FIELD TESTS OF A CAPACITIVE THROUGHPUT SENSOR INSTALLED ON A POTATO CONVEYOR DIGGER*

F. Kumhála, V. Prošek, J. Procházka, D. Pronitsin

Czech University of Life Sciences Prague, Faculty of Engineering, Prague, Czech Republic

Yield monitoring whilst harvesting in combination with a harvester positioning system is a fundamental source of information for field yield maps. In this research, a capacitive throughput sensor for potatoes has been tested under field conditions. Two testing days were arranged in the summer and autumn harvesting periods. The best results were obtained during the second harvesting day in autumn under better harvesting conditions. Correlation coefficients between the electronic apparatus output voltages and the weights of harvested potatoes varied in the range from 0.76 to 0.83. The suitability of the capacitive throughput sensor method for continuous potato throughput measurement under real field conditions was proved. However, a further series of tests with a more sophisticated potato harvesting machine are needed.

capacitive sensor; throughput; potato

INTRODUCTION

Precision agriculture is focused on improving management to increase profitability. To achieve this goal, a large amount of data is required. Spatial and temporal cropping potentials are expressed via yield maps (Hennens et al., 2003; Persson et al., 2004). Yield monitoring is an essential tool for this purpose. That is why different yield monitoring systems have been studied over the past decade (Persson et al., 2004). For non-combinable products, such as potatoes and sugar beet, only few yield measurement systems are available (Ehlert and Algerbo, 2000). The non-smoothed flow, the high mass yields and the wide range of harvesting conditions cause serious problems (Hennens et al., 2003). Nevertheless, some principles of sensors for potato yield measurements have been tested and reported in the literature.

DeHaan et al. (1999) used a bulk yield monitor for potato yield mapping. They reported that, after calibration, the bulk recorded weights had been within 5% of actual weights. Ehlert, Algerbo (2000) gave a short overview of possible potato throughput measurement principles. They reported that known methods included: radiometric measurement, an incorporated weighing cell in the continuous conveyor belt, optical measurement with photo evaluation and deflection plate measurement.

Gonigeni et al. (2002) developed an image-based system for sweet potato yield and grade monitoring. However, when sweet potatoes moved on the harvester's conveyor belt, the weight estimations correlated rather poorly with the actual weights ($R^2 = 0.91$).

Hofstee, Molena (2002) tested a machine vision based yield mapping system for potatoes. Recently, Hofstee, Molena (2003) used a similar system for volume estimation of partly soiled potatoes. They concluded that there were good prospects for their system using 2 D information; however, further research into this method is necessary.

Persson et al. (2004) developed an optical sensor for tuber yield monitoring. Under field conditions, authors measured the linear relationship of yield monitor data in relation to the measured weight with a coefficient of determination $R^2 = 0.95$.

Mostofi, Minaei (2009) tested two weighing systems (cantilever transducers fitted to the conveyor belt mechanism and a load cell system supporting the total weight of the conveyor and crop) for potato mass flow rate measurements under laboratory and field conditions. However, in muddy conditions, the weight of dirt was greater than 12% which introduced errors into the recording of crop mass.

Furthermore, several other systems and methodologies have been developed for other non-combinable crops which can be suitable for potato as well, e.g. measurement of mass accumulation rate (Godwin, Wheeler, 1997; Saldana, 2006).

The capacitance sensor technique can be used for the determination of different properties of plant materials. The function of capacitance sensors depends on the fact that the dielectric constant of an air/material mixture between two parallel plates increases with material volume concentration. Capacitance sensors

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could be used for determining the content of plant material moisture (Lawrence et al., 2001).

Stafford et al. (1996) used a capacitive sensor to determine grain mass flow. They reported that the disadvantages of using a capacitive sensor for that purpose were that the sensor responded to variation in grain moisture content and furthermore was sensitive to material distribution within the sensing volume. According to their research, the effect of moisture content can be compensated by measuring capacitance at two widely spaced frequencies (one section of the sensor ran at 10 kHz and the other at 2 MHz).

Martel, Savoie (1999) observed a capacitance controlled oscillator placed at the discharge end of the forage harvester spout to measure changes induced by forage particles. This equipment showed a linear drop of the oscillator's frequency as the wet mass flow increased. Recently, Savoie et al. (2002) used a similar capacitance controlled oscillator for their measurement. However, the frequency drop of the capacitance controlled oscillator correlated poorly with mass flow rate but correlated better with water flow rate.

Williams et al. (2000) used electrical capacitance tomography for particular solids flow rate measurement on a conveyor belt. This sophisticated method can be used to measure an image of the dielectric constant directly in a cross-section of conveyor belt with transported solids and showed potential for on-line feed rate measurement.

In our previous paper, we designed a parallel-plate capacitance sensor for potatoes and sugar beet throughput determination. A theoretical model of the capacitive throughput sensor has been developed; the model incorporates all the most important physical parameters that influence material throughput measurement. Two basic dependencies of the sensor capacity on material throughput can be derived from the proposed model, a hyperbolic dependence and a linear one. The method of filling the sensor with measured material is the most important model factor explaining sensor behaviour. The theoretical considerations have been confirmed by dynamic laboratory experiments with potatoes and sugar beet (Kumhála et al., 2009).

As becomes obvious from the literature review, yield mapping systems for potatoes are theoretically known but not commonly used in practice. There are still too many unpredictable errors under field conditions and in some cases the measurement devices (radiometric measurement, machine vision systems)

Figure 1. The view of parallel plate capacitive throughput sensor integrated to one row conveyor potato digger Akpil (Akpil Co., Poland)

as well as the principle of sensor function (machine vision, electrical capacitance tomography) are not simple and often need further development. On the other hand, the advantages of the capacitive sensor are its relative simplicity suitable for often complicated operating conditions of agricultural machines and its relatively low cost.

The capacitive sensor can be a good option for potato throughput measurement. That is why the main aim of this research was to evaluate the suitability of the capacitive sensor for potato throughput measurement under real field conditions.

MATERIALS AND METHODS

A modified parallel plate capacitance sensor as described in detail by Kumhála et al. (2009) when used for sugar beet and potato throughput measurement was used for potato throughput measurement purposes. The parallel plate capacitance sensor consisted of two metal sheets 2 mm thick. Upper (active) plate dimensions were 580 mm in length and 150 mm in width. Bottom (ground) plate dimensions were 580 mm in length and 450 mm in width. The upper plate was fixed at one of the ends of the bottom plate via a 10 mm thick insulating compound (Fig. 1). The distance between the plates was 120 mm. The width of the sensor plates corresponded with the working width of the digger separating conveyor. The capacitive throughput sensor and the whole oscillating circuit ran at 6 MHz. The design and dimensions of the parallel plate capacitive sensor were compatible with a Akpil one row potato conveyor digger manufactured by the Akpil Company, Poland (Fig. 1).

The capacitor was fed by an oscillator via a resistor or by another capacitor with the same reactance. The resistor together with the capacitive sensor acted as a voltage divider and thus the measured output voltage of the divider depended on the sensor electrical capacity and the permittivity between the sensor plates.

Infield tests with the measurement equipment described above were carried out during two days, July 7th and October 10th, 2010 in the Czech University of Life Sciences Prague experimental and demonstrational field (50°07´N, 14°22´E) at the University campus. The total area of this field is 7 ha. In 2010, potato varieties Bernadette, Impala, Lenka etc., were grown here in a cultivated area of 0.75 ha. The soil in this field is described as 'chernozem loamy'.

Three approximately 25 m rows of Impala potatoes were harvested on the first day of the experiments. The relatively humid summer weather in combination with the chernozem loamy soil in our experimental field resulted in very cloddy soil conditions.

Three rows of Bernadette potatoes between 14 and 18 m long were harvested on the second day of infield tests. More suitable weather conditions were experienced during this autumn harvesting period; hard soil clods were not observed.

During the experiment, voltage data from the measuring apparatus were recorded every 0.5 s and saved into a notebook carried in the tractor cab. After harvesting, the potatoes were placed back onto the surface of the row by the potato digger. Each row with picked-up potatoes was then divided into 2 m intervals in length. Potatoes (or potatoes with clods) from each 2 m interval were then collected together, weighed by hand and the values recorded. The tractor operating speed was also recorded. When harvesting the first row during summer measurement the second reduced forward speed (0.404 $m.s^{-1}$) was used. The first reduced forward speed (0.278 $m.s^{-1}$) was then used for subsequent measurements during summer and autumn. It was confirmed during the measurements that the values measured by hand corresponded with voltage values recorded in the notebook. This allowed for comparison of the actual weight of potatoes in the row with measuring device output voltage signal later. Statistical processing of the data was performed using MS Excel.

RESULTS AND DISCUSSION

In order to evaluate the potential of using the measuring apparatus output signal to predict potato yield, the curves of measured data versus time obtained from the electronic unit and by hand weighing were compared. Two meters of potato row were harvested during app. 5 s when second reduced working speed was set and app. 7 s when first reduced working speed was used. This means that during these time periods 10 or 14 values of output voltage were recorded by the measuring device. A moving average from 10 measured values for the first measurement (second reduced) and from 14 values for all subsequent tests (first reduced) was used to enable visual comparison of the resultant curves.

The design of the capacitive throughput sensor ensures that sensor filling was by single particles and the linear dependence of the sensor output voltage on the amount of measured material is predictable in this case (Kumhála et al., 2009). This allowed us to evaluate the dependencies of the data obtained from the electronic measuring unit by comparison with the data obtained from hand weighing. This was also confirmed statistically by coefficients of determination.

During the first day of the measurements it was noted that the Impala variety potato tubers were oval in shape with an average length about 65 mm. As is normal during harvesting, the second reduced working speed of the tractor was used. However, it became obvious during the harvest of first row that a lot of hard soil clods were not being separated by the potato digger conveyer and were being passed through

Table 1. Calculated correlation coefficients between weight of potatoes with clods, potatoes only and recorded output voltage from July 7th, 2010

Correlation coefficients		Output voltage (V)	Weight of potatoes with clods (kg)	Weight of potatoes only (kg)
1st row	Output voltage (V)	–	0.46	–0.08
	Weight of potatoes with clods (kg)	0.46	–	0.33
	Weight of potatoes only (kg)	–0.08	0.33	–
2nd row	Output voltage (V)	–	0.37	–0.2
	Weight of potatoes with clods (kg)	0.37	–	–0.05
	Weight of potatoes only (kg)	–0.2	–0.05	–
3rd row	Output voltage (V)	–	0.7	0.05
	Weight of potatoes with clods (kg)	0.7	–	0.19
	Weight of potatoes only (kg)	0.19	0.05	–

the capacitive throughput sensor. This was a serious problem because the soil clods were wet and therefore were recognized as harvested material by the measuring device. It was decided to collect from the surface of the harvested row potato tubers with clods, weigh them together, then separate potato tubers from clods and weigh them again. It was determined after harvesting the first row that the weight of potatoes was only 14% of the total collected material.

The tractor was set to a slower working speed (first reduced) for the next rows with the hope of achieving better separation of soil clods. Results were better for the second and third rows. However, the amount of potato tubers in the collected material still remained relatively low, 38% or 27%, respectively. Unfortunately, it was not possible to ensure better clod separation with the relatively simple potato digger available at the time. That is why it was finally decided to try to evaluate sensor performance with combined potato and clods weight and also with potato only weight.

The results of statistical evaluation for the measurements from July 7th, 2010, are given in Table 1. It can be seen in this table that coefficients of determination between the weight of potatoes with clods and the weight potato tubers only are rather low (0.33) or near zero (± 0.05). It means that there was no link between the weight of potato tubers and potato tubers with clods, in other words the amount of potato tubers in potato and clods mixture varied. That is why the dependence of the electronic apparatus output signal on the potato tubers weight was not possible to anticipate. Nevertheless, some dependence between the weight of potato tubers with clods and output voltage signal could still be found. For the first measurement the coefficient of determination was r = 0.46 which implies that maybe some dependence can exist. Nevertheless the result for second harvested row was even worst, r = 0.37. This was caused by unsuitable arrangement of the connection between potato digger and measuring capacitor. Because of the relatively

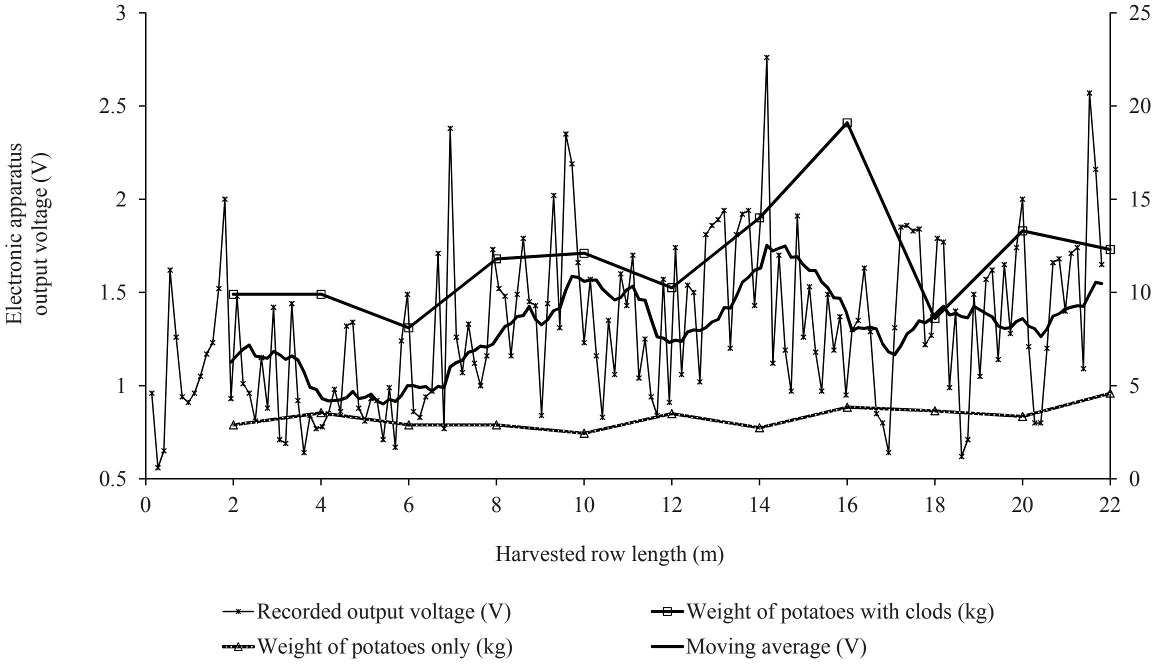
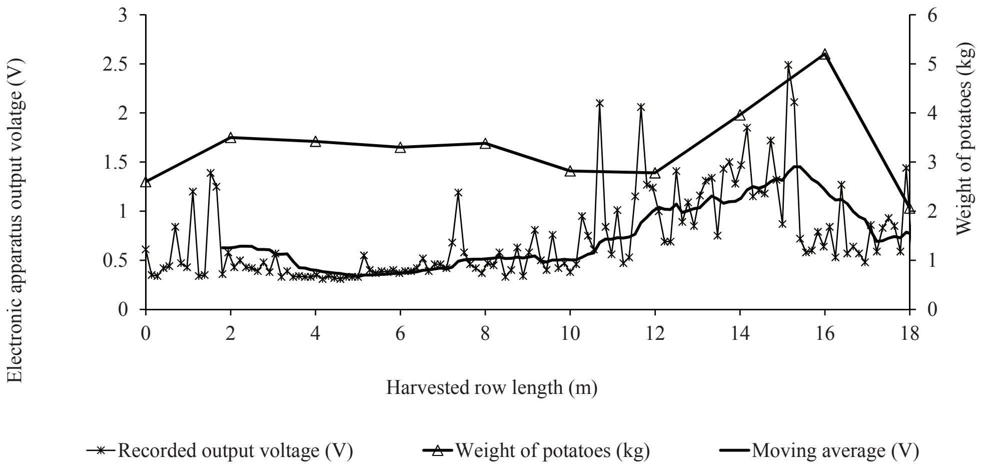
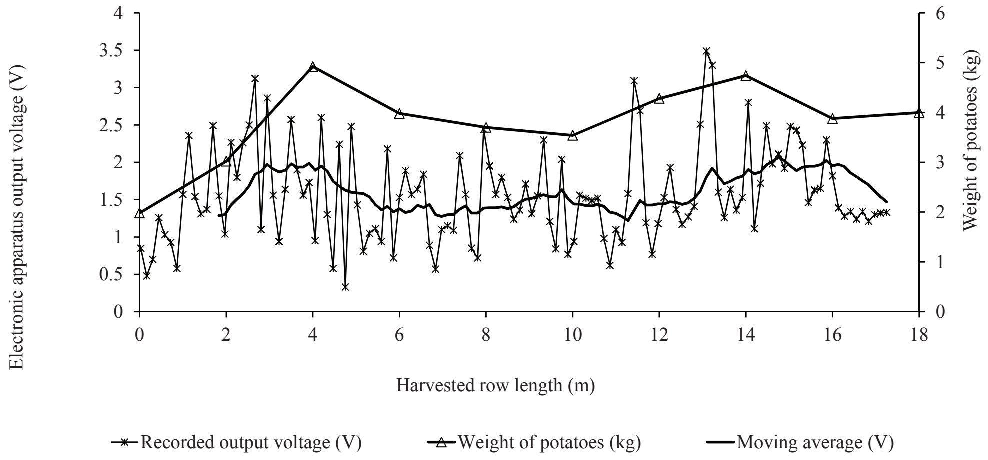


Fig. 2. Course of electronic apparatus output voltage, weight of potatoes and weight of potatoes with clods from 3rd harvested row, July 7th, 2010

1st harvested row



2nd harvested row



3rd harvested row

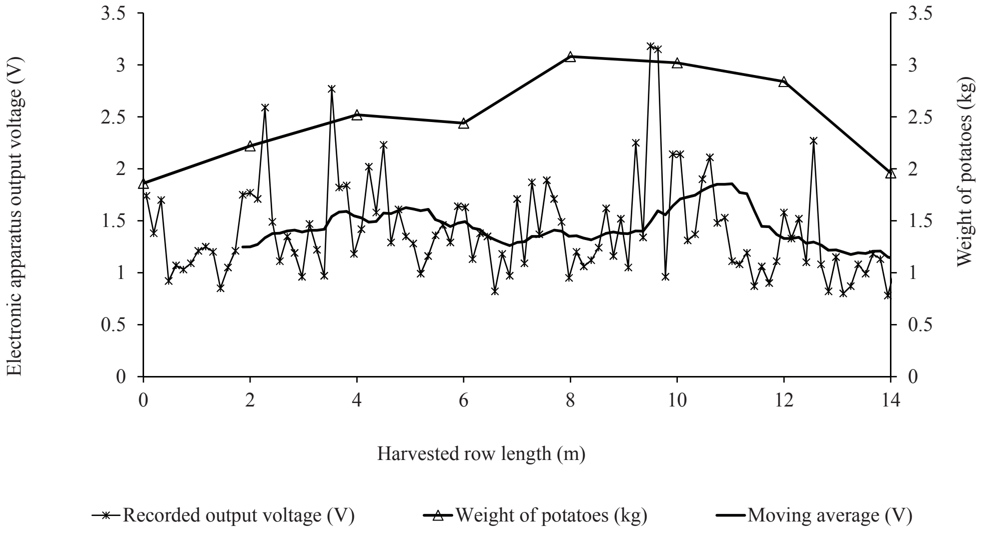


Fig. 3. Course of electronic apparatus output voltage and weight of potatoes from all three harvested rows, October 10th, 2010

Table 2. Calculated correlation coefficients between weight of potatoes and recorded output voltage from October 10th, 2010

Correlation coefficients		Weight of potatoes (kg)
Output voltage (V)	1st row	0.83
	2nd row	0.76
	3rd row	0.8

higher speed of the digger conveyor resulting from the lower set tractor speed (higher engine rpm were used) some material didn't pass through the capacitor. It was necessary to improve the material flow direction between the capacitor plates. After this improvement, a better correlation coefficient (r = 0.7) was achieved during the 3rd row harvesting. Graphical representation of the results from the 3rd row measurement is shown in Fig. 2.

It can be seen in Fig. 2 that the course of the electronic device output signal moving average curve generally follows the curve of weighted values of potatoes with clods. The function of the sensor at the ends of harvested rows was a bit worst in comparison with starts. This was caused by soil adhering to the bottom capacitor plate. When the values from the first 16 m of the row only were evaluated, the correlation coefficient was even better (r = 0.87). Despite all the described complications, the result from the last measurement from the first day of tests encouraged us to repeat the measurements under better soil conditions.

During the second day of the measurement in autumn, October 10th, 2010, the Bernadette potato variety (oval shape with average diameter about 60 mm) was harvested. Soil conditions were considerably better in comparison with the summer period. The potato digger was able to separate almost all soil clods from harvested material. Only the relationship between the weight of potatoes and the electronic apparatus output voltage was studied for that reason. The same set up of the measuring device (first reduced working speed, improved connection of capacitor with digger, same electronic apparatus) was used. The results of statistical analysis are given in Table 2. It can be derived from the results given in Table 2 that there was correlation between the measuring apparatus output voltage and the weight of harvested potatoes. Calculated correlation coefficients varied from 0.76 to 0.83, and a better result was probably not possible to anticipate with such a simple harvesting machine. In Fig. 3, the course of the measuring apparatus output voltage values curve with moving average and the course of the potato weight values obtained by hand measurement is charted for each of the measured rows.

It can be derived from Fig. 3 that the courses of the measured apparatus moving average curves follow the courses of the potato weights measured by hand in the corresponding section of the harvested row. This means that the measuring device worked satisfactorily from a relative values comparison point of view. However, comparing absolute values, the situation was less satisfactory. It can be seen from the 1st harvested row chart that the average weight of potatoes is about 3.3 kg and the corresponding average output voltage of the electronic apparatus is about 0.73 V. For the 2nd harvested row, the average weight is 3.8 kg and the average voltage just 1.56 V and for the 3rd row 2.7 kg weight and 1.4 V average voltage can be calculated. For the 1st harvested row, the recorded output voltage of the electronic apparatus was significantly lower in comparison with the recorded outpur volatages of the 2nd and 3rd harvested rows. This was caused by wet soil particles adhering to the bottom plate of the capacitor during the1st row harvesting, as discussed before. Those particles raised the zero point of the electronic measuring device and consequently raised the voltage values recorded during subsequent measurements. To avoid this situation, cleaning of the capacitive throughput sensor inside plates after each measurement would be necessary.

CONCLUSION

As the results showed, the parallel-plate, capacitive throughput sensor is a potential approach for potatoes continuous throughput measurement under field conditions. Nevertheless, the assessment of this sensor when installed on a more sophisticated potato harvesting machine and further tests under real field conditions is recommended.

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KUMHÁLA, F. – PROŠEK, V. – PROCHÁZKA, J. – PRONITSIN, D. (Česká zemědělská univerzita v Praze, Technická fakulta, Praha, Česká republika)

Testy kapacitního čidla průchodnosti na dopravníkovém vyorávači brambor v polních podmínkách

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Informace o okamžitém výnosu sklízené plodiny je společně s informací o okamžité poloze stroje základem pro vytvoření výnosové mapy. Příspěvek se proto zabývá testováním vhodnosti kapacitního čidla okamžité průchodnosti rostlinných materiálů pro určování průchodnosti brambor v polních podmínkách. Za tímto účelem bylo čidlo namontováno za prosévací dopravník jednořádkového vyorávače brambor firmy Akpil. Byly uspořádány dva měřící dny, jeden v letní sklizňové sezóně a druhý v podzimní sklizňové sezóně. Vysoká vlhkost půdy při prvním dnu měření v létě způsobovala na experimentálním pozemku tvorbu takového množství hrud, se kterým si jednoduchý vyorávač brambor nedokázal poradit. To negativně ovlivnilo výsledky měření z prvního měřícího dne. Nicméně v podzimním období byla situace lepší. Druhý den měření bylo ověřeno, že korelační koeficient závislosti výstupního napětí z kapacitního čidla a hmotnosti brambor zjištěné vážením se pohyboval v rozmezí 0,76 až 0,83. Vhodnost kapacitního čidla pro okamžité měření průchodnosti brambor v polních podmínkách tak byla prokázána. Nicméně je nutno doporučit integraci čidla se složitějším sklízečem brambor a jeho další testování v polních podmínkách.

kapacitní čidlo; průchodnost; brambory

Contact Address:

Prof. Dr. Ing. František Kumhála, Česká zemědělská univerzita v Praze, Technická fakulta, katedra zemědělských strojů, Kamýcká 129, 165 21 Praha 6-Suchdol, Česká republika, tel: +420 224 383 135; e-mail: kumhala@tf.czu.cz