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Semi-automatic coupling of an agricultural tractor and a trailer

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Abstract: In this research a system assisting the operator of an agricultural tractor in coupling a trailer was developed. The system utilized knowledge of the dimensions of the trailer, width and drawbar length, in calculating the towing eyelet location from laser range finder measurements using iterative end-point fit. The tractors speed and curvature are then automatically controlled to align the draw hook with the towing eyelet. Curvature is controlled using pure pursuit algorithm and speed with Smith-predictor and P-controller. In final field tests the system provided 10 successful connections out of 10 attempts. Further research is required to make the system more general and robust to environmental anomalies. Overall performance was satisfactory.

Keywords: iterative end-point fit, pure pursuit, Smith-predictor, autonomous work machines

1. INTRODUCTION

Coupling an agricultural tractor to a trailer is not a trivial task: the hook is difficult to see from the cabin and the operator has to work in an unergonomic position, reversing the tractor while looking backwards to monitor the trailers position. Therefore it is a fine application for an automated solution. The goal of this research was to develop methods enabling semi-automatic connection of the trailer, requiring the operator only to press a button and activate cruise control. Automation only considered the mechanical connection: the operator was still required to connect the optional hydraulic and electric cables.

There is not much previous research regarding this problem. Ahamed presented an automatic coupling system for a hitched implement using a laser range finder and an agricultural implement fitted with reflectors for localization (Ahamed, 2006). Bernhardt et al. presented a patent utilizing a 6-degree-of-freedom rear hitch with a coupling frame and suitable sensors to connect a hitched implement (Bernhardt, et al., 2002).

2. METHODS

In this chapter the approach taken along with the test equipment are presented. After that the methods used are presented in more detail.

In our approach the idea was to connect to a standard trailer with no modifications. As a means for locating the trailer a SICK LMS221 laser range finder was fitted to an agricultural tractor suitably modified for research purposes. The algorithm for locating the eyelet is presented in more detail in the following chapter.

Once the trailer has been successfully located we naturally need to navigate our tractor towards it. As a starting point it is presumed that the tractor is located at a reasonable position relative to the trailer, driven to such position either by an operator or by an automated navigation system. By reasonable position we mean a position that is not 12m farther from the trailer and that the trailer isn't offset more than five meters from the tractors centre line. These are not the absolute technologically imposed limits of the workspace but based on a professional farmers definition of a reasonable starting point.

Even though a tractor is kinematically a MIMO-system, we control the velocity and steering separately. For steering control a method frequently used in autonomous mobile robots called pure pursuit was used. The speed was controlled with a P-controller coupled with a Smith-predictor to compensate for the delays in the system.

Fig. 1 Tractor and trailer used in the research

A tractor based on a Valtra T132 was used (Fig. 1). It was instrumented to enable curvature (the inverse of the turning circle of the tractor) control over ISO 11783 network using standard messages. ISO 11783 is a standard for the communication between a tractor and its implements. It expands the CAN 2.0B –protocol by defining the physical layer as well as layers above OSI level 3. It is harmonized with SAE J1939, a common communication standard in the heavy vehicle industry. (ISO, 2005)

The laser scanner was connected to a Moxa serial-to-ethernet –server which passed the measurements to a HP Elitebook 8460p laptop computer with Intel Core i5-2520M CPU with 4 gigabytes of memory, running Windows 7, acting as the ECU. The ECU application was implemented mostly in Simulink (MathWorks, 2013) environment using a software platform previously developed in the Agromassi-project (Oksanen, et al., 2011). Graphical user interface was created using PoolEdit (Öhman, et al., 2008) and associated parsers. The architecture of the system is depicted in Fig. 2.

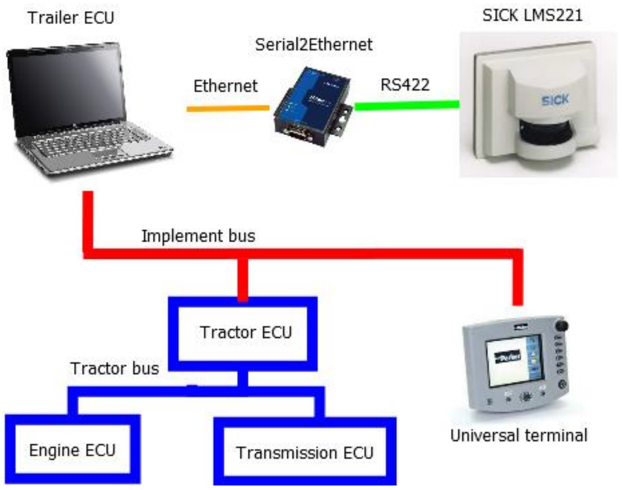

Fig. 2 Architecture of trailer coupling system

2.1 *Locating the trailer*

The possible mounting positions of the laser scanner were quite limited, so the scanner was installed in a relatively high position on the tractor. This imposed a requirement on height of the trailers front wall. We also needed to measure the trailer width and length of the drawbar.

First the 181 distance measurements are read from the laser scanner. To eliminate outliers, measurements are filtered by taking five temporally sequential measurements (1), removing the smallest and the largest and taking average of the remaining three(2).

$$S = \langle d_k \dots d_{k-4} \rangle \tag{1}$$

$$d_{fk} = \frac{1}{3}\sum(S - \min(S) - \max(S)), \tag{2}$$

where d_k is the measured value at step *k*, *S* is set of five measurements and d_{fk} the filtered value. The measurements where then converted from polar coordinates to Cartesian coordinates. Then the measurements were split into line segments using iterative end-point fit –algorithm to get a smoother view of the environment. (Ramer, 1972) (Douglas & Peucker, 1973) Suitable threshold value i_{tol} was tuned by analysing the irregularities of the trailers front wall.

As there were problems with iterative end-point fit and far-away points, the measurements were filtered again in Cartesian coordinates for the spring season tests, with an algorithm illustrated in Fig. 3. We compare measurement m_{i+1} with measurements m_i and m_{i+2}. If height h is above tolerance h_t and bottom length b above threshold b_t, the measurement m(i+1) is a new point on the polyline, otherwise it's discarded.

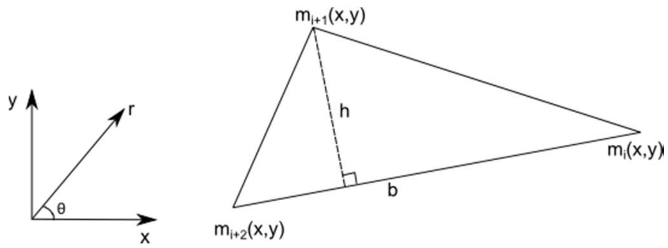

Fig. 3 Illustration for the second filtering

From the line segments obtained above, segments within a suitable margin w_{tol} of the measured trailer width were sought. Once the trailer wall was found, the position of the towing eyelet, (x_{target}, y_{target}), was calculated using the known tow bar length l_{bar} and vector product.

$$x_{tc} = \frac{x_{tl} + x_{tr}}{2} \qquad y_{tc} = \frac{y_{tl} + y_{tr}}{2} \tag{3}$$

$$x_{target} = x_{tc} + x_{offset} + l_{bar} \cdot \frac{y_{tr} - y_{tl}}{d_{lr}} \qquad y_{target} = y_{tc} + d_{s2h} + l_{bar} \cdot \frac{x_{tl} - x_{tr}}{d_{lr}}, \tag{4}$$

where x_{tc}, y_{tc}, x_{tl}, y_{tl}, x_{tr} and y_{tr} are the x- and y-coordinates of the centre, left corner and right corner of the trailer's front wall, respectively, d_{s2h} the horizontal distance between the laser scanner and the draw hook and x_{offset} a calibration variable for the horizontal direction.

2.2 *Pure pursuit in path tracking*

Methods for the path tracking of a non-holonomic vehicle, such as the tractor used in this research, can be divided into roughly three categories: geometric, kinematic and dynamic methods. The basis for choosing pure pursuit method for this research was a report by Snider (Snider, 2009), as in this application high speeds are not required, the algorithm is robust and easy to implement.

Pure pursuit is a geometric method for path tracking of non-holonomic vehicles. The name of the algorithm comes from aeronautics and it can be easily derived geometrically. The desired curvature for reaching the goal point is given by

$$\gamma = \frac{2x}{l^2}, \tag{5}$$

where γ is the wanted curvature, x the horizontal distance to the goal point and l the distance to the goal point(Fig. 4). [5] Term d is an auxiliary variable used in deriving the formula. A modification was made to limit the maximum absolute value of curvature when close to the goal point. The point of origin for the algorithm is in the middle of the rear wheels, which is somewhat different from the target point calculated in the previous chapter. The error caused by this was deemed insignificant. To smoothen the controls, the value given by the algorithm was passed through a second order low-pass filter before giving the curvature reference to the tractor.

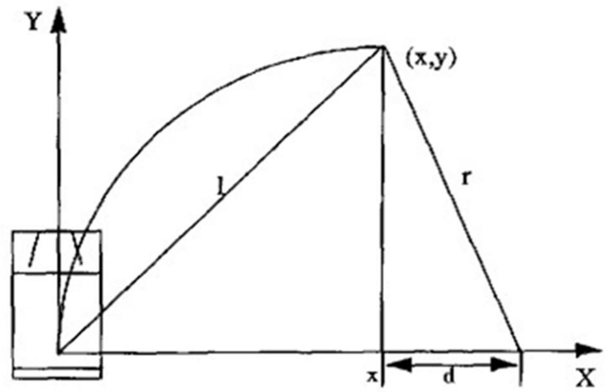

Fig. 4 Pure pursuit algorithm geometry (Coulter, 1992)

2.3 *PI-controller in path tracking*

As an alternative approach to pure pursuit a simple PI-controller was also tested for steering. The error fed to the controller was simply the x-coordinate of the towing eyelet position(Fig. 5).

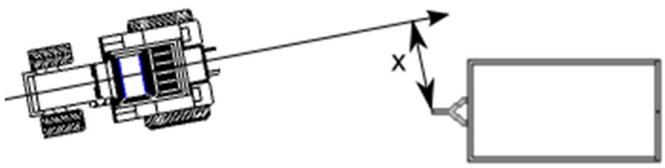

Fig. 5 Principle of PI-controller based steering

2.4 *Speed control*

To enable position control of the tractor we needed a dynamic model of the tractors longitudinal motion. The transfer function from tractors cruise control setpoint to distance traversed by tractor was assumed to be a first-order lag integrating process with time delay (FOLIPD). To identify the dynamics a set of predefined speed trajectories was executed from which the dynamic parameters were identified using MATLABs System Identification Toolbox [3].

The identified dynamics were used to tune a special formulation of Smith-predictor designed for integrating processes with disturbances. Smith-predictor is a controller structure used to compensate for pure delay in a system. (Rice & Cooper, 2003)

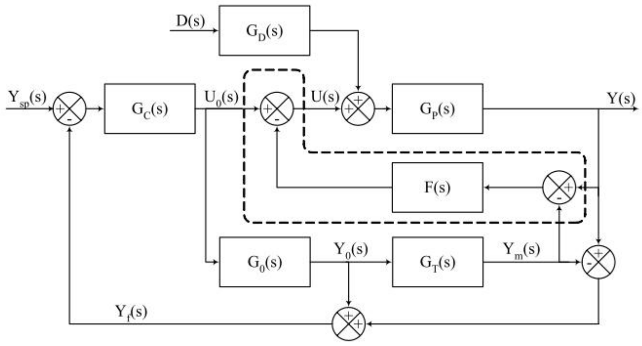

Fig. 6 The Smith-predictor structure used in this research (Rice & Cooper, 2003)

In the diagram (Fig. 6) $G_C(s)$ is the controller, which in this research was a P-controller(6)

$$G_C(s) = K_C, \tag{6}$$

where K_C is the controller proportional gain. The unmeasured disturbance D(s) and its associated transfer function $G_D(s)$ is attributed to the unidealities of the tractor's cruise control, dynamics of the tires etc. $G_P(s)$ is the actual process, here the longitudinal dynamic behaviour of the tractor (7)

$$G_P(s) = \frac{K_P}{1 + sT_P} e^{-\theta_P s}, \tag{7}$$

where K_P is the system gain, T_P is the dynamic delay and θ_P the dead time delay. G_0 is the delay-free model of the system (8) and G_T (9) is the pure delay of the system. F(s) is a factor for compensating the disturbance (10).

$$G_0(s) = \frac{K_P}{1 + sT_P} \tag{8}$$

$$G_T(s) = e^{-\theta_P s} \tag{9}$$

$$F(s) = \frac{1}{2\theta_P K_P} \tag{10}$$

As the system was used in a computer controlled system, the controller was discretized using zero-order hold. The actual Simulink-model used to control the tractor's speed is presented in Fig. 7. The PID-controller block is used with I and D terms set to zero.

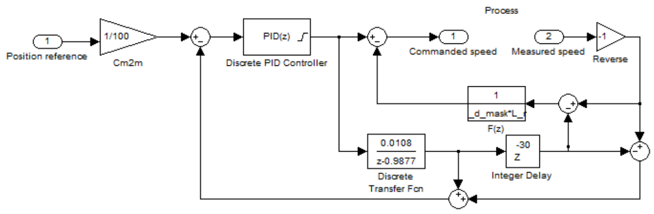

Fig. 7 The Smith-predictor used for the process

2.5 *Operational logic*

To bind the aforementioned functionalities together and manage the behavior of the tractor, a Simulink Stateflow (MathWorks, 2013) chart was created. Most states in the state machine have a corresponding view on universal terminal(UT) interface, which is a device used to display data and get input from the operator (ISO, 2004).

When the system is started and set into automatic mode via UT, it first searches the environment for trailers matching the given trailer wall length. Once found, it presents the coordinates of the towing eyelet and instructs the operator to engage automatic control by first pressing a button on the UT and then dipping the accelerator pedal to engage tractors cruise control (Fig. 8). The tractor then reverses to a predefined approach position, at which the UT instructs the operator to lower the draw hook and then engage the cruise control again. Finally it informs the operator of a successful connection. The UT used is manufactured by Parker Vansco.

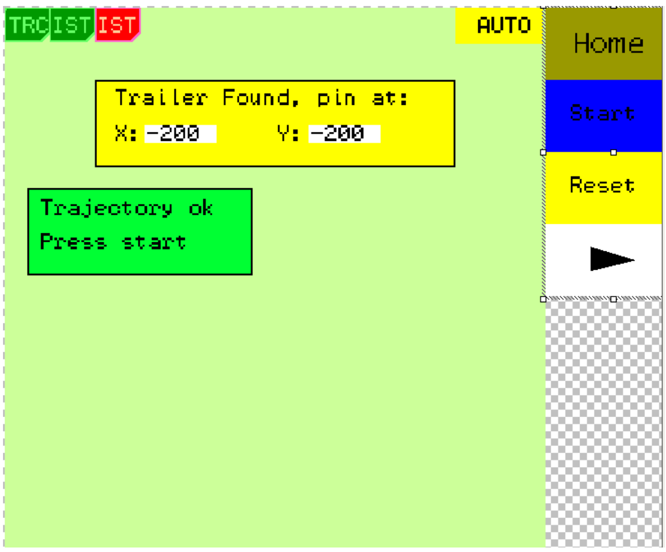

Fig. 8 Universal terminal view of the trailer interface

2.6 *Test setup*

Functionality of the system was tested in a tarmac backyard which was covered with ice and snow during the first tests. The trailer used was a traditional multi-purpose agricultural trailer with a corrugated plate front wall. Initial position of the tractor relative to the trailer was not measured as initial tests showed that the position didn't have a significant effect on system performance.

3. RESULTS

In this section we first present the parameters of the system. After that the results from test runs are presented. In **Table 1** the parameters related to the tractor are presented.

Table 1 Tractor parameters

Variable	**Value**
Longitudinal distance between LMS221 and draw hook d_{s2h}	25cm
LMS221 height	178cm
Speed limit	1.5m/s
Speed controller proportional gain K_C	0.5
Dynamic delay T_P	0.88s
Dead time delay θ_P	0.3s
Time step dt	0.01s
Steering controller gain P	2
Steering controller integral gain I	1
Second filter bottom threshold b_t	10cm
Second filter height threshold h_t	0cm
Iterative end-point fit threshold i_{tol}	16cm
Trailer width threshold w_{tol}	40cm
Pure pursuit low-pass gains k(0,1,2)	(0.4,0.3,0.3)
Horizontal calibration constant x_{offset}	3cm

The discrete transfer function for the tractor's transverse dynamics is (11)

$$F_{trailer}(z) = \frac{0.0108}{z - 0.9877} z^{-30} \tag{11}$$

Now that we have all the necessary variables related to the tractor introduced, we also need a few parameters for the trailer. Trailer 1 (**Table 2**) was used in the first test set during winter while trailer 2 (
Table 3) was used in the spring season tests.

Table 2 Trailer 1 parameters

Variable	Value / cm
Draw bar length	133
Front wall width	200

Table 3 Trailer 2 parameters

Variable	Value / cm
Draw bar length	130
Front wall width	200

Three different test sets of 10 runs each are presented in **Table 4**: winter test with steering control using P-controller, winter test with pure pursuit steering control and spring season test with pure pursuit steering control and additional filtering of the laser measurements.

Table 4 Results of the three test sets

Test	Success rate	Rate of large failure	Lateral error	Longitudinal error
Winter1, PI-controller	3/10	6/10	10,3cm (+4,7 -6,3)	3cm (+1 -1)
Winter2, Pure pursuit	2/10	4/10	3cm (+1 0)	-2,8cm (+6,7 -44)
Spring	10/10	-	-	-

4. DISCUSSION

Overall the system performed surprisingly well, considering the various nonideal properties like delays, deformation of tires, and the irregularity of the trailer wall. Especially the accuracy of repetition was impressive.

A possible solution for improving lateral accuracy is tilting the laser downwards before the final approach to measure the hook position. This solution would leave longitudinal positioning to be solely done using odometry, which is in turn problematic when centimeter-grade accuracy is required.

As line segments of similar length can be detected in the environment as well, segments directly behind the tractor could be considered the most possible ones matching the trailer and weighed above the others. In a demonstration situation people walking around in the rear sector of the tractor disturbed the algorithm.

While limit to the curvature stabilized the control response when close to the trailer, the limit provided some problems when approaching from a large angle: the constant curvature could not be held to the end. Failure when approaching from large angles can also be attributed to ignorance of the full kinematics of the tractor.

The need for a calibration constant in the x-coordinate of the towing eyelet position can be attributed to two possible factors: the orientation of the laser scanner was not measured exactly and neither was the curvature control of the tractor calibrated, so there might be some angle error in it.

The time delay of 30 steps, 300ms, is rather long. This encouraged keeping the controller gain rather low to keep the final speed close to a crawl, even with the predictor present. The effect of which discretization method gives the best model for controlling the tractor was not investigated in this research.

While the use of two different trailers in the tests makes comparison between the test sets uninformative, it also acts as a proof of generality, ie. the algorithm is not tuned for simply one trailer.

The location of the laser scanner would have to be redesigned in an actual commercial application. Placing the scanner near the roof of the tractor would leave the upper link point available for connecting hitched implements, but then the suspended cabin could disturb the measurements. Possibility of using other sensors and fusing sensor data is viable.

5. CONCLUSIONS

In this research a method to assist a driver in coupling a trailer to an agricultural tractor is developed. To the authors' best knowledge, this was the first method for this exact case.

The presented navigation method gave a systematic response when the starting point was reasonable. The localization of the trailer from LMS 221 range measurements worked well in a static environment. As a whole the system met the research goal, being a system that truly makes the process of coupling a trailer to a tractor simpler.

6. ACKNOWLEDGEMENTS

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