Application of an evolutionary algorithm to a software suite for determining degrees of tilt in cylindrical structures based on terrestrial laser scanning data

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Abstract. This article describes a software suite for determining degrees of tilt in cylindrical structures based on one of the simplest search optimization methods (the evolutionary algorithm). The software was designed using Visual Basic for Applications. It contains several blocks (subprograms), with each of them performing a specific task.

Introduction
In this article, a particular type of cylindrical structures, namely flue-gas stacks, is considered (Figure 1). As these objects are intensively operated, their performance gradually deteriorates. Geodetic monitoring is required in order to timely detect problems and take appropriate measures. Flue-gas stack inspection, including geodetic monitoring, should be done during the first year after commissioning, after which it should be done every five years.

Figure 1. Flue-gas stack
In addition to planned inspections, there are situations which require that urgent geodetic surveys should be done in order to assess the current state of a flue-gas stack. One of the main tasks here is to determine the degree of tilt.

1. Geodetic methods of determining the degree of tilt

According to the manual [1] and the book [2], there are different geodetic methods for determining the degree of tilt in tall structures:

1) multilateral – leveling, vertical measurement methods, linear measurement methods, angular measurement methods, coordinate measurements, and photogrammetric methods;
2) unilateral – linear and angular methods, coordinate measurements, and vertical measurement methods;
3) perspective – satellite methods, laser scanning, measurements taken by UAVs, and video measurements.

Today, the latter group of methods is becoming more popular as geodetic equipment is constantly being improved. One of the advantages of these methods is data visualization which they provide. Laser scanning, one of the most promising methods, plays a special role because it is this method (provided that it continues to be improved) that can ensure instant data collection.

Very often, the production process requires that operational data should be collected instantly in order to assess the current state of the object. In view of this task, we developed a software suite for determining degrees of tilt in tall structures during field surveying (with no need for conducting analysis in the office) based on terrestrial laser scanning data.

2. Software suite

The software suite consists of the following subprograms (blocks):
- initial data input (laser point coordinates);
- section cutting;
- detection of gross errors;
- circle approximation of measurement results;
- calculation of the degree of tilt (angle and direction);
- data output.

Initial data input. Before entering data into the program, the image obtained in field surveying should be approximately tied to the local coordinate system. When laser scanning is done, structural elements (antennas, ladders, fittings, reinforcement elements, etc.) are scanned too (Fig. 2). They are not only useless for determining the degree of tilt but can also significantly distort the final result. It is therefore desirable that data on these elements should be partially excluded before entering initial data into the program.

![Figure 2. Examples of various structural elements of flue-gas stacks](image-url)
Initial data is put into the program using a .txt file. Each line contains \(X, Y,\) and \(Z\) coordinates for a laser point separated by spaces.

Section cutting. Next, three sections are analyzed: upper, middle, and lower. The width of each section is set by the user. Points falling into these intervals are chosen (Figure 3).

![Figure 3. A diagram of a flue-gas stack with sample areas](image)

Detection of gross errors. In addition to large structural elements, there are also smaller elements present (chipped bricks, small reinforcement elements, etc), which can also distort calculation results. Data on such objects are rejected using the method described in [3]. This program block is responsible for general quality control (\(\chi^2\)-control) and control of deviations of each point from the constructed circle (Grabbs – Smirnov criterion).

Circle approximation of measurement results. This program block is based on an evolutionary algorithm which inscribes a circle in each section, i.e. it determines the coordinates of the centre of the circle and its radius. The objective function is as follows (Equation 1):

\[
f(x, y, r) = \sum_{i=1}^{j} \left[ \sqrt{(x_i - x)^2 + (y_i - y)^2} - r \right]^2
\]

where \(x\) and \(y\) are the coordinates of the center of the circle, \(r\) is the radius of the circle, \(x_i\) and \(y_i\) are coordinates of the points on the circle, and \(j\) is the number of points measured.

Calculation of the degree of tilt. The angle and direction of tilt are found using classical equations (Equations 2-4):

\[
l = \sqrt{\Delta x^2 + \Delta y^2},
\]

\[
\alpha = \arctg \frac{\Delta y}{\Delta x},
\]

\[
\phi = \arctg \frac{l}{H},
\]

where \(l\) is the total linear value of tilt, \(\Delta x\) is the difference between the abscissas of the centers of the two sections, \(\Delta y\) is the difference of the ordinates of the centers of the two sections, \(\alpha\) is the angular value of tilt, which determines its direction; \(\phi\) is tilt angle, and \(H\) is flue-gas stack height.

Data output. Intermediate data and final results are displayed in MS Excel and User Form.

3. Search methods. Evolutionary algorithm
Let us consider in more detail the program block which is responsible for circle approximation of measurement results.

The only drawback of terrestrial laser scanning is that it produces a lot of redundant data. Data cloud can contain hundreds of thousands of points, and sample areas may contain thousands of points. However, only three points are needed to inscribe a circle in a sample area, and when there is redundant data, the problem of optimizing the solution process arises.

The purpose of the optimization problem is to find a solution in accordance with an objective function (a criterion of efficiency or quality), for example, the sum of squares of measurement corrections \( V^2 = \min \) or the sum of correction modules \( |V| = \min \). Mathematical programming methods are used to solve optimization problems, the most effective being search methods.

The simplest search method is to repeatedly calculate the objective function while changing one or more variables until the minimum of the objective function is reached. Search methods have been known for a long time, but they have been little used because of low computer performance [4]. This issue is no longer relevant because modern computers can perform millions of computational operations in seconds. This is why search methods are becoming more popular in solving optimization problems.

Recently, genetic (evolutionary) algorithms have become very popular in different areas. These algorithms were copied from nature and they involve different tools of ‘natural’ selection. When describing evolutionary programming, simplified biological terminology is used.

Let us consider the most primitive type of natural selection (random mutation) and whether it can be described as a computer program.

We have a function which depends on \( n \) parameters. Each parameter ‘mutates’ (changes) in one direction or another. Mutations can be both beneficial and harmful. The best combination in terms of the objective function is selected out of each \( m \) ‘mutants’. The remaining combinations are rejected. If we are not happy with the result, we will repeat these steps until we are finally satisfied.

Genetic programming is, in effect, a process of scanning possible parameters of the objective function and selecting the best of them (Figure 4).

We have already successfully used other search methods (the variable step search method [5] and the parabolic optimization method [6]) for solving such geodetic problems as determining parameters for connecting two coordinate systems to each other and circle approximation of measurement results.

Search methods seem to be the most promising among other mathematical programming methods due to their advantages:
- a wide variety of mathematical algorithms which have already been developed;
- an opportunity for combining these algorithms with each other, as well as and with other nonlinear programming methods;
- ease of software development;
- independence from the accuracy of the preliminary values of the parameters being analyzed (values that are far from the true ones can be chosen without negatively influencing the solution process);
- there is no need in correction equations or constraint equations, and neither is there any need in using a system of normal equations and solving them;
- there is no need in linear calculations.

It is known that any problem can be solved using different methods. The only question is how rational each of these methods is. Optimization problems are a special class of problems which need to be solved rationally with a minimum expenditure of time and resources. It is not always possible to solve these problems using traditional methods. In their turn, search methods are easy to use in programming. A large number of these methods and the development of new search algorithms make it possible to adapt them with a view to solving any problems.
Summary
The main objectives of this study are:
- to create a software suite for determining the degree of tilt which could be used in geodetic surveying.
- to solve the optimization problem of approximating measurement results in the presence of a huge amount of redundant data.

Both problems were successfully solved.
The advantages of the software suite which was designed include:
- quick problem solving;
- data visualization;
- an opportunity for adapting the program to other tasks, for example, axis alignment in rotating objects;
- input data flexibility (both laser point coordinates and coordinates measured by a total station can be used as input data).

What makes this software suite special is the fact that it uses a search method (the evolutionary algorithm) to solve optimization problems. It means that, firstly, search methods can be used in solving geodetic problems and, secondly, despite a large number of iterations these methods turn out to be the most effective in solving optimization problems.

References
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