Robotic mowing of agricultural grass fields with spatial variability using adaptive cruise control system

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***Abstract*— In agriculture, mowing operation is used to cut the grass before collecting for feed or non-food purposes. Mowers cut the grass and the grass is left on the field for wilting, to decrease the moisture content before collection. In this study, a drum type mower was used, which cuts the grass on knife impact without counter shears and therefore the velocity of blades needs to be high, up to 80 m/s. The required power to drive the drums depends on the driving speed. On the other hand, the grass fields are not homogenous, so higher speeds may be used in the areas of light grass density and vice versa. In this study, the autonomous tractor was equipped with an agricultural size mower. The system requires various subsystems to be autonomous and durable. The subsystem discussed in this paper is adaptive cruise control for an autonomous mower, to maximize operational efficiency with constrained power available. The system utilizes a mechanical torque sensing of the power train and coupled with the dynamics of the vehicle, an automatic control system was developed.**

I. INTRODUCTION

In agricultural operations, autonomous and semiautonomous machines are considered becoming common in the near future. Currently, the fields are considered partially open structure, even if the boundaries of the field plot are known in global coordinate system, the conditions are changing year to year and operation to operation. Another challenge is that the field plots are not usually bounded by fences that guarantee keeping human beings or large wildlife off the field. Therefore, robotics in arable farming is still under development.

Agricultural fields are not only used for crop production, but also for energy production. In this study, the focus is in harvesting grass from the areas that are not suitable for crop farming, to be used for bio gas production. Lightweight robotic vehicles enable utilizing such land areas that are not otherwise suitable for production, like wetlands.

The main function of an autonomous mower is the mowing system itself. The mower has two tasks: cut the plant and transport it to form a windrow, for wilting. Mowers cut the grass, either by using knives with or without countershear. In this study, we use a mower without countershear and in that type of mower the cutting is based on impact, so the velocity of blade tip needs to be high, up to 80 m/s. Both drum mowers and disc mowers cut the plant with the same principle. [1]

The basic shape of power consumption of a drum mower depends on power losses which is constant and on the forward speed of the mower which increases power consumption linearly. The power loss can be divided into two parts, for a tip speed related factor and a constant describing the internal friction. However, it is not necessary to split the power loss as long as the angular speed is constant in mowing. [2]

To control the driving speed based on biomass density, two approaches to sensing can be used: direct or indirect measurement. The direct measurement requires a mechanical torque sensor and thus it is possible to create a feedback control system for regulation. The indirect measurement could be based on other sensors measuring the biomass, like pendulum-meter [3] or grass weight measurement in mower-conditioner [4]. In indirect measurement, the control principle has to be feed-forward; or estimation methods are required to estimate the power.

The function in a vehicle regulating the speed is commonly called the cruise control system, or auto-cruise. These are common not only in passenger cars, but also in modern tractors [5]. Automotive industry has used a term adaptive cruise control (ACC) for any system that has some ability to adjust the speed, not only regulate to fixed level. For instance, a system that is using a sensor to detect the distance to the car in front and keeping the distance fixed is an example of ACC.

In this paper, we use direct measurement to regulate the mowing power in the drum type mower. An adaptive cruise control system for a mower is presented. The objective of the system is to regulate the power used by the mower by adapting the forward speed of the autonomous tractor.

The main motivation to regulate the power of the mower by controlling the driving speed is to prevent the continuous overloading of the mower parts and to maximize the operational efficiency with the set constraint. For autonomous usage, the durability of the system is crucial for continuous operation, as there is no human being to replace the parts.

II. MATERIALS

The autonomous tractor is a prototype, originally built in 1990's and completely refurbished and modernized in the years 2009-2013. The tractor is powered with a diesel engine and the power train is hydrostatic. The tractor weighs 5800 kg and standard agricultural implements may be attached to three point hitch with category 2. The tractor

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provides power for the implements with 540 RPM power take-off (PTO) and auxiliary hydraulic valves.

The mower used in the study was JF 265 F (model 2013) manufactured by Kongskilde Industries A/S. The mower was connected to the tractor with three point hitch and 540 RPM type 1 PTO shaft. The measured working width of the mower as 2.62 m. The mower consists of four drums, three blades / knives attached to each of them, for impact cutting. The internal drive train of the mower contains three gearings: 13:23 angular gear, 25:34 belt drive and 17:23 rotor gearbox on top of drums. With the nominal PTO speed, the peripheral velocity of blades is 60 m/s. The system is presented in Fig. 1.

Figure 1. The autonomous tractor and the mower

The tractor is equipped with four wheel steering and the maximum steering angle is 17 degrees. The wheelbase is 2.7 m, which leads into the minimum turning radius of 4.4 m. The internal speed control of the vehicle limits the acceleration to 1.0 m/s^2 electronically, to prevent failures. Fig. 2. presents the velocity response of the vehicle, with the stepwise input signal which is filtered to 1.0 m/s^2 rate. The figure shows that the response follows the trajectory well, but a clear time delay is identified. The identified transfer function to explain the dynamics is presented in (1).

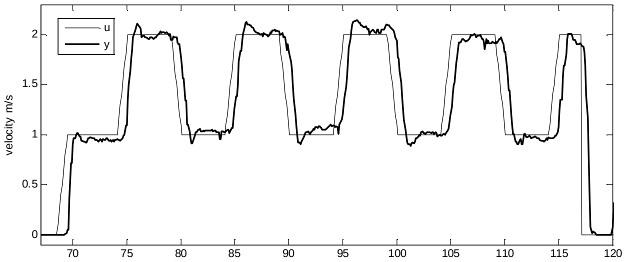

Figure 2. Velocity control of the tractor.

$$v(s) = \frac{1}{0.045s^2 + 0.32s + 1} e^{-0.3s} \tag{1}$$

III. MEASUREMENT

The mower is powered with PTO shaft. A torque sensor was installed on PTO drive shaft, to measure the maximum torque of 1800 Nm at 100 Hz (Datum 420-series with RS-232 interface). The sensor also transmits the angular speed of the shaft, or RPM.

The speed of the tractor is measured both in the wheels of the tractor, by using encoders. However, the encoders have some mechanical backlash [6], which causes error while changing the direction of travel. In one way driving, the backlash is closed on the other side constantly.

The other measurement, for speed, is based on RTK-GPS receiver with the virtual base station. The speed of GPS antenna measures the course of the tractor, so it is not the true forward speed of the mower when the steering angles are non-zero. On the other hand, GPS speed is on average the true speed, but contains shorter term noise compared with the encoders.

To fuse the encoder and GPS speeds, a full Kalman filter was done, to fuse both the wheel encoders with the steering angles of each wheel, to GPS speed and course and also GPS position signals. The extended Kalman filter also estimates the longitudinal wheel slip, but with the mower the slip is relatively small. Fig. 3. shows a snapshot of measurements and the estimated (fused) speed.

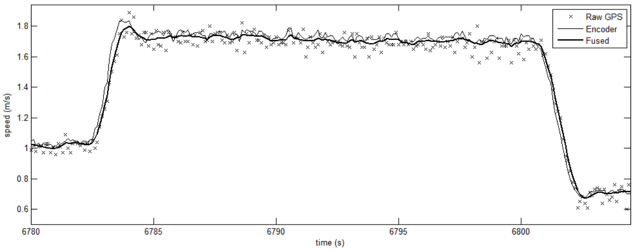

Figure 3. Example of fused signal with Kalman filter.

IV. CONTROL DESIGN

The control design is feedback-feedforward.

The model for the needed for the feedforward part was derived in the tests of the first test plot. The test was carried out autonomously, by using pseudo-random step-wise input for the forward speed and the by measuring the power consumption of the mower, in PTO shaft. The measurements are presented in Fig. 4, showing the linear trend as expected by the model presented in [2]. The linear function identified by using robust regression is presented in (2), the unit of v_f is m/s and the unit of P is kW.

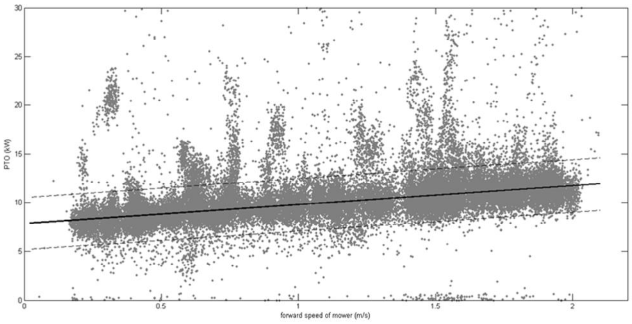

Figure 4. Example of fused signal with Kalman filter.

$$P(v_f) = 7.8 + 1.94 v_f \tag{2}$$

Thus, the inverse function of (2) is utilized in the feedforward part.

Due to the maximum acceleration of the tractor drive, or rate limited speed control reference signal, it was decided to use the differential form of PID controller in the feedback. That form supports better the differential constraint of the reference signal to the speed controller of the vehicle. The feedback controller incorporates the saturation of the output, with the anti-windup function.

The overall design architecture is presented in Fig. 5. r_P indicates the reference power for the mower, y_P is the measured power and u_v is the control signal to the vehicle, for the setpoint of velocity. The feedback controller is type P. The driving speed is constrained to range 0.8 to 2.2 m/s externally, to prevent the vehicle from stopping in case of a small blockage and on the other hand the maximum speed for navigation is 2.2 m/s.

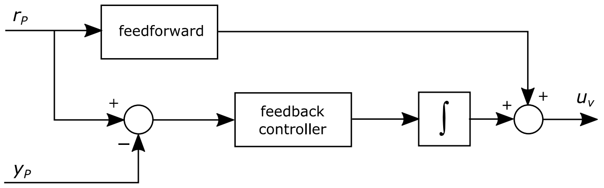

Figure 5. The control design architecture.

V. RESULTS

The control system was tested in the test plot, with light grass. The test plot was prepared by removing the grass in the middle of test swaths, to create a stepwise pattern to the field to mimic maximal variation. The width of the step was 27.6 m and before and after the natural variation of the grass field appeared.

During the test, the autonomous mode of the tractor was used. The guidance system is able to navigate with accuracy of +/- 10 cm [7]. In the test, the swath width was set to 2.5 m, which results in 12 cm overlap. However, in each swath the mowed width was 2.5 m, except in the first one.

Fig. 6. presents the control result of a single swath. On the top, the true driving speed is presented, the dashed lines show the constraints. On the bottom, the measured power for the mower is presented. The intentionally created step is in the range from 1296 to 1311 s. During that period, the control system accelerates and reaches the maximum speed and after decreases the speed back to the level before. At the end of the swath the natural variation and previous tests in the field cause acceleration. Fig. 7. illustrates the setup where the autonomous tractor is approaching the step, approximate at time 1290 s.

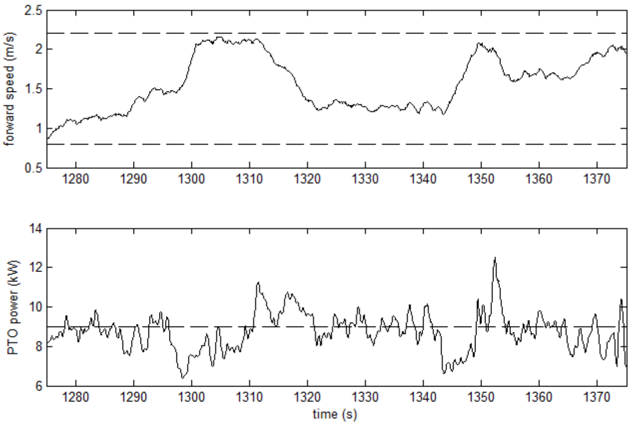

Figure 6. The control response.

Figure 7. The autonomous tractor-mower is approaching the the cleaned area in the test plot.

VI. CONCLUSIONS

For the type of mower used, it is necessary to regulate the tractor speed to reduce the stress on the mower when mowing dense grass. An experimental adaptive cruise control system for the autonomous mower tractor was developed and tested in the field. It was found that the power consumption response to the forward speed follows the textbook pattern and the parameters for the model were found in the test plot. For the system with rate limitation, a control design with the differential form of PID controller with feedforward was utilized.

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