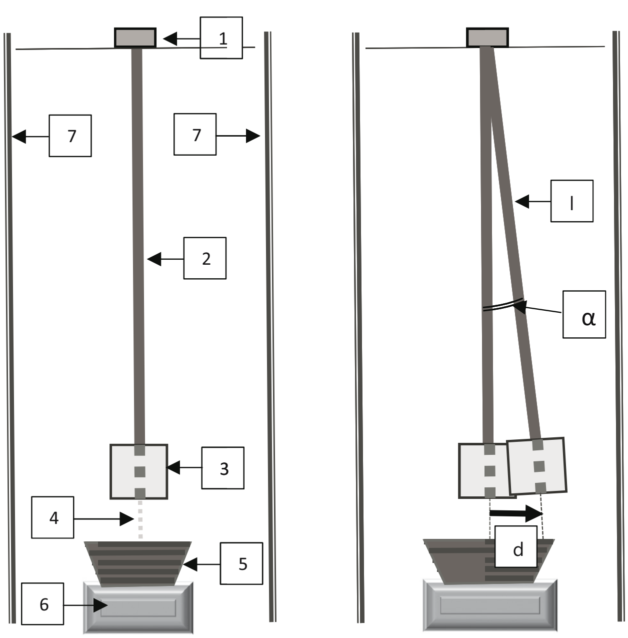

Figure 2: (a) Scheme of the designed inclinometer and (b) the work principle of the instrument (l – length of the fibre, α – inclination angle, d – movement vector) – own elaboration.

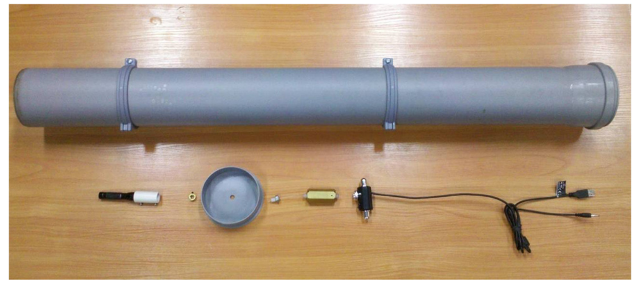

Figure 3: Components of the proposed set of the optoelectronic fibre-based inclinometer (own elaboration).

The angle of the swing is calculated according to the formula:

$$\tan \alpha = \frac{d}{l}$$

where d – inclination vector and l – length of the pendulum.

The image sequences recorded by the in-built camera formulate a complete film. While analysing particular frames, we get a picture of a bright spot of 1 mm in diameter (Figure 4). Its location is subject to automatic detection as well as it is continuously analysed by a dedicated application developed in the Matlab® environment [6]. The authors used their own developed algorithm, referring to image analyses. Its main principle is based on the automatic recognition of an 'energetic centre' of the detected light spot within the analysed frame. The recognised energetic centre is represented by a certain point with local XY-coordinates. While analysing subsequent film frames, we obtain a data set containing the

Figure 4: The bottom view of the hanging weight with the glowing core of the optical fibre (own elaboration).

series of plane coordinates which represent the displacement trace of a measured structure.

4 Instrument examination

The operational precision of the device was checked by performing the test explained schematically in Figure 5. For this purpose, the especially developed examiner was used, which consisted of a reference plane placed on the tribrach coupled with professional machine bubble.

The relative accuracy of the bubble is defined as 0.05 mm/1 m. While observing the indications of the precise machine bubble, the inclination of the examiner's plane was changed, and at the same time, the sequence of images was recorded with the attached CCD camera. Then, the vertical deflection was increased in 10 s-step using the tribrach screws. The full test consisted of ten such cycles (Table 1) – in total 1,000 measurements.

Based on experimental research, the scale of recorded images was determined. Furthermore, it was established that the size of one pixel corresponded to the value of 0.016 mm.

The standard deviation based on the results of the 10 measurement cycles concerning the X and Y axes of the local coordinate system expressed in pixels equalled ±0.06 pix, which corresponds to the linear value of ±0.001 mm. In addition, the authors also determined the operational range of the designed instrument, which equals 10 mm/1 m functional length of the fiber line.

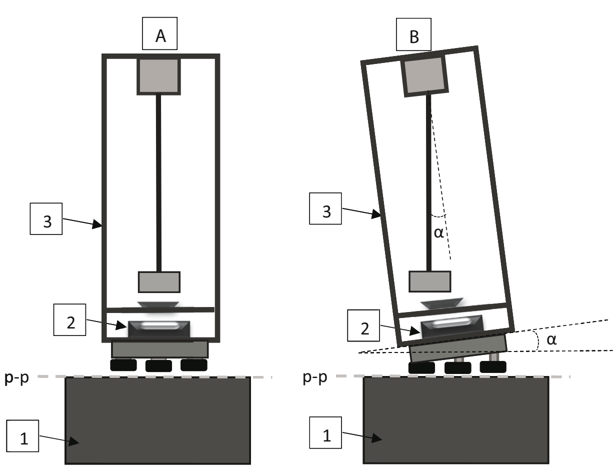

Figure 5: Testing scheme of the optoelectronic inclinometer: (a) normal position, (b) forced inclination; where (1) concrete pillar, (2) machine bubble, (3) inclinometer, p–p – horizontal axis of the pillar, α – inclination angle of the plummet examined by the bubble (own elaboration).

Table 1: Averaged positions of the fiber core in the following ten measuring cycles (own elaboration)

Measurement cycle	*X*-axis [pix]	*Y*-axis [pix]
1	268.33	199.92
2	268.37	199.95
3	268.36	199.96
4	268.38	199.95
5	268.37	199.94
6	268.37	199.96
7	268.39	199.96
8	268.43	199.98
9	268.47	200.04
10	268.55	200.08
Average	268.40	199.98
Std. dev. [pix]	0.064	0.048
Std. dev. [mm]	0.001	0.001

Figures 6–8 illustrate the position of the inclinometer's pendulum in three representative cycles: at the beginning (Cycle 1), in the middle (Cycle 2) and at the end of the test (Cycle 3).

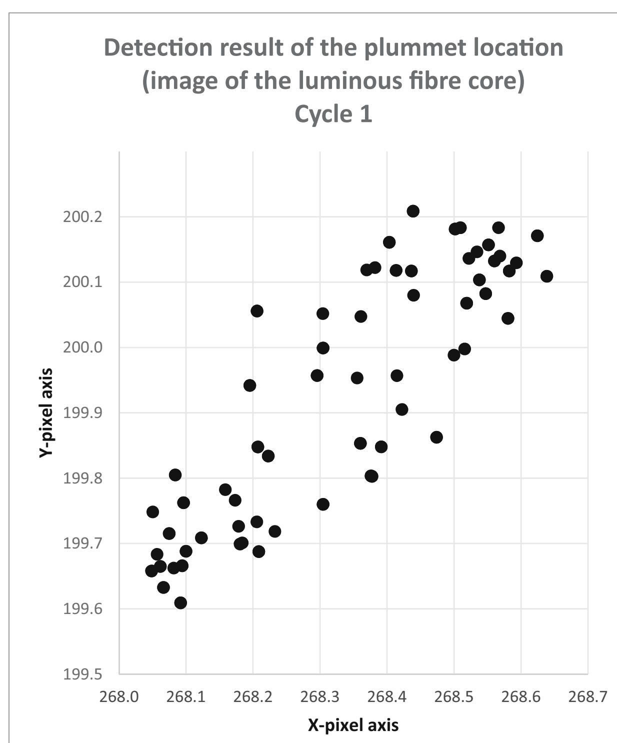

Figure 6: Detection result of the plummet location (image of the luminous fibre core) – Cycle 1 (own elaboration).

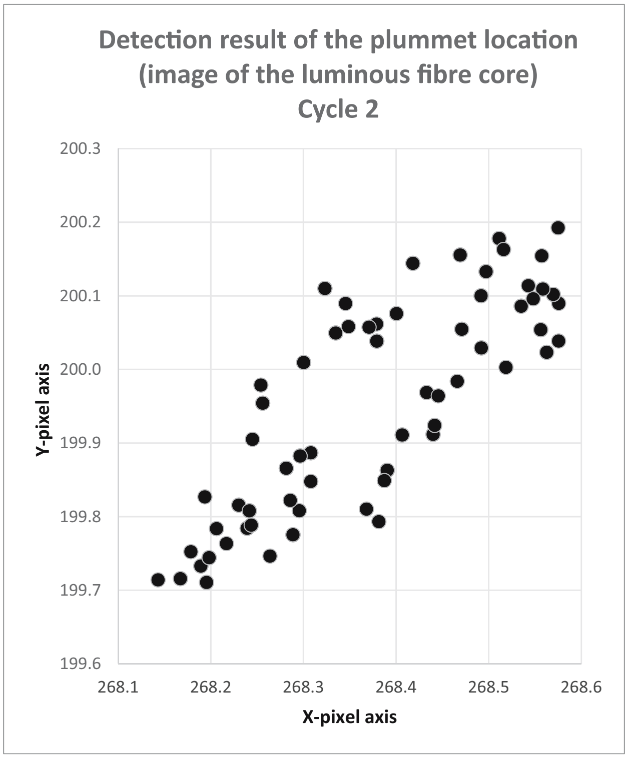

Figure 7: Detection result of the plummet location (image of the luminous fibre core) – Cycle 2 (own elaboration).

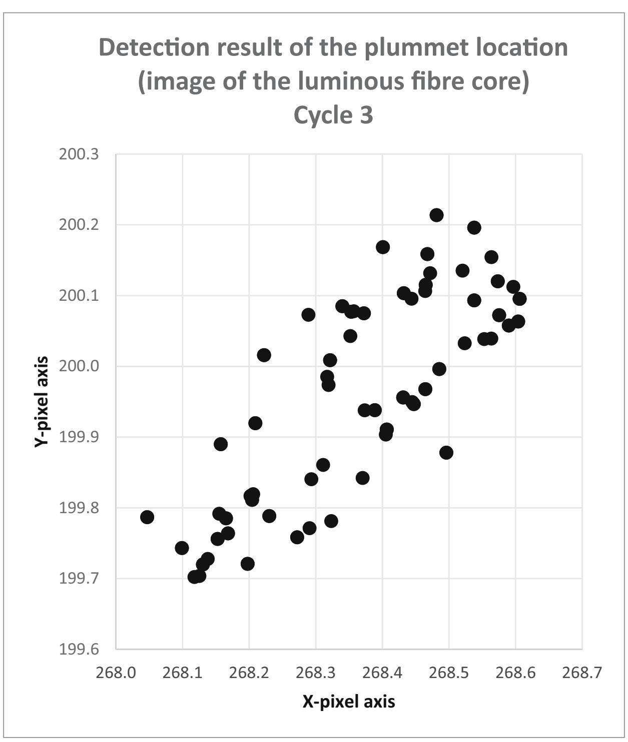

Figure 8: Detection result of the plummet location (image of the luminous fibre core) – Cycle 3 (own elaboration).

As one can see in the pictures, the dispersion of particular pendulum's readings detected by the camera has stabilised (the stabilisation time is less than 30 s). At the end of the test, all readings have become coherent, which means that the instrument could be used in long-term surveying of structural movements.

5 Conclusions

Based on the performed accuracy tests and functional analyses, it is possible to formulate several conclusions.

Above all, the authors' modification of the existing original solution that had been used before significantly improved its functional aspect. After the adjustment, different sources of systematic errors – mainly damping – were considerably reduced. In addition, a fibre line loaded with a unique weight equipped with damping edges precisely represents the plumb line. Their shifts can be recorded by the underneath placed camera. Such a construction does not utilize any optical intermediary between a light ray and CCD array. Moreover, single-fibre lines are resistant to twisting, which significantly stabilises the light ray projection onto the camera's CCD array. It converts to stable analyses of subsequent pictures presenting light spots and – finally – brings coherency in determining inclination angles of tested objects.

The instrument presents the simple construction and offers easy access to it. To prevent the whole set from unexpected, immediate vibrations or shocks, it can be mounted on a structure using shock absorbers widely used in similar installations (the simple ones made of the gum or more sophisticated – hydraulic-based devices).

The studies show that the designed instrument can be used in any continuous measuring programme offering the highest possible precision. Second, the solution using the pendulum with hexagonal weight results in a fast stabilisation and reduction of readings' spread. It positively affects the reliability of the measurements and provides universality of the solution.

The original device allows for collecting continuous information about the occurring phenomena (inclination of the object) and expressing them in the local *XY* coordinate system assigned to the object. The instrument makes it possible to determine relative displacements – which in many cases constitutes crucial, desirable data about the object's structural health. In addition, this is a low-cost type project – i.e. the cost of all components, as well as of the entire solution is almost negligible compared to existing devices offered by recognised manufacturers.

The micro-light source (the emission from the luminescent diode through the optical fibre) may undergo further miniaturisation. Similarly, one can modify the length of the optical fibre, which can be adjusted depending on the needs (on the type of object on which the device is to operate). Both the length of the fibre-optic pendulum arm and the test weight of the pendulum can determine the final measurement accuracy. These parameters can, therefore, be modified and adapted to the current requirements related to the object. Moreover, to increase the reliability and reduce the measurement uncertainty, multimode fibre can be used in this construction. Such an approach would require conducting additional research and extending the existing Matlab-application by adding an algorithm analysing the images of other light spot traces projected on the CCD matrix. The construction developed is subject to further studies considering the instrument's applications in different ambient conditions.

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