DEVELOPMENT OF CAPACITIVE THROUGHPUT SENSOR FOR PLANT MATERIALS

František KUMHÁLA[1]

[1]Department of Agricultural Machines, Faculty of Engineering, Czech University of Life Sciences in Prague, 16521 Prague– Suchdol, Czech Republic, E-mail: kumhala@tf.czu.cz, Phone: +420-2-24383135

Abstract
The aim of this article is to introduce the steps of development of capacitance throughput sensor for plant materials. Main results of sensor function with forages, sugar beets, potatoes, chopped maize and hop are discussed. The theory of capacitive throughput sensor function and its influence on sensor behavior in practical conditions is also presented as well as the influence of measured material moisture content changes. Capacitive throughput sensor is a relatively inexpensive and sufficiently robust and accurate alternative to other methods of plant materials throughput measurement.

Key words: *theory of function; forages; potatoes; sugar beet; maize; hop.*

INTRODUCTION

A plant materials throughput sensor can be useful not only in several applications of precision farming. Information about the variable throughput of plant materials can be used e.g. for calculating site-specific crop yield for a yield map, but also in order to control of technological process in more complex agricultural or food processing machines. For this reason, considerable attention has been paid to the development of these sensors in the past.

Plant material throughput sensors first appeared in combine harvesters, i.e. grain harvesting machines. At present, it can be stated that since 1993 farmers have commercially available yield monitors, working on a number of different principles. However, all these yield monitors are located between combine cleaning shoe grain outlet and the grain tank. Monitors can be divided into two large groups. One measures the volume of purified grain on its way to the combine and the other measures its weight (*Stafford et al., 1996; Arslan et al., 2000; Reyns et al., 2002;* and others). Nevertheless, some problems associated with the measurement of grain throughput on the combine harvester were later pointed out e.g. by *Lark, Stafford & Bolam (1997), Arslan & Colvin (2002)* or *Whelan & McBratney (2002).*

In addition to cereals, there have also been an attempt to measured throughput of other plant materials in the past. *DeHaan et al. (1999)* used a bulk yield monitor for potato yield mapping. They reported that after calibration the bulk recorded weighs had been within 5 % of actual weights. *Ehlert & Algerbo (2000)* gave a short overview of possible potato throughput measurement principles. They reported that radiometric measurements, weighing cells in the continuous conveyor belt, optical measurements with photo evaluation, and deflection plate measurements were all known techniques. *Gonigeni et al. (2002)* developed an image-based system for sweet potato yield and grade monitoring. However, when sweet potatoes moved on the harvester conveyor belt, the weight estimations correlated with the actual weights rather poorly. *Hofstee & Molena (2002)* tested a machine vision based yield mapping system of potatoes and recently, *Hofstee & Molena (2003)* used a similar system for estimation of volume with potatoes partly covered with a soil residue. They concluded that there were good prospects for their system using 2 -dimensional information; however, they reported that further research into this method was necessary. *Persson, Eklundh & Algerbo (2004)* developed an optical sensor for tuber yield monitoring.

Sugar beet yield sensors have also been studied. Weight-sensing systems have been studied in several applications (*Isensee & Lieder, 2001; Schwenke et al., 2002; Walter & Backer, 2003; Hall, Backer & Hofman, 2003*). The main disadvantage of all systems is that they are sensitive to contaminants such as mud, plant rests, small stones etc. For that reason, *Schmittmann & Kromer (2002)* tried to measure the mass flow of clean beet. They based their method on online counting of beets and calculating specific yield by multiplying the number of beets the average mass of single beets. They reported that in field tests the system worked successfully, but only under optimized conditions.

Hennens et al. (2003) developed a mass flow sensor for sugar beet harvesters based on the use of a curved impact plate to measure momentum. The sensor was designed in accordance with a mathematical model of beet flow and was installed in the beet harvester cleaning unit. Using only momentum to predict mass flow, errors up to 20 % were discovered. However, this error rate was reduced to 3 % when material velocity corrected momentum was used. *Konstantinovic et al. (2007)* evaluated an ultra wideband radar system for sugar beet yield mapping. They tried to distinguish sugar beet and its dimensions from the surrounding agricultural soil. Sugar beet detection and mass determination potentials under field conditions were evaluated. The simple threshold detection approach to the reflected energy showed insufficiently accurate results and further research into this method is necessary.

Several other systems and methodologies have also been developed for other non-combinable crops which may be suitable for potato and sugar beet as well, e.g. measurement of mass accumulation rate (*Godwin & Wheeler, 1997; Saldana et al., 2006*).

Forages throughput sensors have also been studied in the past. *Vansichen & De Baerdemaeker (1993)* calculated yield from the torque of a forage harvester's blower. Another possibility is to measure the distance between feeder rolls of the harvester *(Ehlert & Schmidt 1995; Auernhammer, Demmel & Pirro., 1996; Barnett & Shinners, 1998; Martel & Savoie, 1999; Schmittmann, Kromer & Weltzien, 2001; Diekhans, 2002)*. A mass flow sensor for a pull type (trailed) forage harvester based on a reaction plate in the spout was constructed and tested by *Missotten et al. (1997)*. Similar sensors were tested by other authors (*Barnett & Shinners, 1998; Martel & Savoie, 1999, Schmittmann, Kromer & Weltzien, 2001*) for self propelled forage harvesters. *Martel & Savoie (1999)* measured electrical capacitance in the spout of a forage harvester and *Schmittmann, Kromer & Weltzien (2001)* measured crop layer thickness. Some of these methods (e. g. distance between feeder rolls, reaction plate, and crop layer thickness) are very interesting and showed a good coefficient of determination (R^2 = 0.94 to 0.98). Some methods (e. g. distance between feeder rolls, electrical capacitance in the spout of a forage harvester) have to be supplied with several calibration parameters.

Site-specific measurement of biomass in growing cereal crops has been proposed by *Ehlert, Volker & Kalk (2002)* using a pivoted cylindrical body moving horizontally through a plant population (moving pendulum). The angle of deviation of this pendulum varies with the plant properties.

The feed rate measurement technique for mowing machines was also tested. *Demmel et al. (2002)* used a principle based on belt weighing technology in the windrowing device of a mower. Recently, *Ruhland, Haedicke & Wild (2004)* determined yield by means of determining the torque requirements in the windrowing device of a mower. Both methods are suitable only for mowing machines equipped with a windrowing device. A pulse radar system for grass yield measurements was also introduced (*Wild, Ruhland & Haedicke, 2003*). The results obtained from the measurement showed that the sensors need further improvement.

Shinners, Barnett & Schlesser (2000) developed and evaluated systems to measure material feed rate on a self-propelled forage windrower. They tested conditioning roll force, conditioning roll rise and swath shield impact force as a predictors of material feed rate. The only system to show promise of adequately predicting material feed rate through the machine was impact force on the swath shield. Recently, *Shinners, Huenink & Behringer (2003)* equipped a windrower to measure material feed rate by the following sensors: pressure sensor to measure the load at the platform drive motor; speed pick-up to measure conditioning roll speed, load cell to measure crop impact on the swath forming shield and rotary potentiometers to measure crop volumetric flow past swath forming shield. The crop volumetric flow was well correlated with material feed rate when the sensor output was combined with platform inclination and roll speed. The results from these measurements were meaningful (R^2 = 0.94).

In the past, we have also been developing and testing sensors for measuring the throughput of mowing machine. Principles based on torque sensor in machine’s conditioner shaft and curved impact plate mounted at the exit of the machine *(Kumhála & Prošek, 2003; Kumhála et al., 2003; Kumhála, Kroulík & Prošek 2007)*. However, while developing and testing these two contact methods, we have faced with some of their disadvantages. Problems can be caused by foreign particles in the harvested forages, such as stones, which can damage the measuring device.

Non-contact measurement methods are preferable from this perspective. For example, the use of capacitive measurement methods could be interesting. The advantages of capacitive sensor are its relative simplicity, its possible suitability for the often difficult operating conditions found on agricultural machines, and its low cost.

Capacitance sensor techniques can be used for the determining different properties of a range 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 increasing. According to many authors *(e.g. Kim et al., 2003; Nelson, 2005; Wild & Haedicke, 2005; Jones et al., 2006)* the dielectric properties of many materials depend on frequency, moisture content, volume density, temperature, chemical composition, and permanent dipole moment association with water and other constituent molecules.

Capacitance sensors have been widely used for plant material moisture content determination *(Lawrence, Funk & Windham, 2001)*. *Eubanks & Birrell (2001)* determined the moisture content of hay and forages by using multiple frequency parallel plate capacitors. *Osman et al. (2002)* built a parallel plate capacitor with variable spacing for hay and forage moisture measurement. *Snell et al. (2002)* used a radio-frequency application device for sensing dry matter content of various agricultural products.

However, there were also efforts to use a capacitive sensor to measure throughput. *Stafford et al. (1996)* used a capacitive sensor to determine grain mass flow. *Martel & Savoie (1999)* observed a capacitance controlled oscillator placed at the discharge end the forage harvester spout to measure changes induced by forage particles. Recently, *Savoie, Lemire, & Thériault (2002)* used a similar capacitance controlled oscillator for their measurement. *Williams et al. (2000)* used electrical capacitance tomography for particular solids flow rate measurement on a conveyor belt.

Based on the information from this literature review and also our own experience, it was clear that the principles of measuring plant materials throughput are known, but still not often used. Measuring systems are sometimes too complicated and still not enough robust and to use contactless capacitive measurement principle could be a promising way to improve this situation. That is why in 2006 we started to develop capacitive sensor suitable for plant materials throughput measurement. The main aim of this paper is therefore to present the steps of capacitive throughput sensor for plant materials development and the results achieved.

MATERIALS AND METHODS

Since we had experience in measuring the throughput of the forage through the mower and mower was still available, we first tried to develop a capacitive sensor suitable for this machine in 2006.

The parallel plate capacitance sensor consisted of two metal sheets 2 mm thick and with the dimensions 830 mm in length and 260 mm in width. The distance between the plates was 300 mm. The inside parts of metal sheets were insulated by two plastic sheets 1 mm thick with the same dimensions which were stuck on metal sheets. Sides of the capacitance sensor were made from 10 mm thick acrylic glass. A shielding 2 mm thick metal plate with the dimensions 830 mm in length and 280 mm in width were fixed to mentioned acrylic glass sides in the distance 430 mm from the capacitor's shielded plate (see Fig. 1). This metal plate shielded the capacitance sensor from surrounding influences which could affect the measurement. The design of a sensor and its dimensions we tried to develop just ready for practical using on small rotary mower equipped with conditioner (ŽTR 186, Agrostroj Pelhřimov Company).

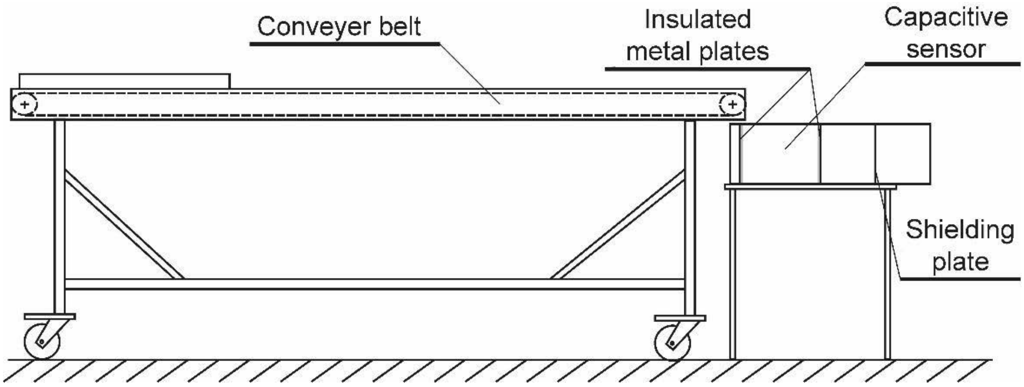

Fig. 1 Arrangement of measurement device for laboratory tests in 2006.

The laboratory set-up consisted of a conveyer belt carrying a measured quantity of material into sensor equipped with the electronic measurement apparatus (Fig. 1). Material from the conveyer belt passed through the sensor between its plates. Material was transported through parallel plate capacitance sensor for approximately five seconds for each test run.
A very important part of our capacitive throughput sensor is its electronic circuit. The sensor - capacitor and the whole oscillating circuit was driven at 27 MHz frequency. The exact connection of the measuring circuit is in the Fig. 2. The capacitor was fed with AC-voltage from the oscillator via resistor or another capacitor with the same reactance. The resistor together with two measuring capacitor plates made up a voltage divider and thus the output voltage of that divider depended on the capacity on the measuring capacitor and that capacity is dependent on the dielectric matter between the plates again. The dielectric constant of the measuring capacitor varied according to the amount and type of material paced between the plates, it means according to proportion material/air. The AC output voltage of the divider was then rectified in an AC/DC rectifying module and amplified with an amplifier. Rectified output voltage just can be measured and saved. In this case we used 0.5 s interval for saving.

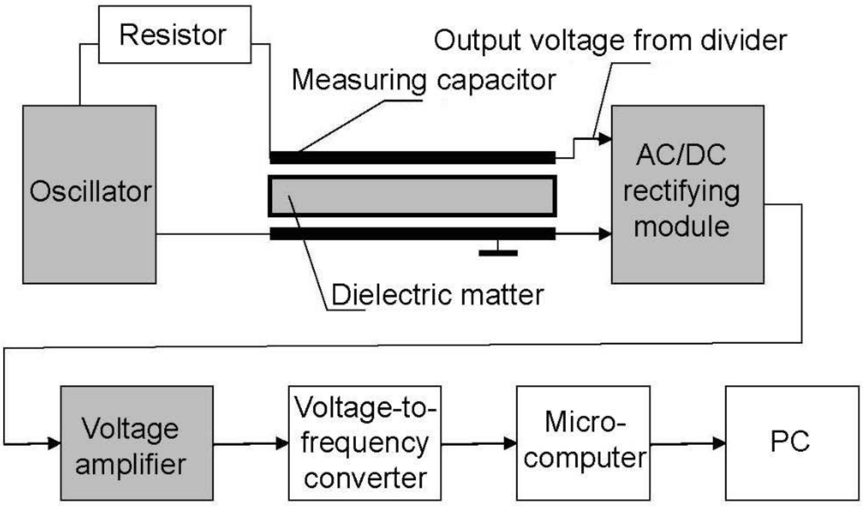

Fig. 2 Block diagram of electronic apparatus arrangement for plant material throughput measurement. Oscillator worked at 27 MHz frequency.

This relatively simple proposed connection of electronic circuit is very sensitive (capable of measuring very small capacitance changes), but within a narrow measuring range. However, this narrow measurement range was perfectly suited to our needs.
In 2006, measured material was grass from natural meadow. Closer description of methodology used in this year can be found in *Kumhála et al. (2007)*.
During the measurement in 2006, it appeared that it is necessary to partially change the arrangement of the measuring device. The arrangement was improved with the aim to achieve more uniform material distribution within the sensing volume. The capacitive sensor was mounted directly on the conveyer as follows: bottom metal sheet of the capacitor was inserted under the elastic belt and the center of the belt was just in the middle of the metal sheet length. The capacitor was placed near to the end of the conveyor. This arrangement of measuring device is in Fig. 3. In 2007, this arrangement was used for the measurements repeated with grass during spring period and for the measurements with sugar beets and potatoes in autumn period of this year. Closer description of measuring device can be found in ASABE paper No. 084700 (*Kumhála et al., 2008*).
Measurements with sugar beets and potatoes in 2007 showed the need to determine the theoretical assumptions of the sensor function. The most important conclusions from the theoretical considerations of the capacitive sensor function were as follows.

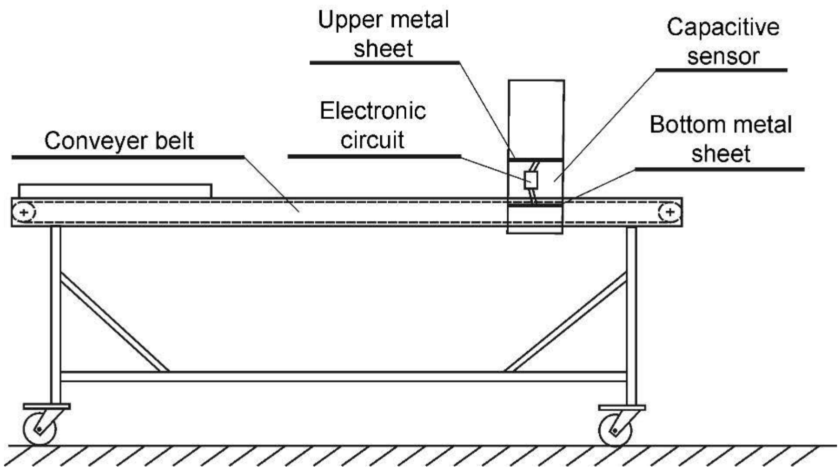

Fig. 3 Arrangement of measurement device for laboratory tests after improvement.

Bearing in mind the filling of the a real capacitive sensor with some dielectric material, two important separate cases have to be considered.
I. Layer filling (LF). This case is characteristic by using the whole plate area for transporting the material through the sensor (Fig. 4 left) and the differences in throughput is realized by increasing thickness c_1 of the analyzed material. This regime of sensor operation is typical for materials formed by small particles when the sensor is used for higher throughput values. Resulted relationship between the sensor capacity C and the throughput value Q is described as an equation of the shifted hyperbola.
II. Filling by simple particles (FSP) In this case the plate area for transport is covered partially (Fig. 4 right) and the throughput differences are solved only by the degree of the plate covering that is expressed by a length a_1 in Fig. 4 right. This case describes lower throughput regimes and/or regimes working with particles with dimensions nearly comparable with the plates distance c. Linear dependence of the sensor capacity and the sensor throughput is achieved in this case.

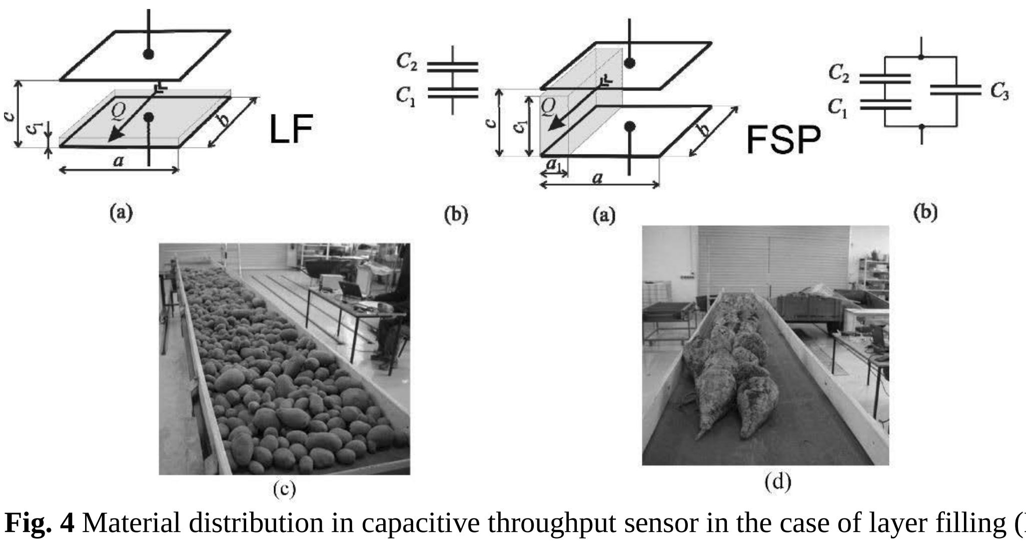

Fig. 4 Material distribution in capacitive throughput sensor in the case of layer filling (LF) and filling by single particles (FSP); (a) initial material throughput layer; (b) substituted model; (c) LF realized using potatoes (Q=12.6 kg s^{-1}); (d) FSP realized using sugar beet (Q=12.7 kg s^{-1}); a capacitive throughput sensor plate length; b capacitive throughput sensor plate width; c distance between capacitive throughput sensor plates; c_1 thickness of material layer in capacitive throughput sensor; C_1, C_2, C_3 capacity of substituted capacitors; Q direction of measured material throughput.
In working conditions both cases (LF and FSP) can be combined. Nevertheless if the average diameter of measured material particle is relatively small compared to the capacitor plates distance the resulting capacity tends to be described as LF depending on material throughput and conversely, when the average

particle dimension approaches the distance c the resulting capacity tends to depend on throughput as FSP. This means that every plot of C versus Q starts at low throughputs as FSP and changes to LF at high throughputs when this is allowed by the sensor construction parameters and the particle dimensions of the product. Closer description of these theoretical considerations including equations can be found in *Kumhála, Prošek & Blahovec (2009).*
The suitability of capacitive sensor for chopped maize throughput measurement was also tested in 2008. Since the moisture content of chopped maize during harvesting is lower compared to previous materials tested, the experiments were focused on the effect of moisture content on plant material throughput measurement. Stationary laboratory experiments with balsa blocks were arranged. Another, smaller laboratory capacitor was made for that purpose. The capacitor was integrated into an electronic circuit similar to the ones used for other experiments. The dimensions of capacitor plates were 67 mm in length and 40 mm in width. The distance between the plates was 20 mm. Four balsa blocks with the dimensions 57 mm in length, 40 mm in width and 16 mm in height were used for those experiments.
At start of the experiments, balsa blocks were moistened to about 80% of moisture content and then slowly dried in our laboratory. After about 45 minutes of drying, balsa blocks were placed into plastic bags and sealed in order to homogenize moisture content distribution inside each of balsa blocks. After that, each balsa block was separately weighted and placed between smaller capacitor plates. The values of balsa blocks weight and measuring circuit output voltage were logged and used for further calculations of balsa blocks moisture content and charting. This procedure was repeated until balsa blocks equilibrium moisture content was achieved. During the measurements the dimensions of balsa blocks were checked to make sure that they hadn't changed. Detailed description of materials and methods used for these experiments is in *Kumhála, Prošek & Kroulík (2010).*
Based on the results achieved, in 2011 and 2012 there was an effort to use a capacitive sensor to monitor hop throughput on the hop picking machine. All harvesting experiments were done using a stationary hop picking machine PT-30 produced by Chmelařství družstvo Žatec, CR, and located in Stekník. This machine uses picking conveyer system. At the beginning of the picking process, hop vines are loaded into the picker manually using feed track intake. Then, hop cones are separated from the vine stalk by two picking walls (equipped with picking conveyers) along their entire length with subsequent secondary picking of long ends. Picked hop cones are then separated by air separators and inclined separating conveyers. At the end of the hop picking machine clean hop cones falling down from inclined separating conveyers are transported away from the machine by a horizontal elastic belt conveyer. Main parts of PT-30 can be seen in Fig. 5.

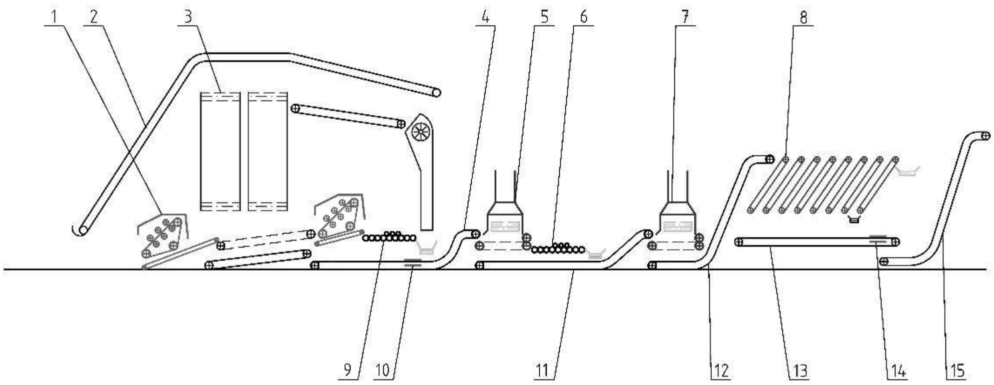

Fig. 5 Main parts of stationary hop picking machine PT-30. 1-lateral pickers for secondary picking of long ends, 2-feed track intake, 3-picking walls, 4-belt conveyer to separation part, 5-primary air separator, 6-pinch rollers, 7-secondary air separator, 8-inclined separating conveyers, 9-waste conveyers, 10-pinch rollers, 11- location of capacitive throughput unit for throughput control, 12-belt conveyer to secondary air separator, 13-belt conveyer to inclined separating conveyers, 14-horizontal elastic belt conveyer, 15-location of tested capacitive throughput unit, 16-belt conveyer to drying machine.
A modified capacitive throughput unit was made to be mounted on our PT-30 hop picking machine. The main difference was in capacitor dimensions. Dimensions of the bottom, grounding plate were 1222 mm in length and 300 mm in width. Dimensions of the upper, active plate were 1170 mm in length and 300

mm in width. Both plates were made of 1.5 mm thick metal sheet. In order to increase the strength of the plates their edges were bent by 90 degrees. The upper plate was insulated from the rest of the machine by two pertinax blocks with dimensions of 300 x 70 x 20 mm. For practical reasons the distance between the plates had to be set to 80 mm. The electronic measurement apparatus of this unit was mounted on the insulation block at the left side of the upper plate and run at 6 MHz frequency in this case. A more detailed description of the materials and methods used in 2011 and 2012 is in *Kumhála, Kavka & Prošek (2013)*.
Based on previous encouraging results, the sensor was used to control the hop picking process in 2013. The parallel plate capacitance sensor was mounted on a PT-30 hop picking machine (label 11 in Fig. 5). The dimensions of the bottom, grounding plate were 1000 mm in length and 300 mm in width. The dimensions of the upper, active plate were 890 mm in length and 300 mm in width. Both plates were made from 1.5-mm thick metal sheet. In order to increase the strength of the plates their edges were bent by 90 degrees. The upper plate was insulated from the rest of the machine by two insulating blocks with the dimensions of 290 x 60 x 8 mm. The distance between the plates was 165 mm. The upper plate was covered from the top by a plastic sheet in order to prevent its clogging by impurities. The capacitance sensor was equipped with an electronic measurement apparatus, which was mounted on the insulation block at the right side of the upper plate and worked at 6 MHz frequency.
For the purpose of wet hop material instantaneous throughput measurement and consequent control, the capacitance sensor was mounted on the pocket belt conveyer transporting picked hop material to the separation part of the machine (Fig. 6). The sensor was placed in the last third of the conveyor, just before the beginning of its sloping part. The total transport length of the conveyor belt was 6.26 m; the transport width was 0.9 m. The conveyor pockets were made from 1-mm thick metal sheet and their height was 70 mm. The conveyor velocity could be set in the range of 0.23–0.46 m s^{-1} using an electric motor drive controlled by a frequency converter. Detailed description can be found in *Kumhála et al. (2016)*.

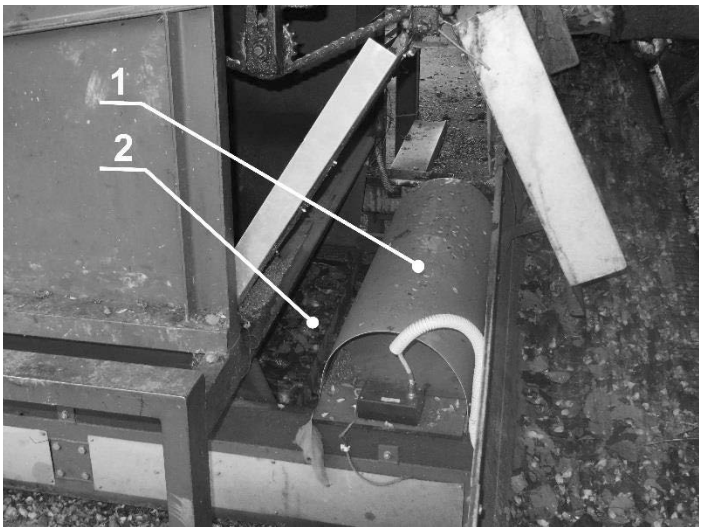

Fig. 6 Location of the capacitance throughput sensor on the pocket belt conveyer of the PT-30 stationary hop picking machine (Fig. 5, label number 11). 1 – capacitance throughput sensor, 2 – pocket belt conveyer with picked hop material.

RESULTS AND DISCUSSION

An example of the measurement results in 2006 is shown in Fig. 7. The forage mass flow determination by means of parallel plate capacitance sensor driven at 27 MHz frequency appeared to be a promising way. The results revealed a strong linear relationship between the feed rates of the wet forage crop material passing through the sensor between its plates and the tested measuring capacitance sensor circuit output. However, the results obtained showed that an improvement of the electronic circuit connection and measuring device arrangement can be recommended.

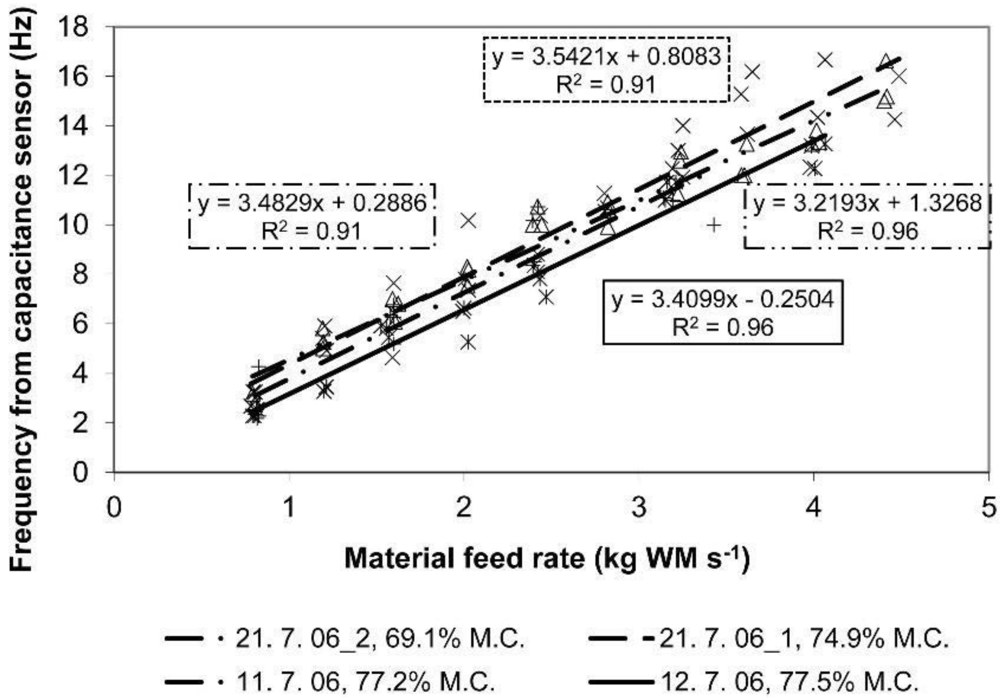

Fig. 7 The dependence of measured circuit output frequency on plant material mass flow (11th, 12th and 21st July 2006). M.C. – moisture content.

An example of the results obtained with partially changed arrangement of measuring device (see Fig. 3) is provided in Fig. 8.

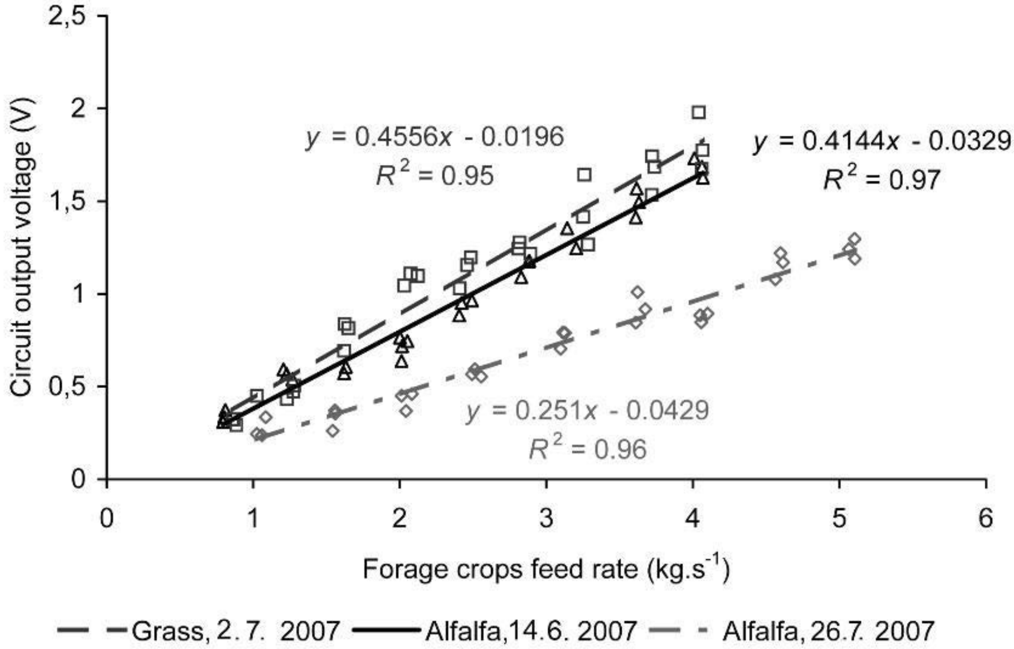

Fig. 8 Dependence of the measuring circuit output on forage crops feed rate (14.6. 2007 alfalfa 66.3 % M.C., 2.7. 2007 grass from natural meadow 74.4 % M.C., 26.7. 2007 alfalfa 75.9 % M.C.).

The linear dependence of the capacitive sensor data on forages throughput was confirmed in 2007. The resulting coefficients of determination were the same or better than in 2006. However, the whole behavior of the measuring apparatus was not entirely logical. It was not clear which of changing factors of

investigated material influenced the measurement more and which less. For example, it was not clear how the measurement was affected by changes in forages moisture content etc.
After measurements with forage crops in the spring and summer of 2007, a functional measuring apparatus remained in our laboratory. During the autumn of 2007, samples of potatoes and sugar beets from other measurements appeared in the same laboratory. Therefore, it was not difficult to decide about testing of our capacitive throughput sensor also with these plant materials. The advantage of potatoes or sugar beets over forage crops lies primarily in the more regular shape of the individual particles.
The results from the measurements with sugar beets and potatoes are in Fig. 9.

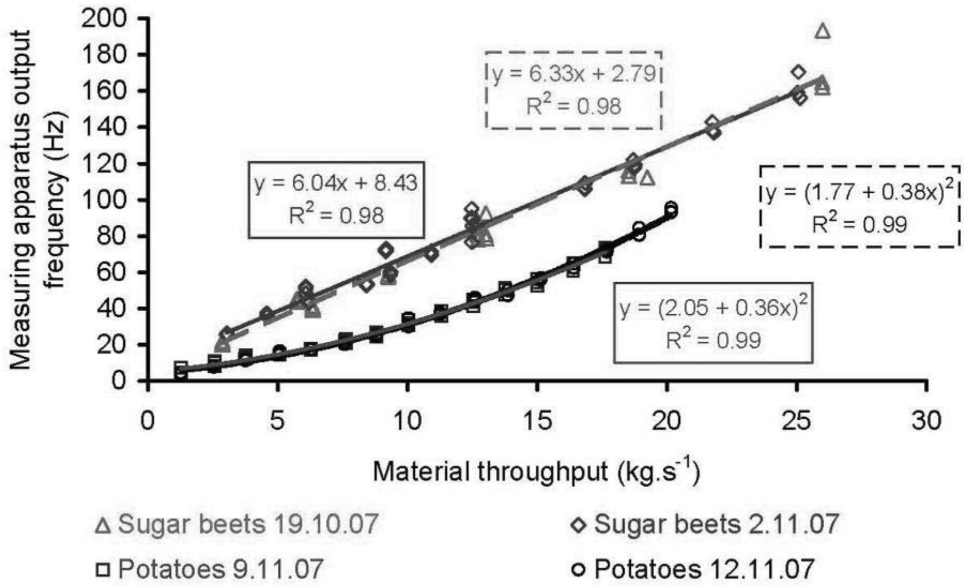

Fig. 9 Dependence of measuring apparatus output frequency (directly proportional to voltage and sensor capacity) on sugar beets and potatoes throughput.

However, the results of this measurement raised more questions than answers. Why we achieved so different output values for comparable material throughput? Why the trend was for sugar beets linear and for potatoes not? It was clear at this point that we do not understand well the behavior of the capacitive throughput sensor. It was necessary to turn back to the theory of capacitive throughput sensor function. The result of theoretical considerations can be seen in Fig. 4. Detailed description of theoretical considerations, its calculation and the results obtained with sugar beets and potatoes can be found in *Kumhála et al. (2008)* or *Kumhála, Prošek & Blahovec (2009).*
Another often harvested plant material is maize for silage making. As the chopped particles are relatively small, hyperbolic dependence of measured output values on throughput resulting from layer filling was expected and confirmed by our measurements in 2008. As already mentioned, copped maize has less moisture content than previously tested materials. The results from our measurements studying the effect of moisture content on plant material throughput measurement can be seen in Fig. 10.
Although the effect of measured material moisture content changes to its throughput measurement is surprisingly not as great as expected (*Stafford et al., 1996*), still some exists. It can be concluded from our results that if materials with relatively high moisture content are measured (i.e. potatoes, sugar beets, carrots, tomatoes etc.), changes of about 5% of material moisture content have very little influence on capacitive throughput sensor measurement and which can therefore be neglected.

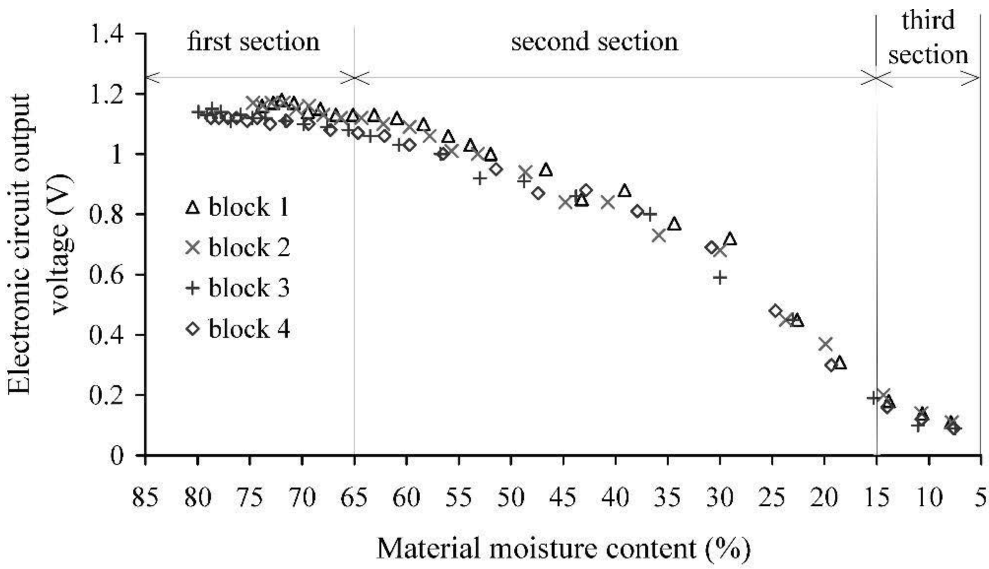

Fig. 10 Dependence of measured capacitive sensor output voltage on balsa blocks moisture content (wet basis) changes. Dry matter content of 1st balsa block was 4.79 g, of 2nd balsa block 4.83 g, of 3rd 3.71 g and of 4th balsa block 3.75 g.

However, in the case when materials with lower material moisture content are measured, the changes in material moisture content itself can influence the results of capacitive throughput measurement. In our case, material moisture content of freshly chopped maize can vary from 40% to about 60%. This is just below 65% and those values fall into the second section of the chart in Fig. 10. This must be respected during the operation of capacitive throughput sensor. Independent measurement of material moisture content can be recommended for plant materials with material moisture content in the range from 65 to 15%.
Results of previous experiments and knowledge of capacitive throughput sensor behavior motivated us to its practical application with the aim to control hop picking process of stationary hop picking machine. The main task of this control was to reduce hop harvest losses resulting from the uneven throughput of the harvested material through different parts of hop harvesting machine (see Fig. 5). An example of the hop picking machine control using signals from capacitive throughput sensor to control it is in Fig. 11.

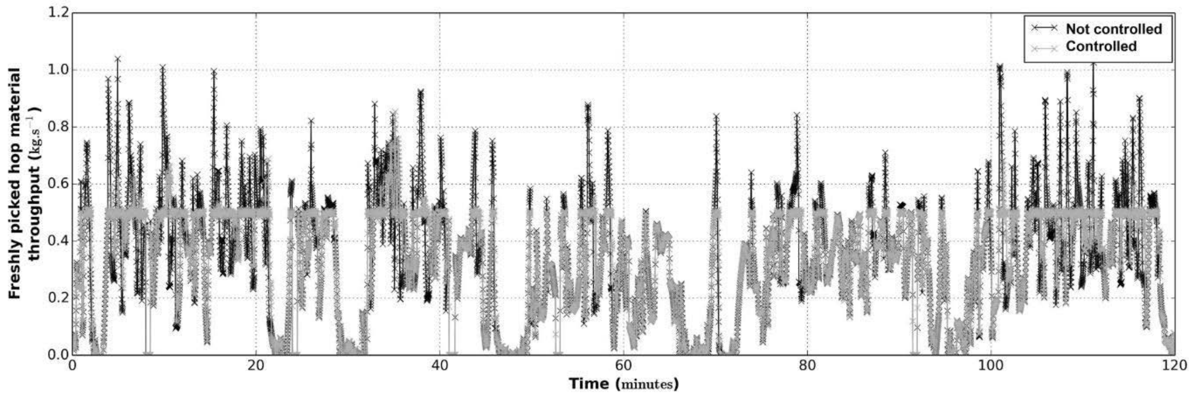

Fig 11 The course of freshly picked material throughput when automatic throughput control is used (gray curve) and when it is not (black curve).

From Fig. 11 it is clear that using the automatic control procedure avoids reaching a material throughput higher than 0.5 kg.s^{-1} (which are the cause of losses) in numerous occasions in comparison with the situation when automatic control is not used. It is realistic to assume that control system functionality can save over 2% of harvesting losses. When harvesting 30 ha per year with the average yield of 1 ton

per ha, this fact represents a saving of 0.6 tons of dry hop cones per one year. When calculating with the estimated control system price of 145 000 Kč (5 650 EUR or 6,250 USD) and the commodity price 150 000 Kč (5 850 EUR or 6,600 USD) per ton of dry hop, the return on investment should be less than two years. Closer description of the results from this practical application of capacitive throughput sensor can be found in *Kumhála et al., 2016*.
Further experiments with capacitive sensor were focused on its division into segments (*Lev, Wohlmuthová & Kumhála, 2012*) or on deeper study of the influence of frequency and material moisture content changes on its function (*Lev et al., 2017*). However, these experiments are just beyond the scope of this article.

CONCLUSIONS

It can be concluded on the base of our results that capacitive throughput sensor is a suitable device for measuring the throughput of plant materials. It is a relatively inexpensive and sufficiently robust and accurate alternative to other methods of plant materials throughput measurement. However, it is to be expected that the filling of the capacitive throughput sensor plays a very important role that has to be respected during its use. Independent measurement of material moisture content is recommended for plant materials with material moisture content in the range from 65 to 15%. The potential of the capacitive throughput sensor has also been tested under normal operating conditions during hop harvesting with satisfactory results.

ACKNOWLEDGMENT

This study was supported by many national and also international research projects. I would like to thank a lot to all those who participated in the presented research, namely my colleagues Mr. Václav Prošek and Prof Jiří Blahovec.

REFERENCES

1. Arslan, S. & Colvin, T. S. (2002): An Evaluation of the Response of Yield Monitors and Combines to Varying Yields. *Precision Agriculture 3*(2), 107-122.
2. Arslan, S., Inanc, F., Gray, J., & Colvin, T. (2000). Grain Flow Measurements with X-ray Techniques. *Computers and Electronics in Agriculture 26*(1), 65-80.
3. Auernhammer, H., Demmel, M., & Pirro, P. J. M. (1996). Lokale Ertragsermittlung mit dem Feldhäckslern. (Local Yield Monitoring in a Forage Harvester). *Landtechnik 51*(3), 152-153.
4. Barnett, N. G. & Shinners, K. J. (1998). Analysis of Systems to Measure Mass-flow-rate and Moisture on a Forage Harvester. *ASAE Paper No. 981118*.
5. DeHaan, K. R., Vessey, G. T., Holmstrom, D.A., MacLeod, J. A., Sanderson, J. B., & Carter, M. R. (1999). Relating potato yield to the level of soil degradation using a bulk yield monitor and differential global positioning systems. *Computers and electronics in Agriculture 23*(2), 133-143.
6. Demmel, M., Schwenke, T., Heuwinkel, H., Locher, F., & Rottmeier, J. (2002). Lokale Ertragsermittlung in einem Scheibenmähwerk mit Aufbereiten. (Local Yield Monitoring in a Mower Conditioner with Windrowing Device). In: *Proceedings of Conference Agricultural Engineering 2002* (pp. 139–143). VDI Verlag GmbH.
7. Diekhans, N. 2002. Ein praxisnahes Verfahren für eine Ertragsmessung an Feldhäckslern. (A Practical Solution for Yield Measurement on a Forage Harvester). In: *Proceedings of Conference Agricultural Engineering 2002*. (pp. 133-137). VDI Verlag GmbH.
8. Ehlert, D. & Algerbo, P-A. (2000). Yielding mapping with potatoes. *Landtechnik 55*(6), 436-437.
9. Ehlert, D. & Schmidt, H. (1995). Ertragskartierung mit Feldhäckslern. (Yield Mapping in Forage Harvesters). *Landtechnik 50*(4), 204–205.
10. Ehlert, D., Volker, U., & Kalk, W.-D. (2002). Sensorgestützte Stickstoffdüngung in Winterweizen. (Sensor Based Nitrogen Fertilization in Winter Wheat). In: Proceedings of Conference Agricultural Engineering 2002 (pp. 127-132). VDI Verlag GmbH.
11. Eubanks, J. C. & Birrell, S. J. (2001). Determining moisture content of hay and forages

using multiple frequency parallel plate capacitors. *ASAE paper No. 011072.*

12. Godwin, R. J. & Wheeler, P. N. (1997). Yield mapping by mass accumulation rate. *ASAE paper No. 971061*.
13. Gonigeni, S., Thomasson, J. A., Wooten, J. R., White, J., Thompson, P. G., & Shankle, M. (2002). Image-based sweetpotato yield and grade monitor. *ASAE Paper No. 021169*.
14. Hall, T. L., Backer, L. F., & Hofman, V. L. (2003). Sugarbeet Yield Monitoring for Site-Specific Farming Part II-Field Testing. *Precision Agriculture 4*(4), 433 – 444.
15. Hennens, D. Baert, J., Broos, B., Ramon, H., & De Baerdemaeker, J. (2003). Development of a Flow Model for the Design of a Momentum Type Beet Flow Sensor. *Biosystems Engineering 85*(4), 425 – 436.
16. Hofstee, J. W. & Molena, G. J. (2002). Machine vision based yield mapping of potatoes. *ASAE paper No. 021200*.
17. Hofstee, J. W. & Molena, G. J. (2003). Volume estimation of potatoes partly covered with dirt tare. *ASAE paper No. 031001*, 12 p.
18. Isensee, E. & Lieder, W. (2001). Ertragmessung in der Rübenernte [Yield measurement during sugar beet harvesting]. *Landtechnik 56*(4), 272-281.
19. Jones, C. L., Stone, M. L., Maness, N. O., Solie, J. B. & Brusewitz, G. H. (2006). Plant biomass estimation using dielectric properties. *ASABE paper No. 063092*.
20. Kim, K. B., Lee, J. W., Lee, S. S., Noh, S. H., & Kim, M. S. (2003). On-line measurement of grain moisture content using RF impedance. *Transaction of ASAE, 46*(3), 861-867.
21. Konstantinovic, M., Woeckel, S., Schulze Lammers, P., & Sachs, J. (2007). Evaluation of a UWB Radar System for Yield Mapping of Sugar Beet. *ASABE paper No. 071051*.
22. Kumhála, F., Kavka, M., & Prošek, V. (2013). Capacitive throughput unit applied to stationary hop picking machine. *Computers and Electronics in Agriculture 95*(6), 92–97.
23. Kumhála, F., Kroulík, M., Mašek, J., & Prošek, V. (2003). Development and testing of two methods for the measurement of the mowing machine feed rate. *Plant, Soil Environment 49*(11), 519-524.
24. Kumhála, F., Kroulík, M., Kvíz, Z., Mašek, J., & Prošek, V. (2008). Sugar beets and potatoes throughput measurement by capacitive sensor. In *Agricultural Engineering - Landtechnik 2008* (pp. 199-204). VDI Verlag GmbH, Germany.
25. Kumhála, F., Kroulík, M., & Prošek, V. (2003). Development and evaluation of forage yield measure sensors in a mowing-conditioning machine. *Computers and Electronics in Agriculture 58*(2), 154-163.
26. Kumhála, F.; Kvíz, Z.; Kmoch, J. & Prošek, V. (2007). Dynamic Laboratory Measurement with Dielectric Sensor for Forage Mass Flow Determination. *Research in Agricultural Engineering 53*(4), 149-154.
27. Kumhála, F., Lev, J., Kavka, M., & Prošek, V. (2016). Hop-Picking Machine Control Based on Capacitance Throughput Sensor. *Applied Engineering in Agriculture 32*(1), 19-26.
28. Kumhála, F. & Prošek, V. (2003). Laboratory Measurement of Moving Machine Material Feed Rate. *Precision Agriculture 4*(4), 413-419.
29. Kumhála, F., Prošek, V. & Blahovec, J. (2009). Capacitive throughput sensor for sugar beets and potatoes. *Biosystems Engineering 102*(1), 36-43.
30. Kumhála, F., Prošek, V. & Kroulík, M. (2010) Capacitive sensor for chopped maize throughput measurement. *Computers and Electronics in Agriculture 70*(1), 234–238.
31. Kumhála, F., Prošek, V., Kroulík, M. & Kvíz, Z. (2008). Parallel Plate Mass Flow Sensor for Forage Crops and Sugar Beet. *ASABE paper No. 084700*.
32. Lark, R. M., Stafford, J. V. & Bolam, H. C. (1997). Limitations on the Spatial Resolution of yield Mapping for Combinable Crops. *Journal of agricultural engineering research 66*(3), 183-193.
33. Lawrence, K. C., Funk, D. B., & Windham, W. R. (2001). Dielectric moisture sensor for cereal grains and soybeans. *Transaction of ASAE, 44*(6), 1691-1696.
34. Lev, J., Křepčík, V., Prošek, V., & Kumhála, F. (2017). Capacitive throughput sensor for plant materials - Effects of frequency and moisture content. *Computers and Electronics in Agriculture 133*(2), 22-29.
35. Lev, J., Wohlmuthová, M., & Kumhála, F. (2012). Qualito of Material Distribution Imaging with Segmental Capacitive Sensor using Landweber's Iterative Algorithm. In: *Proceedings of 11th International Scientific Conference on Engineering for Rural Development* (pp. 239-244). Latvia University of Agriculture.

36. Martel, H. & Savoie, P. 1999. Sensors to Measure Forage Mass Flow and Moisture Continuously. *ASAE Paper No. 991050*.
37. Missotten, B., Broos, B., Strubbe, G., & De Baerdemaeker, J. (1997). A Yield Sensor for Forage Harvesters. In: *Precision Agriculture 1997. Proceedings of the 1st European Conference on Precision Agriculture* (pp. 529-536). BIOS Scientific Publishers.
38. Nelson, S. O. (2005). Dielectric properties measurement for agricultural applications. *ASABE paper No. 053134*.
39. Osman, A. M., Savoie, P., Grenier, D., & Thériault, R. (2002). Parallel-plate capacitance moisture sensor for hay and forage. *ASAE paper No. 021055*.
40. Persson, D. A., Eklundh, L., & Algerbo, P-A. (2004). Evaluation of an optical sensor for tuber yield monitoring. *Transaction of the ASAE 47*(5), 1851-1856.
41. Reyns, P., Missotten, B., Ramon, H., & De Baerdemaeker, J. (2002). A Review of Combine Sensors for Precision Farming. *Precision Agriculture 3*(2), 169-182.
42. Ruhland, S., Haedicke, S., & Wild, K. (2004). A Measurement Technique for Determination of Grass. In: *Proceedings of Conference Agricultural Engineering 2004* (pp. 317 – 324). VDI Verlag GmbH.
43. Saldana, N., Cabrera, J. M., Serwatowski, R. J., & Gracia, C. (2006). Yield mapping system for vegetables picked up with a tractor-pulled platform. *Spanish Journal of Agricultural Research 4*(2), 130-139.
44. Savoie, P., Lemire, P., & Thériault, R. (2002). Evaluation of five sensors to estimate mass-flow rate and moisture of grass in a forage harvester. *Applied Engineering in Agriculture, 18*(3), 389-397.
45. Shinners, K. J., Barnett, N. G., & Schlesser, W. M. (2000). Measuring Mass-Flow-Rate on Forage Cutting Equipment. *ASAE Paper No. 001036.*
46. Shinners, K. J., Huenink, B. M., & Behringer, C. B. (2003). Precision Agriculture as Applied to North American Hay and Forage Production. In: *Proceedings of the International Conference on Crop Harvesting and Processing. ASAE Publication Number 701P1103e.*
47. Schmittmann, O. & Kromer, K-H. (2002). Teilflächenspezifische Ertragsmessung von Zuckerrüben [Site-specific yield measurement of sugar beet]. In: *Proceedings of the Conference Agricultural Engineering* (pp. 259 – 264). VDI Verlag GmbH.
48. Schmittmann, O., Kromer, K-H., & Weltzien, C. (2001). Yield Monitoring on Forage Harvester. In: *Proceedings of PMA 2001* (pp. 286 – 291). CUA Prague, Czech Republic.
49. Schwenke, T., Demmel, M., Rothmund, M., & Rottmeier, J. (2002). Ertragsermittlung im selbstfahrenden Zuckerrüben Köpf-Rode-Bunker [Local yield detection in a self-propelled sugar beet harvester]. In: *Proceedings of the Conference Agricultural Engineering* (pp. 253 – 258). VDI Verlag GmbH.
50. Snell, H. G. J., Oberndorfer, C., Lücke, W., & Van den Weghe, H. F. A. (2002). Use of electromagnetic fields for the determination of the dry matter content of chopped maize. *Biosystems Engineering 82*(3), 269-277.
51. Stafford, J., Ambler, B., Lark, R., & Catt, J. (1996). Mapping and interpreting the yield variation in cereal crops. *Computers and Electronics in Agriculture, 14*(2-3) 101-119.
52. Vansichen, R. & De Baerdemaeker, J. (1993). A measurement technique for yield mapping of corn silage. *Journal of Agriculture Engineering Research 55*(1), 1-10.
53. Walter, J. D. & Backer, L. F. (2003). Sugarbeet Yield Monitoring for Site-Specific Farming Part I-Laboratory Tests and Preliminary Field Tests. *Precision Agriculture 4*(4), 421-431.
54. Whelan, B. & McBratney, A. (2002). A Parametric Transfer Function for Grain-Flow Within a Conventional Combine Harvester. *Precision Agriculture 3*(2), 123-134.
55. Wild, K., Ruhland, S., & Haedicke, S. (2003). Pulse radar systems for yield measurements in forage harvesters. In: *Precision Agriculture, Proceedings of the 4th European Conference on Precision Agriculture* (pp. 739-744). Wageningen Academic Publishers.
56. Wild, K. & Haedicke, S. (2005). Improving the accuracy of moisture sensors for forage crops. In: *Book of Abstracts 5 ECPA-2 ECPLF* (pp. 326-328). JTI Sweden.
57. Williams, R. A., Luke, S. P., Ostrowski, K. L., & Bennett, M. A. (2000). Measurement of bulk particulates on belt conveyor using dielectric tomography. *Chemical Engineering Journal 77*(1-2), 57-63.

Corresponding author:
prof. Dr. Ing. František Kumhála, Department of Agricultural Machines, Faculty of Engineering, Czech University of Life Sciences Prague, Kamýcká 129, Praha 6, Prague, 16521 Czech Republic, phone: +420 22438 3135, e-mail: kumhala@tf.czu.cz