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Model-in-the-Loop Tuning of Hitch Control Systems of Agricultural Tractors

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Abstract

The farming industry worldwide is facing challenges in order to be more productivity, efficient and leave a smaller footprint on the environment. The success relies on the efficient operation of the agricultural machinery including the agricultural tractor.

One of the major and even one of the most energy consuming operations for an agricultural tractor is soil preparation, especially ploughing. To be efficient, the tractor should be able to transform the highest possible amount of the engine power into a pulling force on the implements, i.e. the plough. From theory of tire mechanics, it is known, that slip is necessary in order to transmit force. Slip, which is relative speed between the pulling wheel and the ground, is also an expression of loss. Hence, it is crucial to have just enough slip to pull the implement without wasting to much energy.

The well-known electro-hydraulic hitch control system for agricultural tractors facilitates a control scheme, that based on sensors can relax the hitch by lifting the implement, reducing the pulling load and limits the slip without compromising working depth too much. Even though this technology is mature, the tuning of the control parameters poses a major challenge, partly because the set of parameters must fit both very hard dry soils as well as wet soil – and these conditions are difficult to obtain within a short time period. In other words, identification and tuning of the parameters can be challenging in terms of time, conditions and repeatability resulting in semi-optimum set of parameters.

In this paper a model-in-the-loop tuning approach is proposed and demonstrated. By harvesting experimental data, this can be used as foundation for standardized test field in order to conduct repeatable tests. These experimental data can be utilized in a simulation model, that represents the mechanical properties for the plough, tractor and tire-soil interaction. The output of the simulation serves as signal to stimulate the controller on the tractor. By this approach the hitch control parameters can be tuned and improved any time a year without available fields. With the possibility to conduct repeatable tests with no variation on the boundary conditions, the loop time for each iteration can as well be reduced significantly.

Introduction

A modern agricultural tractor that conducts soil preparation facilitates at least a three-point rear hitch system, that can raise and lower an implement in such a way that it can be positioned in a transport mode or working mode. In work mode, precise control of the working depth by adjusting the rear hitch is an integrated part of soil preparation. Therefore, modern tractors with electro-hydraulic controlled hitch includes a control scheme, that makes the operation easier for the operator [1], Fig. 1.

Force/draft control continuously measure the draught force by help of load cells. The purpose of the force control is to avoid stalling the diesel engine if the resistance of the soil increased due to field variation [2]. A modern force control system calculates the average resistance force itself and uses that as a reference [3].

Slip control continuously compare the wheel speed with the ground speed, measured by a radar. If the slip exceeds a reasonable threshold, the controller lifts the implement proportional to the calculated slip. The purpose is to keep the tractor driving forward, if the net traction coefficient of the ground drops [3].

Both force and slip control compromises the working depth, but is necessary assistance to avoid stalling of the engine and to have a fuel-efficient operation, since any wheel slip is equal to loss.

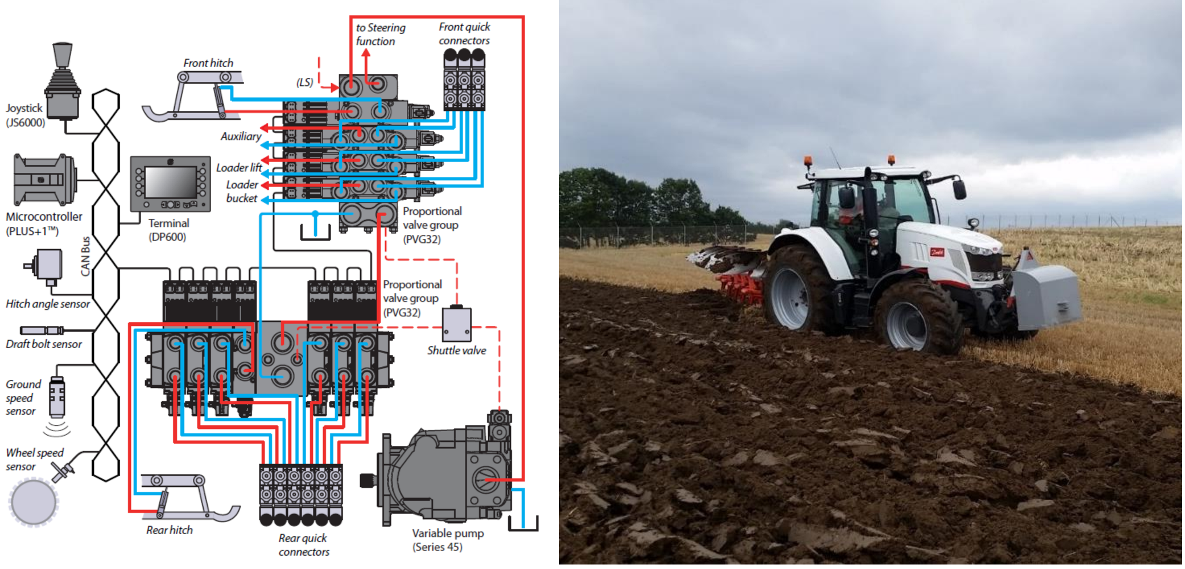

Fig. 1: Hitch control system and ploughing

A modern hitch control system also facilitates other features, such as active damping of the implement to avoid pitching when driving [4,5].

Challenges in Parameter Tuning and Optimization

A wide spread of soil conditions, both net traction coefficient and resistance of the soil, poses a major challenge when the optimum set of control parameters shall be identified. State-of-the-art is to conduct full scale tests in fields at various locations in various weather conditions different times a year. A set of control parameters that might be good for one set of field conditions, might not be working well in other fields – and even at in same field, each set of parameters must be evaluated a relative long distance to overcome statistical deviations of the field. Hereby, tuning and optimization of control parameters (or test of new better adaptive algorithms) may be very time consuming and costly.

This paper proposed instead a model-in-the-loop setup, as shown in Fig. 2. By having a plant model representing the fields and the tractor-plough-interaction with that field, adjusting parameters can be done in a couple of hours, since all conditions can be tested in shorter reproducible loops since the model eliminates the real-world deviation. This even allows the engineers to utilize optimization routines.

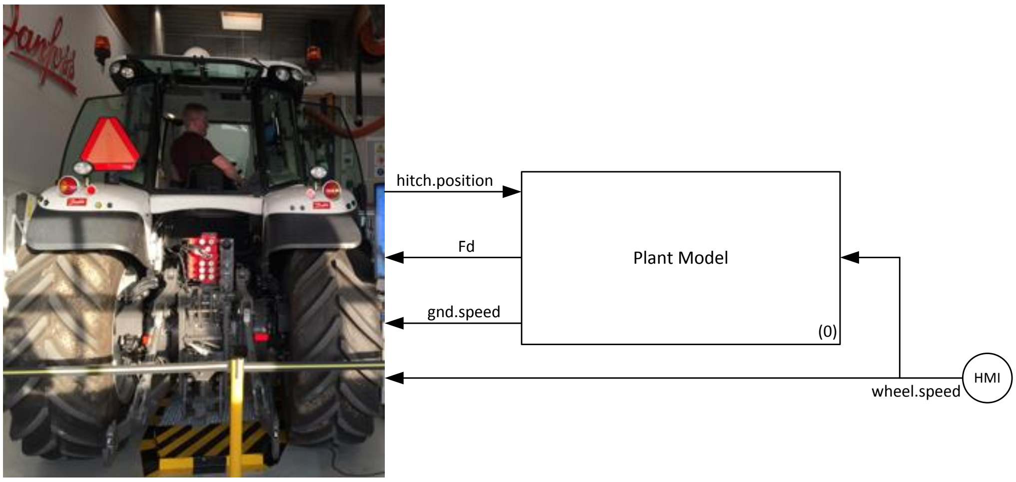

Fig. 2: Model-in-the-loop testing of hitch control system

Tractor-Plough-Soil Model

The content of the Plant Model (0) is shown in Fig. 3. It consists of six blocks (1)-(6) that contains empirical data and mathematical models. For the given problem, it is assumed that the behavior of the system can be approximated to steady-state. This assumption is based on the fact that the sum of forces on the driving direction will only vary slightly around zero, and hence the delay due to inertia will have negligible influence on the results.

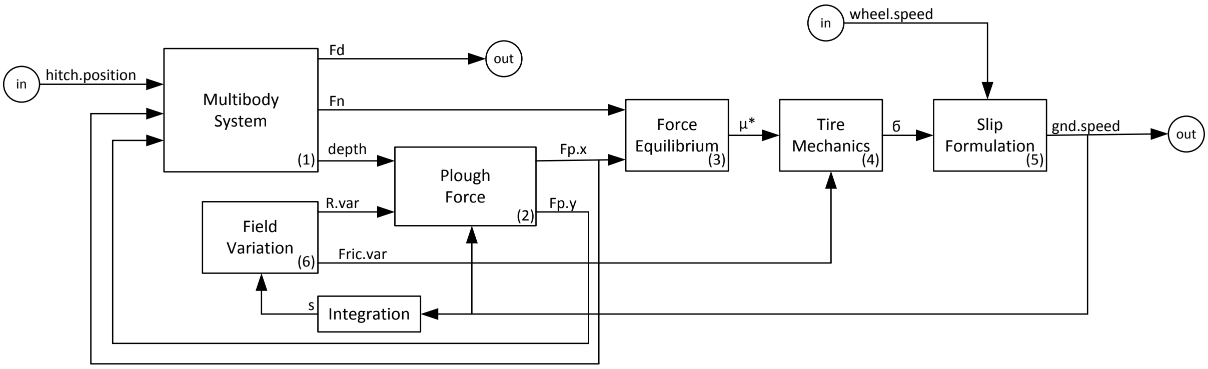

Fig. 3: Tractor-plough-soil simulation model

Multibody System (1)

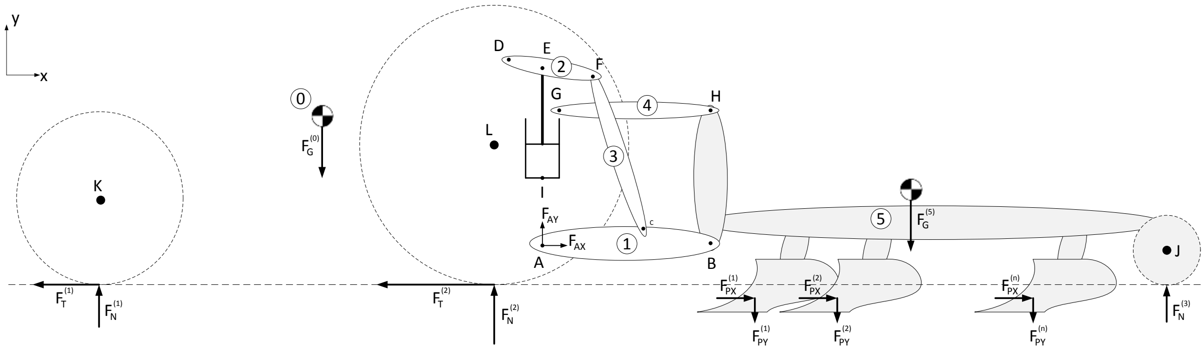

Fig. 4: Multibody system representation of tractor with plough.

The mechanical system of constrained bodies in Fig. 4 must satisfy the set of independent constraint equations:

$$\Phi_{(q)} = 0$$

, where q is the vector containing the global coordinates of the six bodies [6].

Since the system can freely rotate and move vertically with respect to the ground, two additional equations are needed, to determine the complete set of global coordinates:

$$\begin{bmatrix} \sum F_y \\ \sum M \end{bmatrix} = 0$$

It is assumed, that all horizontal forces are attacking in the same vertical coordinate, hence, their contribution to the total torque M is equal to zero.

By solving the above equation, the individual depth of each mouldboard is hereby determined for use in block (2).

The normal forces on the three tires are both needed in above equations, as well as input to block (3). The normal forces are also the vertical tire forces and can be estimated as simple as a spring based on empirical data, or described per the established tire models [7] or the even more advantage studies, such as [8], that takes soft soil and ground deformation into account.

From the multibody model, Fig. 4, it is possible to extract the draught force signal F_{AX} which is sent to the hitch controller for stimulating. The reaction force vector for the multibody model can be determined by:

$$g^{c} = \Phi_q^T \lambda$$

Φ_q^T is the Jacobian matrix (the time derivative of the constraint equations $\Phi_{(q)}$, and λ is a vector containing the Lagrangian multipliers:

$$\lambda = \left(\Phi_q^T\right)^{-1} g^{ext}$$

g^{ext} is vector will all external forces. After determined λ, the draught force can be calculated by

$$F_{AX} = \Phi_q^T(1{:}2{,}1{:}2)\ \lambda(1{:}2)$$

Plough Force (2)

The forces acting in a mouldboard, Fig. 5, can be described by fully of semi-empirical models and data. [9] have shown that both horizontal (x) and vertical (y) force components are acting on mouldboards. [10] have shown, that the draught force is dependent on the geometric properties of tools, such as harrows and ploughs. [11] has developed a detailed force prediction models for mouldboards. All these studies show, that the plough force is highly dependent on ploughing speed and ploughing depth. The faster and deeper, the higher forces.

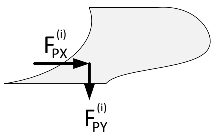

Fig. 5: Forces acting on a mouldboard.

[11] also shows, that the plough forces depend on the soil condition characterized by five parameters 1) bulk unit weight, 2) cohesion, 3) angle of shearing resistance, 4) soil–metal friction angle and 5) adhesion.

Force Equilibrium (3)

Knowing the plough forces and the normal forces on the tires, equilibrium for the x-direction is defined as:

$$\sum F_x = 0 = F_{draught} - F_{traction} = \sum_{i=1}^{n} F_{p.x}^{(i)} - \mu \sum_{j=1}^{2} F_N^{(j)}$$

The friction coefficient μ is an empirical value, but is here treated as an artificial friction coefficient, denoted μ^*. In other words, the necessary friction coefficient for pulling the plough is derived:

$$\mu^* = \frac{\sum_{i=1}^{n} F_{p.x}^{(i)}}{\sum_{j=1}^{2} F_N^{(j)}}$$

The horizontal force equilibrium can be further expanded to include rolling resistance as well, which will give an even more realistic value of the artificial friction coefficient. Values of rolling resistance coefficients can be found in [12].

Tire Mechanics (4)

In tire mechanics, the friction coefficient μ, also called the net traction coefficient, can be determined as a function of the wheel slip σ based on empirical data [12]. Fig. 6 shows the net traction coefficient for different ground types. Hence, the net traction coefficient for a tractor working in the field will vary somewhere between the curves for mud and dry loam respectively. In this paper, oppositely, the wheel slip is determined as a function of the artificial friction coefficient μ^*. Hence, the necessary slip σ for pulling the plough is determined.

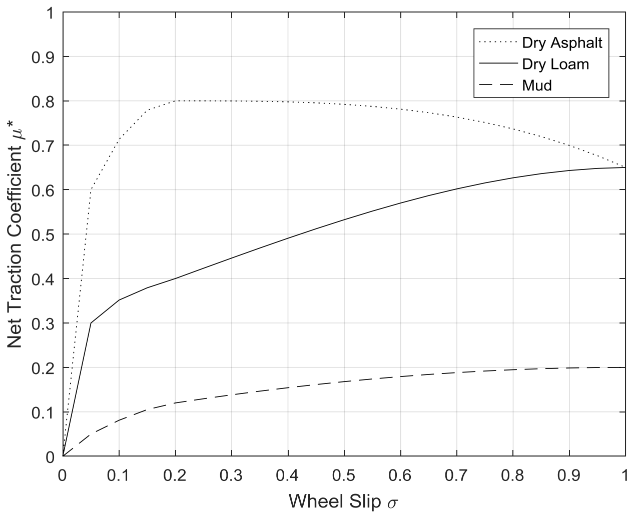

Fig. 6: Net traction coefficient [12]

Slip Formulation (5)

Based on the identified slip σ, the prescribed wheel speed ω and the radius r of either the front or the rear tire, the ground speed $\dot{s}$ can be determined [13]:

$$\sigma = \frac{\omega \cdot r - \dot{s}}{\omega \cdot r}$$
$$\downarrow$$
$$\dot{s} = (1 - \sigma) \cdot \omega \cdot r$$

Field Variation (6)

Field variation represents empirical or user-defined data as a function of the travelled distance, that describes the variation of the net traction coefficient curve, Fig 6, and one or more of the five soil parameters by [12] – at least the bulk unit weight.

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