Digital filtration methods in selected industrial applications

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Abstract. The aim of the article is to present selected methods of digital filtration and their algorithms used in industry. The article presents some examples of the use of digital filtration methods in two areas. The first area of an application of filtration covered the issue related to production technology and surface topography. The second area describes examples of the use of filtration in the navigation of automated guided vehicles (AGV) serving production lines. In the research part, selected methods of digital filtration were tested and their effectiveness was determined.

1. Introduction

Digital filtration is a very important element of modern metrology. It is carried out using filters that are complex mathematical tools. In practice, filters are used to suppress noise, correct data obtained from measuring apparatus and a display important features from the point of view of an analysis.

Surface metrology is one of the most common applications of digital filtration where analyzes of the characteristics of a wide range of surfaces are performed. Digital filtration is widely used, among others in measurements of the geometric surface structure (GSS). The GSS measurement is performed to control the manufacturing process and to predict the functional properties of the surface. The most common is the analysis of surfaces produced in the construction of machines [1]. In the surface control process, roughness parameters are usually analyzed. The subject of control may be waviness, whose occurrence is usually detrimental to the work of machine elements and should be aimed at minimizing it. The use of correct filtration leads to the correct determination of surface roughness and waviness parameters.

Authors of many works, e.g. [2, 3] analyzed differences in roughness parameters after using different filters and found significant differences, also in relation to surfaces with symmetrical distribution of ordinates. The choice of the wavelength limit of the filter is also important. The smaller the elementary section, the more the waviness is suppressed.

Filtration carried out incorrectly can qualify well-made surfaces as deficiencies or, what is more dangerous, poorly made machine elements as correctly made. This is particularly important because the areas usually manufactured in a way that provides certain operational properties are inspected [2–4]. Since the geometric structure of the surface is a reflection of the fact that the features change below the surface. Often the produced elements have geometric surface structures for specific applications, and the analysis of micro-lines is at least as important as the analysis of geometric dimensions.
Another example of the use of filtration in measuring the geometric structure of a surface is [5]. The authors of the work used digital filtration methods to study the parameters of the roughness of corroded steel piles exposed to sea conditions under different exposure conditions. Descriptive statistical parameters adopted in this study were selected from the list of parameters for determining the geometric structure of the surface using spatial methods contained in the ISO 25178-2 standard.

The wood industry is an example of the use of digital filtration algorithms in measuring the geometric structure of the surface. The work [6] presents the results of research on the possibility of using a robust Gaussian regression filter in measurements of wood surfaces polished with different grain sizes. An objective and a quantitative assessment of the quality of the treated wood surface requires the use of measuring instruments to collect data from the surface, which are then filtered to leave only irregularities that characterize the roughness. The filtering removes the waviness in the data profile resulting from accidental changes in the machining process or the material being tested. In the case of changes occurring during the machining process, the source of their formation may be vibrations. On the other hand, changes in the material can be caused, for example, by differential contraction in the growth ring. Filtering is necessary to calculate various parameters characterizing surface quality. Data filtering for wood surfaces is complicated because wood contains specific anatomical structures that create a surface texture independent of any machining process.

Digital filtering methods can also be used in the navigation process of automated guided vehicles. An example of such an application of digital filtering methods was presented by the authors of the work [7]. In the article they presented the results of simulation tests whose aim was to select the appropriate method of filtration which will eliminate the unfavorable phenomena arising during the determination of the current position of the AGV vehicle and allow determining the radius of the arc on which the vehicle moves.

This will allow determining the correction to the navigation calculation algorithm and to make the current course correction. The tests carried out concerned the AGV vehicle which used the odometry to determine the current position. This way of determining the position of the vehicle is burdened with many errors [8–11] and requires correction. A number of measurement methods are used in the correction process. After the measurement, the vehicle's course is corrected. The correction can be entered continuously or cyclically after passing a given segment or passing a specific marker – a reference point. To investigate and determine the effectiveness of the filtration methods considered and their algorithms, the authors of the work [7] analyzed the numerically generated courses reflecting the real trajectories of an automated guided vehicle. One of the main errors of the considered navigation system, which is odometry, is the selection of the wrong ratio of left wheel radiiuses to the right wheel. This error is included in the group of systematic errors and causes the vehicle to deviate from the specified direction of the route and performs curvilinear motion along an arc with a constant radius. Measured actual routes are characterized additionally by occurrence of oscillations resulting from the applied control system, as well as disturbances and random errors of measurement resulting from the used measurement sensors.

The purpose of this article is to present selected methods of digital filtration and their algorithms used in practical applications. Since the application of digital filtration in measurements of the geometrical structure of surfaces produced in machine construction is fairly well documented in specialist literature [2, 3, 12, 13], the article presents the possibility of using digital filtration in AGV navigation.

The results of experimental research presented in the article concerned the application of selected digital filtration algorithms in the process of recognition and mapping of the environment in which the AGV vehicle will move. The mapping of the AGV vehicle environment was carried out using measurements from a laser rangefinder. As the results obtained from measurements are subject to interference, they must be filtered. Currently, there are many techniques for filtering data. Each of the existing filtration algorithms has properties that narrow the scope of their application.
2. Filtration methods

In the studies described in the next part of the study, aiming to investigate the effectiveness of various filtration methods, it was decided to limit to the Gaussian regression filters of zero and the second order and the spline filter. Such choices were made on the basis of own experience acquired during the performance of many works [2, 3, 7].

The designation of the middle line of the Gaussian regression filter \( w(x) \) of zero order is done using regression function. The advantage of this filter is that for each point of the measured section the value of the mean line of the filter is defined. The regression arrangement can be mathematically described by the following relationship [7, 14]:

\[
\int_{x_i}^{x_j} (z(x) - w(x))^2 \cdot s(x) \cdot dx \rightarrow \min_{w(x)}
\]  

(1)

The value of the mean line of the filter \( w(x) \) of the filtered profile reduces the squared deviation of the measured profile \( z(x) \) weighted by \( s(x) \) and integrated in the range of \( 0 < z(x) < 1 \) \( (l \text{- measured length}) \). The limits of integration are defined in such a way that guarantees analysis of the entire section measured.

The mean line of the filter \( w(x) \) is described by the following formula:

\[
w(x) = \int_{x_i}^{x_j} z(x) \cdot s(x) \cdot dx \text{ where } s(x) = s(x)/\int_{x_i}^{x_j} s(x) \cdot dx
\]  

(2)

In addition, the regression filter performs a weighted averaging (shown in equation 2). Averaging occurs in a finite interval. The weight function \( s_0(x) \) is scalable, so its area is always set to 1. The regression filter corresponds to the filtration with phase correction in accordance with ISO 11562 standard, when the weight of \( s(x) \) is replaced with a Gaussian probability function and the limits of integration are in the range. The Gaussian regression filter allows the avoidance of the effects of the final profile by changing the weight function for the initial and final parts; \( -\infty < x < \infty \). The Gaussian regression filter allows the avoidance of the effects of the final profile by changing the weight function for the initial and final parts [7].

The Gaussian regression filter of the second order can approximate distinct form components since it fits a polynomial curve locally.

Spline filter is a special type of discrete linear filter. Spline filters are characterized by the spline function to obtain a filtered output signal. The function of \( S(x) = S(x, \Delta x) \) defined on the interval \( <a, b> \) is called the function splined to the degree of \( m \) \( (m \geq 1) \) if:

1. \( S(x) \) is a polynomial of degree at most \( m \) in each interval \( (x_i, x_{i+1}) \), \( i = 0, 1, ..., n-1 \).
2. \( S(x) \) and its derivative step 1, 2, ..., \( m-1 \) are continuous in the intervals.

Any kind of function very often comes close to spline functions. This is easily linked to the designation of their values and convergence for the numerous classes of functions. In practice, functions splined to the third degree (cubic) are often used, which for many issues are sufficiently smooth and the speed of their convergence is satisfactory [7].

The current study demonstrated the flexibility and usability of spline filters for industrial applications. Filters based on spline curves are based on natural cubic spline functions.

The weight function of this type of spline filters cannot be specified unambiguously. Therefore, filter equations are used instead of weight functions to describe the spline filter. However, the numerical calculation of the weight function for spline filters is always possible, if necessary. If the sampling interval is small enough and the spline filter is based on the cubic curve, weight can be approximated by a continuous function [7, 15]:

\[
s(x) = \frac{n}{\lambda_c} \sin \left( \frac{\pi}{\lambda_c} |x| \right) + \frac{n}{4} \exp \left( \frac{\pi}{\lambda_c} |x| \right)
\]  

(3)

Filter equations are based on cubic splines and have the following form: \((1 + \alpha^4 Q)w = z\); where \( Q \) is the \( n \) dimensional matrix.
In a non-periodical case:

\[
Q = \begin{pmatrix}
1 & -2 & 1 \\
-2 & 5 & -4 & 1 \\
1 & -4 & 6 & -4 & 1 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
1 & -4 & 6 & -4 & 1 \\
1 & -4 & 5 & -2 \\
1 & -2 & 1 \\
\end{pmatrix}
\]

In a periodical case:

\[
Q = \begin{pmatrix}
6 & -4 & 1 & 1 & -4 \\
-4 & 6 & -4 & 1 & 1 \\
1 & -4 & 6 & -4 & 1 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
1 & -4 & 6 & -4 & 1 \\
1 & -4 & 6 & -4 \\
-4 & 1 & 1 & -4 & 6 \\
\end{pmatrix}
\]

However, the parameter \( \alpha \) is expressed by the formula:

\[
\alpha = \frac{1}{2 \sin \frac{\pi \Delta x}{\lambda_{co}}}
\]

where \( n \) – number of measured points in the profile, \( z \) – vector with a dimension of \( n \) that contains the coordinates of the profile before filtration, \( w \) – vector with levels after filtration, dimension of \( n \) that contains the levels after filtration, \( \lambda_{co} \) – wavelength limit of filtered profile, \( \Delta x \) – sampling interval.

Filters described above are widely used in surface metrology; however, areas of their application are wider.

3. Experimental research

3.1. Object of the study

AGV vehicles are increasingly used in industry. They are intended mainly for transport operations inside factories, warehouses and closed areas. A very important stage in the construction of an AGV vehicle is equipping it with an appropriate guidance system that facilitates movement along the assumed route. This route can be predefined or dynamically generated. Various navigation techniques are used to drive an AGV vehicle.

At the moment the odometry is the most widespread. It consists in determining the current position of the vehicle based on the distance travelled by the characteristic point of the vehicle. Unfortunately, this way of driving a vehicle is burdened with numerous errors resulting from the operational errors of the vehicle and working conditions (wheel slip, surface irregularities) [8–11].

Many measurement methods are used to correct errors. Measurements can be made at a fixed frequency (GPS, laser, gyroscope) or after approaching a specific point, line, reference surface (magnetic, video, laser, ultrasonic) [10, 16]. After the measurement, the vehicle's course is corrected. The vehicle used for experimental tests is also based on odometry, which is additionally supported by an additional system that uses measurements from laser rangefinders. In the case of the driving system used in this way, its movement takes place along a virtual trajectory stored in the computer memory by means of appropriate algorithms.

When designing the virtual trajectory very important role is played by knowledge of the environment where it will move an AGV. In the experiments conducted the mapping of the surroundings was carried out using a laser rangefinder located on the tested vehicle.
The object used in the research was equipped with an on-board computer, a set of cards for data acquisition and appropriate control and measurement equipment, including a laser rangefinder SICK DT50 (figure 1).

![Figure 1. Research object – an automated guided vehicle during tests: a) view of the vehicle, b) measurement scheme.](image)

Experimental research was conducted to examine the possibility of using selected digital filtration algorithms in the process of recognizing and mapping the environment where the AGV vehicle will operate. The tests were carried out using a vehicle built at the Rzeszów University of Technology (figure 1).

3.2. Research and an analysis of results

Two measurement scenarios shown in figure 2 were carried out in the research conducted. In the first of them, the vehicle was stationary. The SICK scanner installed on the vehicle measured the surroundings. In the second scenario, the vehicle was in motion. During this movement, measurement data obtained from laser rangefinders were collected and saved in the computer memory.

![Figure 2. Two measurement diagrams: a) a stationary vehicle with SICK scanner, b) a vehicle in motion with laser rangefinder SICK DT50.](image)

The tests consisted of towing the vehicle along the walls of the corridor after which the AGV vehicle will ultimately be driven by itself. The laser rangefinder used is characterized by high accuracy of measurements in stationary conditions. In the measurements performed while towing the vehicle there was a significant increase in the spread of results. And for this reason only data from measurements in motion were used for further analysis. The result of the spread of results are the vehicle vibrations and unevenness of the measured reference surfaces, which were the walls of the corridor. To eliminate these disturbances before using the obtained measurements to build the virtual vehicle trajectory, it was decided to subject the obtained filtration results. For this purpose, selected digital filtration algorithms were used. The Gaussian regression filters (R0) and second order (R2) and the spline (SP) filter were analyzed.
Figure 3 shows an example of the reference surface measurement as the corridor wall. The measurements were made using a laser rangefinder. The figure also shows sample profiles that are parts of the analyzed reference surface. The results of filtration in the form of the obtained mean line were also presented in the diagrams from figures 4–6. The filter's cut-off wavelength varied from 0.1–0.9 with a step of 0.2. Three fragments of the mapped corridor wall were selected for the analysis. The first fragment shows a wall section with a length of 2.5 m (figure 3b). The second fragment maps the section of the wall together with the door (figure 3c). The third fragment is the mapping of the wall section with double doors niche (figure 3d).

Figure 4 presents the profile of the first analyzed fragment and the results of the filtration carried out. The filtration of the profile was based on both zero and second order Gauss regression filters and a spline filter with different cut-off values. As can be seen in the graphs shown in figure 3 at cut-off = 0.1, filters still leave some of the disturbances in the filtered profile (which are not desirable).
With a cut-off greater than 0.3, the interference is completely eliminated both by using a zero and second order Gauss regression filter as well as a spline filter.

Figure 5. Results of filtration for profile for fragment 2.

Figure 5 shows the profile of the second analyzed fragment and the results of filtration carried out. As in the first case, the zero and second order Gauss regression filters as well as the spline filter with different cut-off values were used for filtration. Based on the analysis of the graphs presented in Figure 5, it can be concluded that the best results are achieved by filters at cut-off = 0.1. For such a cut-off value, the profile analyzed is no longer disrupted. This situation applies to all three filters used. In contrast, the use of filters with cut-off values greater than 0.3 causes too much smoothing of the profile, which creates some distortions in the profile analyzed. These distortions relate in particular to the mapped door.

Figure 6. Results of filtration for profile for fragment 3.
The filtration results of the third fragment analyzed are shown in figure 6. In this case, the situation is very similar to that of the analyzed fragment 2. The profile analyzed is completely free of interferences after the use of cut-off filters equal to 0.1. The use of cut-off filters larger than 0.3 causes, as in the previous analyzed case, a large smoothing of the profile, which creates distortions in the profile that change the nature of the profile analyzed. In this case, the distortions concern the mapped door niche. As a result of the operation of the filters, the mapped door corners are tilted. For filtration of the third fragment, the same set of filters was used as in the case of the two previous fragments.

4. Conclusion
The article presents examples of the use of digital filtration methods in two areas. The first area of application of filtration covered the issue related to production technology and surface layer properties. The second area describes examples of the use of filtration in the navigation of automated guided vehicles serving production lines. As part of the research part, selected methods of digital filtration in the navigation of automated guided vehicles were tested and their effectiveness was determined.

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