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Image Processing System for Evaluation of Tillage Quality

The usage of passive image data acquisition technique for generating 3-D maps of the surface of soil by means of stereo vision is investigated. A stereo vision system is mounted onto an electrical powered movable slider of a linear motion frame. To indicate the capability of the method for characterizing quality of tillage, uncertainty of measurement in z-axis was examined theoretically and in preliminary experiments. Quality of tillage can be characterized by comparing slope of the soil surface perpendicular to driving direction before and after tillage, statistic attributes of the 3-D map, roughness of the surface, volume change and working depth. Evaluating the variation of quality of work in practical use was part of this work. Stereo vision is an appropriate method for generating 3-D maps and consecutive measurement in outdoor environments.

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Abstract
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Quality of tillage depends on many independent parameters which are the properties of soil and properties of the tillage system. Due to the enormous amount of influencing parameters it is important to characterize the quality of work for tillage by objective criteria. Characterizing quality of tillage can be achieved by comparing slope of the soil surface before and after tillage, several statistic attributes, roughness of the soil surface, volume change through tillage and working depth. Based on the quality of tillage different tillage systems, tillage tools and even different settings of the same tillage system can be compared.

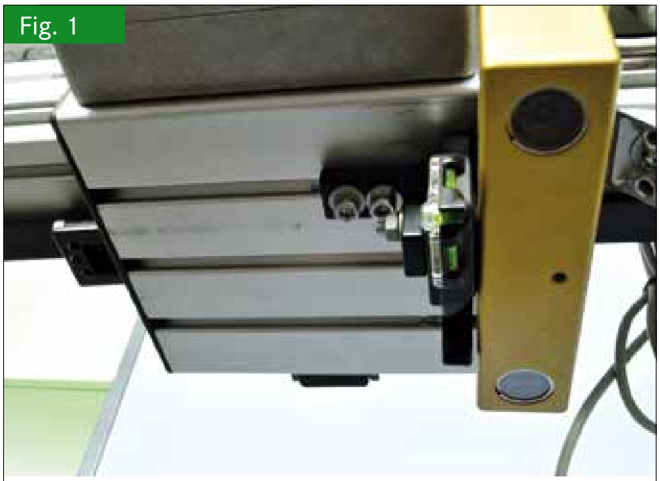
To determine surface roughness and volume change a method for generating a 3-D map of the surface is necessary. Different methods (e.g. image processing or laser scanner) with varying accuracy, resolution, time for data acquisition and captured area are available. In this study the usage of a stereo vision system (SVS) to acquire 3-D maps of the soil surface is investigated and evaluated. Therefore software was developed to utilize a conventional camera system by making use of image data processing techniques. For the comparison of different tools and settings, changes of the surface of an area with side length of one working width of a tillage system must be covered. The benefit of image data processing techniques is the cost-saving hardware, a high degree of automation and the insensitivity to changeable lighting conditions through the passive acquisition method.

Related Work

The tillage index of Colvin et al. [1] bases on height differences perpendicular to the direction of tillage, percentage of soil surface covered by plant residues, roughness of the soil surface and depth of tillage. According to soil surface roughness, Taconet and Ciarletti [2] provide an overview of different roughness indices, grouped into elevation standard deviation, slope-angle and tortuosity index and elevation auto-covariance function. The parameters root-mean square (rms), autocorrelation function (ACF) and the associated correlation length are used to define the characterization of the agricultural soil roughness [3]. The roughness indices RCx and RCy introduced by Taconet and Ciarletti [2] as extension to roughness index RC of Currence and Lovely [4] deal with the demand of height differences perpendicular to the direction of tillage. The working depth is typically defined as the distance between work bottom and the ground surface mean level [5], in other words the difference of the height readings before tillage and the working horizon.

In the past many different systems for the acquisition of height readings from manual to automatic systems were developed. A manual microrelief meter was used to measure the elevation of the soil surface for estimating the total porosity [6]. For analyzing the soil surface roughness an automated profilometer was used. It took about 3–4 hours for taking 4 800 height readings of a plot of 60 x 80 in (152 x 203 cm) [4]. For estimating soil erodibility by wind a soil contacting microrelief meter covering an area of 1 m² with 800 recorded grid

Fig. 1



Stereo vision system *Bumblebee 2 (Photo: Thomas Riegler)*

Fig. 2

Linear motion 3-D scanner frame (Photo: Thomas Riegler)

points was used [7]. A wide spread method for automatic data acquisition is the use of laser scanners mounted on a linear motion frame. Investigations concerning the accuracy of laser scanners based on VDI/VDE Guideline 2634 [8] are shown by Boehler et al. [9]. To analyze the roughness of seedbeds a laser profile meter mounted onto a linear motion frame with a stepper motor was covering an area of 1 x 50 cm [10]. Several regional roughness indices are proposed and discussed from Guillobez and Arnaud [11] by using a 3-D profilograph with a laser cell recording 930 data points with a grid size of 3.2 mm. Droll and Kutzbach [12] use a laser scanner to measure marks of tires on soft ground of an area of 1 000 x 180 mm with an average distance of 1.75 mm between measurements. A portable tillage profiler using a laser scanner was used by Raper et al. [13]. Zhixiong et al. [3] use a laser profiler with a spatial resolution of 1 mm for measuring the agricultural soil roughness. To predict the surface porosity in a cultivated field a laser profiler scanning an area of 2 x 1 m is used [14]. Photogrammetry for investigating and evaluating the behavior of different roughness indices with regard to their spatial sampling size and sampling form was used by Marzahn et al. [15]. Jester and Klik [16] compared roller chain, portable laser scanner, pin-meter and stereo photography as soil roughness measurement techniques with regard to data acquisition and computational effort. While an overview of active optical range imaging sensors can be found in [17], [18] gives an overview of different passive and active range sensing technologies.

Materials and Methods

A SVS called Bumblebee 2 provided by Point Grey Research (**Figure 1**) is mounted onto an electrical 12 V powered movable slider of a linear motion frame (**Figure 2**). The linear motion frame has an extent of 4 m and the SVS is mounted at a height of 60 to 80 cm. The SVS consists of two cameras with CCD sensors which are mounted parallel. The camera system has a 1/3" CCD imaging sensor with 1032 x 776 max pixels (4.65 µm square pixels), a baseline of 12 cm and a lens focal length of 3.8 mm with 66° horizontal field of view (HFOV). A left-handed coordinate system is used, where the y-axis denominates the moving direction of the slider and consequently denominates across driving direction of a tillage system. The x-axis denominates the driving direction of the tillage system and denominates across the driving direction of the slider. The z-axis defines the elevation.

Development of the software

A software package was developed for image data acquisition, generation of the 3-D model and following evaluation. This was built with programming language C#.NET for operating system Microsoft Windows (32 und 64 bit) under usage of libraries FlyCapture SDK (Version 1.8.3.27), Triclops SDK (Version 3.3.1.3) and VTK Visualization Toolkit (Version 5.8.0.607). The resulting report is generated as Microsoft Excel worksheet. The software package, the linear motion slider and the SVS build an integrated system for all working steps of determining characteristics of tillage quality.

A 3-D map is generated out of the images taken from the two cameras by a stereo vision processing pipeline. Images are shot continuously while moving the slider of the linear motion frame with an image frequency of 1 image per second (speed of about 0.13 m/s). The camera provides a 66 degree horizontal field of view resulting in a field of view of about 1 m at a typical operating distance of 0.8 m. The SVS would provide a higher image frequency but due to the field of view it is not needed. Rectification for eliminating lens distortion and align images coplanar is the next step. Edge detection ensures that different brightness in the images does not influence correspondence matching. Correspondence matching is the crucial point in stereo vision, in which the displacement of corresponding pixel is detected. The displacement of the pixels can be represented in a disparity map. By means of triangulation the disparity map is transferred in real world coordinates, resulting in a set of about 620 000 unorganized points. Subpixel interpolation, back and forth validation and surface validation increase the quality

Table 1

Calculated uncertainty of measurement in z-axis

Höhe in z-Achse (z) [mm] ***Height in z-axis (z) [mm]***	**Messunsicherheit in z-Achse [mm]** ***Uncertainty of measurement in z-axis [mm]***
700	0.5
800	0.7
900	0.9
1 000	1.1
1 100	1.3

Fig. 3

Evaluation of the linear motion 3-D scanner (Photo: Thomas Riegler)

of stereo processing. According to the field of view this results in a resolution of about 60 points per cm². To combine fractional point sets into one coordinate system a 3-D rigid body transformation where z-coordinate remains unchanged is done. Final step is a 2-D Delaunay triangulation where the surface is reconstructed by connecting points via edges so that triangles are formed. As result of these steps a comprehensive 3-D map of the scanned area (about 3.5 x 1 m) is available.

To examine volume change through tillage, the volume difference of 3-D maps can be calculated. For calculating the volume difference between two 3-D maps the maps have to be cropped to the same size. This is done by calculating the bounding box of each 3-D map and then by taking the extent in x- and y-direction of the smaller value. Second step is the calculation of the volume difference to plane with z = 0. Therefore the center of gravity of each triangle is determined. From this center of gravity the height reading (z-value) is multiplied with the projected area to get the volume of the three-sided prism. This calculation of the spatial volume of each three-sided prism is done for each triangle of the 3-D map and summed up to get the total volume. The calculation of the volume to plane with z = 0 is repeated with the second 3-D map. Consequently the difference between these two determined volumes gives the volume difference between the two compared 3-D maps.

Results

To indicate the capability for characterizing the quality of tillage of the SVS and the developed software analysis of accuracy and deviation of repeated measurements were analyzed.

According to [19] the uncertainty of measurement in z-axis is based on the equation:

$$\partial z = \frac{-z^2}{fB} m \qquad \text{(Eq. 1)}$$

The parameters correlation accuracy (m), stereo baseline (B) and focal length (f) of the camera are given by the manufacturer of the SVS. The SVS is mounted at a height of 0.7 to 0.8 m and the maximum working depth amounts to 0.3 m, therefore the typical values for z range between 0.7 and 1.1 m.

Table 1 shows the calculated uncertainty of measurement in z-axis [19]. The parameters of the SVS are m = 0.1 pixel, f = 774.3 pixel and B = 120 mm. The results show that the uncertainty depends on the distance between camera and observed surface. It is smaller than 1.0 mm up to a distance between camera and observed surface of about 0.9 m.

Since the correlation algorithm in the developed software needs a well-structured non-uniform surface, it is difficult to measure the distance from the SVS to a plain surface. To show systematic errors and uncertainty of measurement in practical use the volume between two surfaces, modeled with sand of granulation 0.5–2.0 mm was used (**Figure 3**). For investigating systematic errors and uncertainty of measurement two experimental arrangements were elaborated. First a rough surface was built and scanned as reference surface, where a well-defined volume of 6 and 12 dm³ was randomly added to the surface and scanned repeatedly afterwards. In a second arrangement also a reference surface was scanned and then consecutive about 10, 20, 30, 40, 50, 100, 150 and 200 dm³

Table 2

Uncertainty of measurement and systematic error of volume measurement (n = 24)

Zugefügtes Volumen von Sand [dm³] ***Added volume of sand [dm³]***	**Gescannte Fläche [dm²]** ***Scanned area [dm²]***	**Arithmetisches Mittel des gemessenen Volumens [dm³]** ***Arithmetic mean of measured volume [dm³]***	**Standardabweichung des gemessenen Volumens [dm³]** ***Standard deviation of measured volume [dm³]***	**Mittlere Differenz zwischen Spalte 3 und 1 [dm³]** ***Mean difference between column 3 and 1 [dm³]***
6.00	360.62	6.01	0.10	0.01
12.00	360.62	11.90	0.11	0.10

Table 3

Uncertainty of measurement and systematic error of volume measurement with remodeled surface after each scan (n = 4)

Zugefügtes Volumen aus Sand [dm³] *Added volume of sand [dm³]*	**Gescannte Fläche [dm²]** *Scanned area [dm²]*	**Arithmetisches Mittel des gemessenen Volumens [dm³]** *Arithmetic mean of measured volume [dm³]*	**Standardabweichung des gemessenen Volumens [dm³]** *Standard deviation of measured volume [dm³]*	**Mittlere Differenz zwischen Spalte 3 und 1 [dm³]** *Mean difference between column 3 and 1 [dm³]*
9.83	358.13	9.02	0.75	-0.82
19.62	358.13	21.17	2.32	1.55
29.24	358.13	30.33	2.17	1.09
38.92	358.13	39.41	2.18	0.49
48.62	358.13	49.19	2.52	0.57
97.10	358.13	97.97	0.85	0.87
145.58	358.13	145.93	2.16	0.36
194.06	358.13	193.55	0.61	-0.50

were added randomly. As distinction to the first arrangement the surface was remodeled after each repetitive scan.

Table 2 and **Table 3** contain the results of the experiments for evaluating the volume measurement. The mean differences between the actually added volume of sand and the measured volume (see column 5) are used as measurement for a systematic error. For repeated measurements of the same surface (**Table 2**) the standard deviation of the measured volume is lower than the standard deviation of measured volume with remodeled surface after each scan (**Table 3**).

Quality of tillage

For characterizing the quality of tillage three subsequent scans of the examined area are taken:

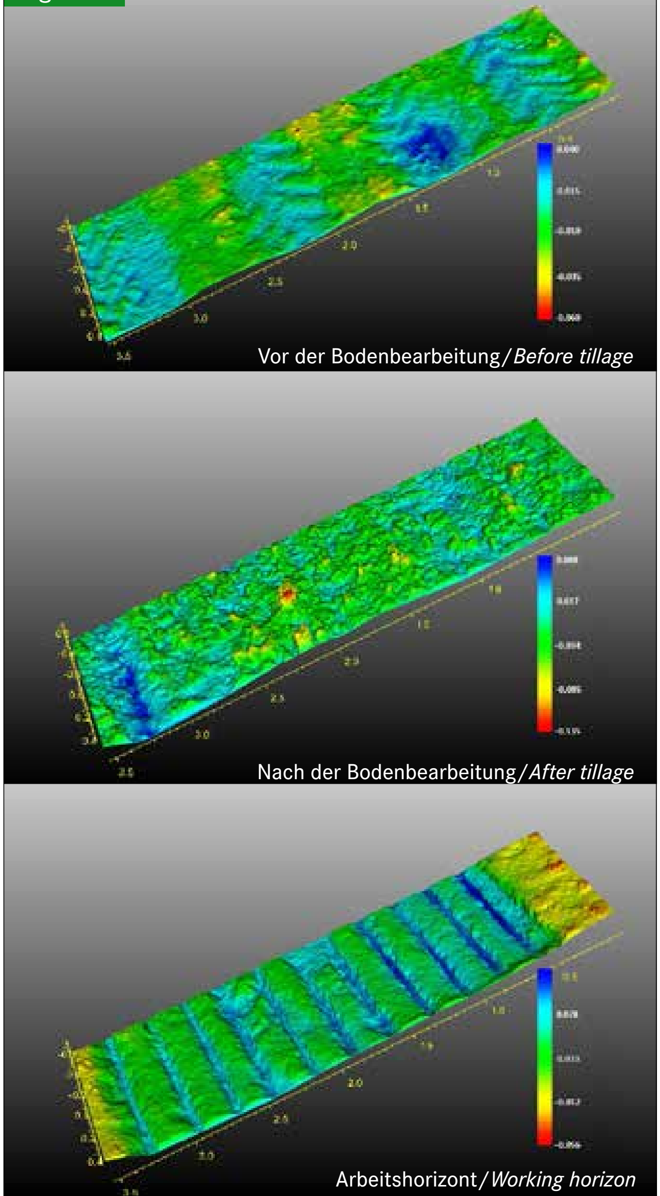
- before tillage (BT),
- after tillage (AT) and of
- the working horizon (WH) by removing the loosened soil.

In **Fiure 4** examples of 3-D maps produced by tilling with a 3-bank stubble cultivator without rear roller at a working depth of 22 cm can be seen. From these 3-D maps (BT, AT and WH) descriptive and comparative characteristics are calculated.

Slope

Average slope describes the trend of lopsidedness in y-direction (across driving direction) by calculating the line of best fit of averaged values in x-direction. A comparison of slope before and after tillage as well as the working horizon describes changes caused by tillage. Since this comparison is relative it is not necessary to align the SVS horizontally or parallel to the soil surface. Through tillage it is possible to gain a divergent tendency of the lines of best fit before and after tillage. This would indicate an unbalanced tillage system. Reasons for such an unbalanced result could be an improper adjustment of the implement or even caused by the functional principle of the tillage system itself (e. g. asymmetric tools, conventional turning tillage, which laterally displaces the soil). Analysis of the slope characteristics can

Fig. 4



3-D maps of different surfaces

also be used to appraise the soil displacement in contour line at the hillside.

Statistic attributes

Statistic attributes like arithmetic mean, median and standard deviation describe key features of the height readings of a 3D-map. Basis of comparison are the z-values before tillage. The arithmetic mean z and median z after tillage describe the height increase of the soil through tillage, whereas the arithmetic mean z and median z of the working horizon represents the average working depth.

Roughness index RC

The roughness index RC is calculated by correcting each height reading for row and column effects, to remove plot slope [4]. Taconet and Ciarletti [2] state that the roughness index RC is a satisfactory index which describes the amplitude variation of the height residuals from the plane of best fit through the data.

Roughness indices RCx and RCy

For non-isotropic structure of the surface averages on one single coordinate can be performed. These roughness indices RCx and RCy are described by Taconet and Ciarletti [2] and describe the roughness of the soil surface in different directions (in driving direction and across driving direction).

Volume increase

By comparing the 3-D map before tillage and after tillage the volume increase resulting from loosening of soil can be determined. If bulk density before tillage is known, the average bulk density after tillage or rather the porosity after tillage can be calculated.

Processed volume

Comparing the 3-D map before tillage and of the working horizon the processed volume can be calculated. This attribute is of interest if a specific draught force for tillage should be determined.

Working depth

The accurate measurement of depth of tillage is trivial in theory but difficult in practice. Surface of soil, even before tillage, is not planar so height readings depend on the location of measurement, just as the working horizon is not planar for accurate measurement. Height readings and subsequent depth of tillage can only be an average of multiple measurements. Complicating some tillage systems (like cultivators) provide a bumpy working horizon. For an average working depth the comparison of median z before tillage and of the working horizon is an adequate method. Advantage of the usage of the median over the arithmetic mean is the insensitivity against boundary effects (beveling to the untilled area). Another possibility is the calculation of the volume difference before and after tillage based on the projected area.

Evaluation in field

To show variation of characteristics in practical use, 11 scans of the same surface before tillage, after tillage and of the working horizon were taken. The characteristics of tillage quality are

Table 4

Characteristics for the quality of work of a cultivator ($\bar{x}$ = arithmetic mean, s = standard deviation)

	Vor der Bodenbearbeitung *Before tillage*		Nach der Bodenbearbeitung *After tillage*		Arbeitshorizont *Working horizon*	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
Steigung y/*Slope y* [mm]	-0.04	0.0	0.04	0.0	-0.17	0.0
Arithmetisches Mittel z/*Arithmetic mean z* [mm]	-0.1	0.5	36.5	0.4	-67.9	0.5
Median z/*Median z* [mm]	0.0	0.0	36.1	0.7	-79.5	0.7
Rauheitsindex RC/*Roughness index RC* [mm]	7.1	0.1	14.6	0.1	11.6	0.1
Rauheitsindex RCy/*Roughness index RCy* [mm]	13.7	0.1	18.6	0.1	34.8	0.1
Rauheitsindex RCx /*Roughness index RCx* [mm]	7.1	0.1	14.1	0.1	9.4	0.0

Table 5

Volume of soil between scanned surfaces ($\bar{x}$ = arithmetic mean, s = standard deviation)

Volumen des Bodens ***Volume of soil***	**Zwischen Oberfläche vor und nach Bearbeitung** ***Between surface before and after tillage***		**Zwischen Oberfläche vor Bearbeitung und Arbeitshorizont** ***Between surface before tillage and working horizon***		**Zwischen Oberfläche nach Bearbeitung und Arbeitshorizont** ***Between surface after tillage and working horizon***	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
Volumen [dm^3/m^2] *Volume [dm^3/m^2]*	35.40	0.22	66.07	0.16	101.47	0.12

based on the 3-D maps shown in **Figure 4**. In **Table 4** and **Table 5** the arithmetic means and the standard deviations of the attributes are shown. The comparison of the slope before tillage and after tillage indicates that the slope has increased, which could be caused by an improper adjusted tillage system. Considering median z, the average working depth can be assumed of about 8 cm. The comparison of the roughness indices before and after tillage shows that the roughness of the soil after tillage is higher than before tillage. Roughness indices RCx and RCy indicate typical values which can be determined by tillage with a cultivator. Thereby a higher roughness across driving direction can be monitored, which is caused by the shafts of the cultivator.

In **Table 5** the volume of soil between surface before and after tillage represents the increase of soil volume caused by tillage. In the present case the increase of soil volume amounts to 54 % by a processed volume of 66.07 dm^3 per square meter.

The standard deviations of all calculated characteristics are relatively low which indicates a low uncertainty of measurement.

Conclusions

Passive image acquisition using a SVS system is capable to generate 3-D maps of soil surface by using a stereo vision processing pipeline. The volume difference of various surfaces has been used to evaluate uncertainty of measurement, which is between 0.01 and 0.1 dm^3 on an area of about 360 dm^2 when the surface is unchanged and between 0.4 and 1.6 dm^3 when the surface is remodeled after each scan. Low deviations of measurement show that this method is suitable for measuring the soil surface.

The advantage of stereo vision is the good applicability in outdoor environments and is therefore well suited for the generation of 3-D maps of the soil surface. By removing the loosened soil through tillage the working horizon can be evaluated. The method is suitable to characterize the quality of work for arbitrary working width of tillage implements though the manageability of the linear motion frame has to be considered. Due to the fact that tillage works in three dimensions future investigations should analyze the processed volume in concern of mixing or aggregate diameter distribution. The image processing system used in this work is not adequate because it examines only the visible surface.

In this study the quality of tillage of a cultivator was characterized. Through the integration of the software system, the linear motion scanner and the SVS a system for covering all working steps for determining attributes of quality of tillage is available.

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