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Online configurable tractor implement models

In order to optimize fuel consumption of tractors holistically, implement models are necessary which are able to describe the demand of draft and torque power at given operating parameters. Typically, existing models aren't able to fulfil parameterization online, i.e. during field operation, because implement and soil parameters are unknown and soil parameters vary strongly. In this article a cluster-based approach is proposed. To recognize different soils and implements, the continous collection of situation-based measurement data and their assignment to a cluster is used. The cluster center is used for a quantification of the average situation to parameterize the models. Therefore simplifying model assumptions have to be done which are also presented. The implements mentioned at DLG-PowerMix are considered.

Keywords
Empirical Modeling, implement, online optimization, DLG-PowerMix

Abstract
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The Chair of Mobile Machines (Mobima) at Karlsruhe Institute of Technology recently investigates a novel control architecture in order to holistically optimize the efficiency of tractors [1]. Since the efficiency of tractors is determined particularly by the implement, the holistic approach has to consider its behavior. By means of operating parameter variation, models have to be developed which are able to predict the demand of power at pulling device and power take off (PTO) according to momentarily measured situation. Hydraulic power isn't regarded in this context due to relatively low absolute values. Necessary information is supposed to be gathered on the basis of available or easily integratable sensor systems. The implements of the DLG-PowerMix are regarded (i.e. cultivators, plows, rotary harrows, mowers and manure spreaders) with the focus on soil cultivation.

Problem and solution approach

Stated objectives imply the use of empirical models to predict draft and rotary power, which are exclusively regarded here. Empirical models generally consist of three groups of parameters:

- Operating parameters: Significant operating parameters, which means those that are accurately adjustable during operation and that have an influence on the behavior of the implement regarding draft and rotary power are velocity v, PTO speed n_{ZW} and processing depth t_{EHR}. These parameters serve as degrees of freedom for the optimization of the system.
- Implement parameters: Implement parameters are construction specific and in contrast to operating parameters generally not adjustable during field operation.
- Soil parameters: Soil parameters like soil type, soil moisture and soil density are subject to commonly strong variation even within a field and are hardly measurable continuously.

The objectives result in the problem that under the specification of operating parameters, implement and soil parameters have to be identified by means of simple sensor signals. The challenge is that soil parameters are especially hard to measure and vary strongly, so they are useless for the direct parametrization of the model.

Here, the solution approach uses a clustering-algorithm. It assigns currently gathered situation-characterizing values like draft force F_{Zug}, PTO torque M_{ZW}, velocity v, PTO speed n_{ZW} and processing depth t_{EHR} as data tuple to a cluster [2]. In this way, similar data tuples are assigned to the same cluster. The balance point S_0 of the cluster, consisting of $F_{Zug,0}$, $M_{ZW,0}$, v_0, $n_{ZW,0}$ and $t_{EHR,0}$ is an averaged data tuple. Thus, different soils and implements can be distinguished. The balance point can be used to determine soil as well as implement parameters of common empirical models. Therefore, parameter dependencies are investigated and simplifications are set. In this way, all unknown parameters can be identified due to a single available cluster balance point S_0 according to **Figure 1**.

Modeling

In the following, models of the implements used in DLG-PowerMix are presented.

Fig. 1

Model of implement in „black box"-design

Cultivators

The model for cultivators is based on ASAE-Standard D497.4 "Agricultural Machinery Management Data" [3]. Accordingly the following formula can be used to calculate the required draft force of various implements:

$$F_{Zug} = S \cdot \left(A + B \cdot v + C \cdot v^2\right) \cdot b \cdot t_{EHR} \quad \text{(eq. 1)}$$

S: Soil parameter
A, B, C: Implement parameters
b: Working width

For cultivators C is set to zero according to ASAE-Standard. Contrary to the ASAE-Standard, it is presumed that the draft force is proportional to the working depth squared. Thereby the progressive incline described by [4; 5] is taken into account.

By analyzing the values of A and B for different implements of this type as given in the ASAE-Standard it is noticeable that the ratio $q = {}^{A}/_{B} = 20$ of these parameters is nearly constant, with a deviation of less than 10 %. Thus, A can be expressed as a function of B, whereby A can be eliminated. This leads to the following formula:

$$F_{Zug} = S \cdot \left(B \cdot q + B \cdot v\right) \cdot b \cdot t_{EHR}^2 \quad \text{(eq. 2)}$$

The remaining unknowns can be merged into one parameter X = S · B · b. Thus only one parameter has to be determined to adjust the model to the momentary operating conditions. This parameter can be calculated by using the current values of S_0:

$$X = \frac{F_{Zug,0}}{(q + v_0) \cdot t_{EHR,0}^2} \quad \text{(eq. 3)}$$

Plows

The model for plows is also based on ASAE-Standard D497.4. The implement parameter B is zero. The formula is again modified so that the draft force is proportional to the working depth squared. Thus measurements of [6; 7] are taken into account. Like the cultivator model, the parameter A is eliminated by presuming a constant ratio $q = {}^{A}/_{C} = 130$:

$$F_{Zug} = S \cdot \left(C \cdot q + C \cdot v^2\right) \cdot b \cdot t_{EHR}^2 \quad \text{(eq. 4)}$$

For q, a mean value of different plow shapes is used. The unknowns again can be merged into one parameter X = S · C · b which can be calculated similar to above.

Rotary harrows

Bernacki [8] describes the calculation of the specific energy of implements with rotating tools. Accordingly the energy which has to be provided during one revolution of the tools in relation to the machined soil volume can be expressed in the following form:

$$w = c_0 k + a_u v_u^2 \quad \text{(eq. 5)}$$

k: Soil parameter
c_0, a_u: Implement parameters
v_u: Circumferential speed of the tools

Based on this approach the PTO torque can be calculated:

$$M_{ZW} = \frac{b t_{EHR} v}{2\pi} \left(\frac{c_0 k}{n_{ZW}} + \frac{4\pi^2 R_{Rotor}^2 a_u n_{ZW}}{i^2} \right) \quad \text{(eq. 6)}$$

R_{Rotor}, i, b: Implement parameters

To simplify the equation, it is presumed that the soil parameter k has a distinct influence on the draft-slip (μ-σ)-characteristic of the tractor tires. Assuming that the operating point of the tire is within the stable range left of the maximum, a nearly constant ratio $c = {}^{\mu}/_{\sigma}$ between draft force and slip occurs depending on the soil. Due to the online determination of c, soil properties, and thereby the soil parameter k, can be estimated.

For the determination of c_0 and b the following fundamental consideration is made: a certain amount of energy per volume is needed to break up soil clods. Different implements with rotating tools have to provide approximately the same amount of energy to achieve similar results (in form of clod crushing). The relation between this energy and the circumferential speed of the tools is shown in [8]. The parameters c_0 and b are set to achieve the best possible correlation of the energy calculated with the model and the characteristic provided by Bernacki [8].

The remaining unknowns R_{Rotor}, a_u and i are merged into one parameter:

$$X = a_u \frac{4\pi^2 R_{Rotor}^2}{i^2} \quad \text{(eq. 7)}$$

This parameter can be calculated similar to above using S_0.

Furthermore a relation between PTO power and draft power exists, depending on velocity and circumferential speed of the tools. This is described by Bernacki [8] using an implement parameter c_x. Based on that, draft force can be estimated in dependency of PTO torque:

$$F_{Zug} = \frac{c_x i}{R_{Rotor}} M_{ZW} \qquad \text{(eq. 8)}$$

the unknowns can be merged into one parameter

$$X = \frac{c_x i}{R_{Rotor}} \qquad \text{(eq. 9)}$$

which can be calculated similarly to above.

Mowers

The Basis for the following models is the calculation of PTO power (P_{ZW}) according to ASAE-Standard EP496.2 "Agricultural Machinery Management" [9]:

$$P_{ZW} = A + B \cdot b + C \cdot f \qquad \text{(eq. 10)}$$

A, B, C: Implement parameters
f: Feed rate

For mowers A and C become zero. This leads to the required PTO torque:

$$M_{ZW} = \frac{B \cdot b}{2\pi \cdot n_{ZW}} \qquad \text{(eq. 11)}$$

B and b are merged to

$$X = \frac{B \cdot b}{2\pi} \qquad \text{(eq. 12)}$$

and calculated by using S_0.

Manure spreaders

Also for manure spreaders, A and B become zero according to ASAE Standard. It is presumed that the spread amount of manure per acreage is a constant equal to c due to control regulations. Therefore the feed rate is proportional to the driving speed. PTO torque can be calculated as follows:

$$M_{ZW} = c \frac{v}{n_{ZW}} \qquad \text{(eq. 13)}$$

The unknown parameter X=c is determined similarly to above.

Balers

For balers, B is zero. According to ASAE-Standard D497.4, the parameter A is very small for various balers (maximal 4 kW); therefore it is insignificant. For the approximate calculation of the PTO torque, constant windrow density ρ_S and cross-section area A_S are presumed:

$$M_{ZW} = \frac{C \cdot \rho_S \cdot A_S \cdot v}{2\pi \cdot n_{ZW}} \qquad \text{(eq. 14)}$$

Again the unknowns are merged to

$$X = \frac{C \cdot \rho_S \cdot A_S}{2\pi} \qquad \text{(eq. 15)}$$

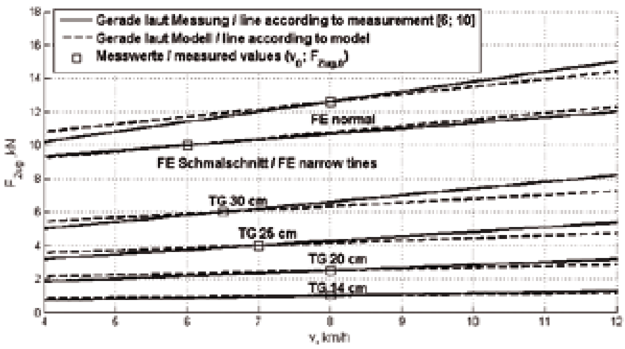
and calculated by using S_0.

Manure spreaders and balers require a draft force to overcome rolling resistance. This resistance is presumed constant. Mowers are also affected by a resistance force in longitudinal direction which is also presumed constant.

Results

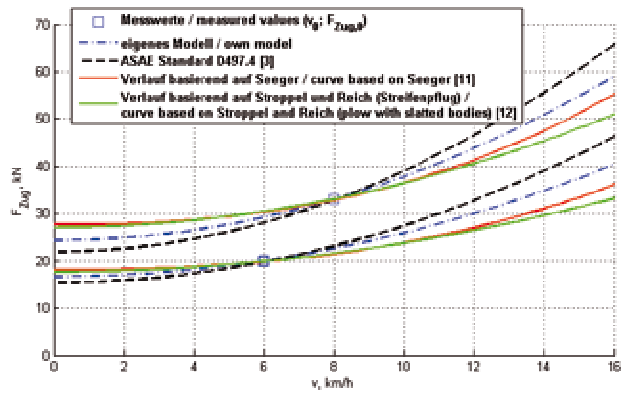
In **Figure 2** and **3**, the results of developed models for plows and cultivators with solely draft force are presented, compared to existing measurement values and well-known models.

Fig. 2



Prediction model of F_{Zug} vs. v for different working depths and non-turning soil cultivation implements (FE = harrow; TG = extirpator)

Fig. 3



Comparison of the own model of turning soil cultivation for the prediction of F_{Zug} vs. v with common models in literature

Conclusion

Thanks to online parametrization of the implement models, good predictions for expected draft force and PTO torque are achieved for small deviations of operating parameters from the measured state. This statement is based on results which were validated using measured data from literature. One reason for this is that the qualitative dependencies between draft force or PTO torque and operating parameters are widely valid for implements of the same type. Therefore, the characteristics of many different implements can be simulated by using only a few different models. Finally, consideration of the current operating state in form of the cluster-center enables an adjustment of the models according to present implement and soil parameters. Such a parametrized model can be used to generate realistic predictions for a theoretical prospective state with modified operating parameters based on the current operating state.

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