Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Cartesian control of an advanced tractors rear hitch – damped least-squares solution

V. Matikainen*. J. Backman*. A. Visala*

*Aalto University, Dept. of Electrical Engineering and Automation,
Otaniementie 17, 02150 Espoo, Finland (Tel: +358503731022; e-mail: ville.matikainen@aalto.fi).

Abstract: Three-point hitch is a mechanism used to connect an agricultural implement, e.g. a plow, rigidly to an agricultural tractor. Movement of a traditional three-point hitch provides only one degree of freedom. This limits the use of hitched implements and forces implement manufacturers to build additional hydraulics into the implement. In this research a tractor was instrumented to provide two rotational and two translational degrees of freedom for the rear hitch. The goal was to develop a control system which allows the operator to control the rear hitch in Cartesian coordinates. In this paper an iterative, damped least-squares (DLS) solution for the rear hitch inverse kinematic transform is presented. The method is tested on the instrumented tractor. The result is a functional control system allowing Cartesian control. The system also provides the rear hitch pose information via a virtual terminal (VT) interface.

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

1. INTRODUCTION

Three-point rear hitch is a mechanism located behind an agricultural tractor and used to rigidly connect different kinds of implements, like plows and harrows, to the tractor. It has not seen major mechanical changes since its initial development in the 1930s. Traditionally only the implements vertical position can be controlled online and while hydraulic cylinders to replace the fixed or manually adjustable rods and links exist, the operator has to control each cylinder individually. With numerous cylinders this is not an easy task, especially when there are constraints placed by the mechanical structure.

In this research the goal was to develop a system that allows the operator to control an instrumented rear hitch (Fig. 1) in a manner natural to a human operator: in Cartesian space. A prerequisite for Cartesian control is an inverse kinematic transform of the mechanism, which is acquired using damped least-squares (DLS) method (Buss, 2009) and a forward kinematic transform.

Damped least-squares method is one way for calculating the inverse kinematic transform when the direct kinematic transform for a given mechanism can be solved but the inverse kinematics can't be solved using algebraic or geometric methods. The damping factor assures smoother actuator movement when close to singularities (Buss, 2009). The method was first applied to inverse kinematics by Wampler (1986) and Nakamura and Hanafusa (1986).

The kinematics of the rear hitch has not seen extensive attention from the robotics community. One solution is the installation of a Stewart-Gough-platform horizontally behind the tractor and attaching a U-frame coupler to it. It presents a full six degrees of freedom for the implement, as compared to the four degrees of freedom presented by the solution in this paper (Berhardt, et al., 2003). Other solution is one proposed previously by the authors, which has the same hardware but uses a geometric approximation of the inverse kinematics (Matikainen, et al., 2013).

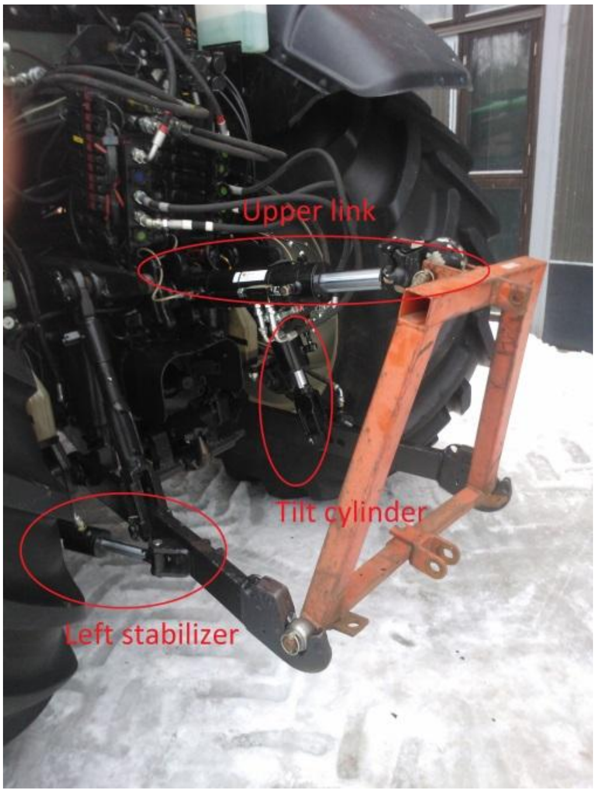

Fig. 1 Rear hitch with additional cylinders. Right stabilizer is not highlighted as it is obstructed by the tilt cylinder and right lower link, but is placed similarly to the left stabilizer

2. TEST CONFIGURATION

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 properties of the bus as well as message structure and a virtual terminal (VT, (ISO, 2004)) for displaying data to the operator, to name a few parts. It is compliant with SAE J1939, which is a communication standard in automotive industry (ISO, 2005).

The upper link, stabilizers and right lift rod of the rear hitch of Valtra T132 tractor used in this research were replaced with hydraulic cylinders (Fig. 1). The original hitch cylinders were rerouted to the same external hydraulics block as the added cylinders and equipped with a pressure limiter to prevent the hitch from topping the tractor over in case of a malfunction. The added cylinders were equipped with internal linear potentiometers which provided position information to millimeter accuracy. The tractor was equipped with an ISO-11783 –conformant tractor-ECU with Class 3 functionalities which enabled controlling the hydraulic valves.

The tractor operator needs to be able to control the hitch so a Bosch Rexroth –joystick was fitted to the tractor. The joystick was SAE J1939-compatible and could therefore be connected straight to the tractors implement bus through CAN-bus. The rear hitch ECU was developed with a software tool chain proposed in (Oksanen, et al., 2011), utilizing Simulink for model-based development, Visual Studio for compilation and deployment, and PoolEdit (Öhman, et al., 2008) for designing the virtual terminal interface, which provided the operator with pose information of the rear hitch.

To determine real-world positioning accuracy an implement with a rectangular horizontal frame was attached to the rear hitch. Tape measure was used to get the heights of the four corners of the frame. From these four measurements the vertical position as well as roll and pitch angles could be calculated. The horizontal position was measured with a hanging pendulum and a stick measure. The sequence of poses was chosen such that first individual degrees of freedom were actuated one at a time and after that, a set of more complex poses.

3. METHODS

A necessary step before designing control for the rear hitch is modeling it. The kinematics was modeled in two steps: first from actuator coordinates to joint coordinates and then from joint coordinates to Cartesian coordinates (Fig. 2).

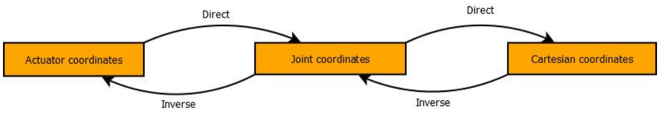

Fig. 2 Principle of coordinate transforms

For the DLS-solution we need the transform from joint coordinates to Cartesian coordinates. To control the hydraulic cylinders according to our calculated joint coordinates, we need the inverse transform from joint coordinates to actuator coordinates.

3.1 Transform from joint coordinates to actuator coordinates

A lower link by itself is a parallel kinematic mechanism: it is connected to the body of the tractor from three different points via the other link end, the stabilizer and the lift rod coupled with lift link (Fig. 3). Despite this complex mechanism, the possible motions of a lower link can be presented with two rotation angles: one about the z-axis and another around x-axis. There is no rotation about y-axis and also the initial orientation of the lower link is parallel to y-axis, when no implement is attached. The location of point **A** (Fig. 3) can be calculated by multiplying the position vector for point **A** with fixed-XYZ rotation matrix $\boldsymbol{R}_{\boldsymbol{XYZ}}$

$$\boldsymbol{R}_{\boldsymbol{XYZ}} = \begin{bmatrix} c\,\alpha\,c\,\beta & c\,\alpha\,s\,\beta\,s\,\gamma - s\,\alpha\,c\,\gamma & c\,\alpha\,s\,\beta\,c\,\gamma + s\,\alpha\,s\,\gamma \\ s\,\alpha\,c\,\beta & s\,\alpha\,s\,\beta\,s\,\gamma + c\,\alpha\,s\,\gamma & s\,\alpha\,s\,\beta\,c\,\gamma - c\,\alpha\,s\,\gamma \\ -s\beta & c\beta s\gamma & c\beta c\gamma \end{bmatrix}, \quad (1)$$

where c is short for cosine and s short for sine and α, β and γ the roll, pitch and yaw angles, respectively. From (2)

$$\boldsymbol{A}_l = \boldsymbol{R}_{XYZ} \cdot \left[0\ d_O^A\ 0\right]^T, \quad (2)$$

we get (3) by replacing α with θ_{xl} and γ with θ_{zl}

$$\boldsymbol{A}_l = d_O^A \bullet \begin{bmatrix} -\cos(\theta_{x_l}) \bullet \sin(\theta_{z_l}) \\ \cos(\theta_{z_l}) \bullet \cos(\theta_{x_l}) \\ \sin(\theta_{x_l}) \end{bmatrix}, \quad (3)$$

where θ_{xl} is the vertical joint angle, θ_{zl} is horizontal joint angle and d_O^A the distance between points **O** and **A**. To simplify equations we shift our coordinate origin from **O** to **Q** and project **A** onto the yz-plane, denoting the shifted and projected point **A** as **Ã**.

To solve the hitch cylinder control we form a system of equations for the intersection of two circles, with origins at **Ã** and **Q** (4):

$$\begin{aligned} |\mathbf{S} - \tilde{\mathrm{A}}| &= d_{\tilde{\mathrm{A}}}^S \\ |\mathbf{S}| &= d_Q^S, \end{aligned} \quad (4)$$

where $d_{\tilde{\mathrm{A}}}^S$ is the distance between points **Ã** and **S** and d_Q^S the distance between points **Q** and **S** (the lift link length). The projected distance $d_{\tilde{\mathrm{A}}}^S$ can be calculated using the Pythagorean theorem from the lift rod length d_A^S and the x-component d_x of the vector from **Q** to **A** (5):

$$d_{\tilde{\mathrm{A}}}^S = \sqrt{(d_A^S)^2 - d_x^2}. \quad (5)$$

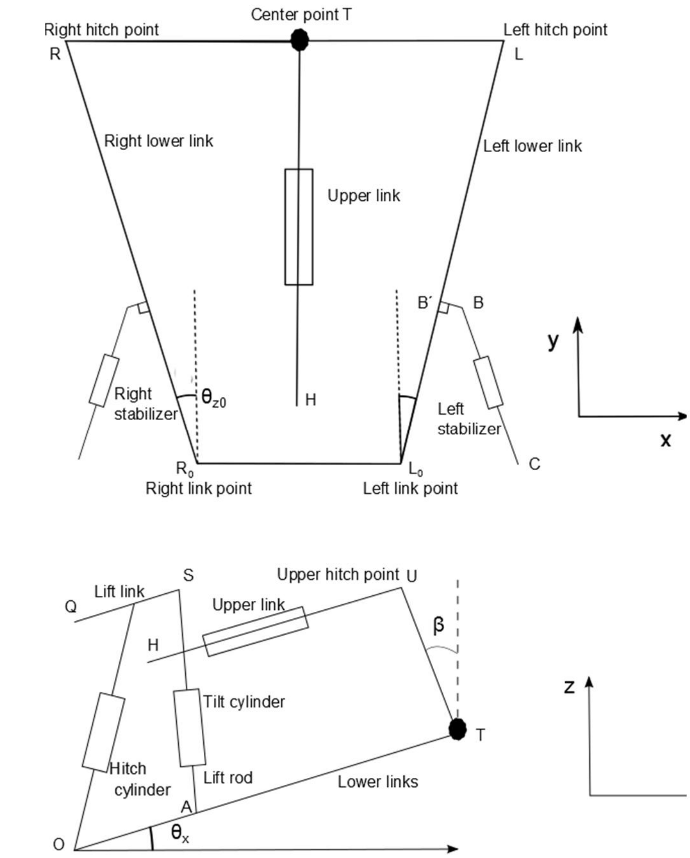

Fig. 3 Two 2D-projections of the rear hitch setup and symbols used. Conceptual drawing, not to scale.

From (4) coordinates of S, y_s and z_s, were solved using MATLABs symbolic solver and of the solutions one on the positive y-axis was chosen. From the coordinates of the point **S** the hitch angle θ_E can be calculated using (6)

$$\theta_E = \sin^{-1}(z_s/d_Q^S). \tag{6}$$

The vertical angle of right lower link is controlled with the tilt cylinder, as the lift links are mechanically coupled, lift cylinders being the only means to adjust left lower link vertically. The point **S** is coincident for the left and right side in the zy-plane. The desired length of the tilt cylinder is given in (7)

$$l_{tilt} = |\mathbf{A_R} - \boldsymbol{S_R}|. \tag{7}$$

To calculate stabilizer lengths the position of point $\mathbf{B}'$ is first calculated in (8) using similar procedure as in (3)

$$\boldsymbol{B}_L^{'} = d_O^{B`} \bullet \begin{bmatrix} -\cos(\theta_{x_L}) \bullet \sin(\theta_{z_L}) \\ \cos(\theta_{z_L}) \bullet \cos(\theta_{x_L}) \\ \sin(\theta_{x_L}) \end{bmatrix}, \tag{8}$$

where $d_O^{B`}$ is the distance between points **O** and $\boldsymbol{B}_L^{'}$. Point $\boldsymbol{B_L}$ can be calculated from point $\boldsymbol{B}_L^{'}$ by cross product (9):

$$\boldsymbol{B_L} = \boldsymbol{B}_L^{'} + d_B^{B'} \frac{\boldsymbol{B}_L^{'} \times [0\ 0\ 1]^T}{\left|\boldsymbol{B}_L^{'} \times [0\ 0\ 1]^T\right|}, \tag{9}$$

subscript L denoting that we are calculating the left stabilizer. The desired length of the left stabilizer l_{ls} can be acquired by calculating the distance between points $\mathbf{C_L}$ and $\boldsymbol{B_L}$ (10):

$$l_{ls} = |\mathbf{C_L} - \boldsymbol{B_L}| \tag{10}$$

The length of the right stabilizer can be calculated similarly by inverting the x-coordinate of $\mathbf{C_L}$. The upper link length remains unchanged at this level of transformation.

3.2 *Direct kinematic transform for lower links*

In the direct kinematic transform the pose of the implements tool point **T** is calculated from joint coordinates. The position and roll-angle of **T** are easy to calculate from the positions of left and right lower hitch points, **L** and **R,** which are calculated similar to (2):

$$\boldsymbol{L} = \boldsymbol{L_0} + l_{vv} \cdot \begin{bmatrix} -\cos(\theta_{xL} \cdot \sin(\theta_{zL}) \\ \cos(\theta_{zL}) \cdot \cos(\theta_{xL}) \\ \sin(\theta_{xL}) \end{bmatrix} \tag{11}$$

$$\boldsymbol{R} = \boldsymbol{R_0} + l_{vv} \cdot \begin{bmatrix} -\cos(\theta_{xR} \cdot \sin(\theta_{zR}) \\ \cos(\theta_{zR}) \cdot \cos(\theta_{xR}) \\ \sin(\theta_{xR}) \end{bmatrix}, \tag{12}$$

where l_{vv} is the lower link length, $\boldsymbol{L_0}$ and $\boldsymbol{R_0}$ are the left and right lower link points respectively and θ denotes angle about axis denoted by the first subscript for the link denoted by the second subscript. Rotations are around fixed coordinate axis. Once we know the location of each hitch point, the location of the tool point **T** is simply the average of the two:

$$\boldsymbol{T} = \frac{\boldsymbol{R} + \boldsymbol{L}}{2} \tag{13}$$

Roll-angle α about y-axis in the tractor coordinates is acquired simply from the lower hitch points:

$$\alpha = \tan^{-1}\frac{z_R - z_L}{x_R - x_L} \tag{14}$$

where z and x are the respective coordinates of points R and L, identified by the subscripts.

The pitch angle β is controlled by the linear actuator of the upper link. As we will later discover, this solution is not needed in the solution presented in this paper, so it is omitted.

3.3 Inverse kinematic solution of the upper link

As we will see later, the inverse kinematic solution of the upper link length is crucial to our implementation of the DLS-method.

As we can calculate the yaw-angle from (11) and (12) and the desired roll- and pitch-angles are known, we can multiply the mast height d_T^U (Fig. 3) with fixed-XYZ rotation matrix (1) and adding to the position of the tool frame **T**, we get the location of the upper hitch point (15).

$$\boldsymbol{U} = R_{XYZ}\left[0\;0\;d_T^U\right]^T + \boldsymbol{T} \tag{15}$$

As the upper link point location **H** is known, we can calculate the desired length of the upper link from (16).

$$d_H^U = |\boldsymbol{U} - \boldsymbol{H}| \tag{16}$$

3.4 Damped least-squares(DLS) method

We denote the desired pose of the implement as vector **t** and the current pose of the implement as vector **s.** The difference between the desired and actual poses shall be denoted with **e**. The inverse kinematic problem formulated with these variables is one of finding values for control vector $\boldsymbol{\theta}$ such that

$$\mathbf{t} = \mathbf{s}(\boldsymbol{\theta}). \tag{17}$$

Jacobian **J** is defined as

$$\boldsymbol{J}(\boldsymbol{\theta}) = \left(\frac{\partial s_i}{\partial \theta_j}\right)_{i,j}, \tag{18}$$

where i is index of the current pose vector and j the index of control vector. A small change in the implements pose with certain controls can be estimated with the equation (19)

$$\Delta \boldsymbol{s} \approx \boldsymbol{J}\Delta\boldsymbol{\theta} \tag{19}$$

Intuitively the change in controls for a certain change in pose can be estimated with the inverse Jacobian. Inverse Jacobian can only be calculated if the matrix is square and has a full rank. In this case the matrix is 4x4 and the parameters are linearly independent. At singular points, when there is huge difference in the scale of the eigenvalues, inverting the matrix becomes numerically unstable. To avoid this problem, we use damping factor λ. We get following equation (20) for the change in controls: (Buss, 2009)

$$\Delta\boldsymbol{\theta} = \boldsymbol{J}^T\left(\boldsymbol{J}\boldsymbol{J}^T + \lambda^2\boldsymbol{I}\right)^{-1}\boldsymbol{e} \tag{20}$$

The Jacobian we have used is an analytical one acquired with element-wise differentiation, in comparison to the geometrical one more often used in robotics. In addition it is worth noting that when we have an implement connected the distance between the lower hitch points is constant. We take care of this by augmenting the following constraint equation (21) into the Jacobian:

$$d_L^R = |\mathbf{R} - \mathbf{L}| \tag{21}$$

The partial derivatives were calculated with respect to each control angle for each lift link. The pose vector **s** and control vector $\boldsymbol{\theta}$ are presented in (22).

$$\begin{aligned} \boldsymbol{s} &= \left[x_T\; z_T\; \alpha\; d_L^R\right]^T \\ \boldsymbol{\theta} &= \left[\theta_{xl}\; \theta_{xr}\; \theta_{zr}\; \theta_{zl}\right]^T \end{aligned} \tag{22}$$

When including the calculation of the pitch angle in the Jacobian some numerical problems occurred. Instead the partial derivatives of the upper link length with respect to the Cartesian reference variables, calculated from the inverse kinematic transform, were augmented into the last line of the inverted Jacobian, taking into account the damping factor.

$$\boldsymbol{J}_U = \left[\frac{\partial d_U^H}{\partial x_T}\;\frac{\partial d_U^H}{\partial z_T}\;\frac{\partial d_U^H}{\partial \alpha}\;\frac{\partial d_U^H}{\partial d_L^R}\;\frac{\partial d_U^H}{\partial \beta}\right]. \tag{23}$$

The value of the damping factor λ was calculated from the ratio of the Jacobians smallest and largest eigenvalue using 2-norm (24): when the matrix is close to singular the damping factor is large, otherwise small.

$$\lambda = 1 - \frac{1}{||\boldsymbol{J}||_2}. \tag{24}$$

The augmented inverted Jacobian $\boldsymbol{J_I}$ is presented in (25).

$$\boldsymbol{J_I} = \begin{bmatrix} \boldsymbol{J}^T\left(\boldsymbol{J}\boldsymbol{J}^T + \lambda^2\boldsymbol{I}\right)^{-1} & \mathbf{0} \\ (1-\lambda)\times\boldsymbol{J}_{\boldsymbol{U}\{\mathbf{1-4}\}} & -\boldsymbol{J}_{\boldsymbol{U}\{\mathbf{5}\}} \end{bmatrix}, \tag{25}$$

subscript of $\boldsymbol{J}_U$ denoting the element(s) we use. The last element was inverted through experience. The complete, augmented pose vector $\boldsymbol{s_a}$ is presented in (26)

$$\boldsymbol{s_a} = \left[x_T\; z_T\; \alpha\; d_L^R\; \beta\right]^T, \tag{26}$$

and the augmented control vector $\boldsymbol{\theta_a}$ in (27)

$$\boldsymbol{\theta_a} = \left[\theta_{xl}\; \theta_{xr}\; \theta_{zr}\; \theta_{zl}\; d_U^H\right]^T. \tag{27}$$

A relevant part of the DLS-solution is iteration: the error term $\boldsymbol{e}_k$, multiplied by the augmented inverted Jacobian $\mathbf{J}_\mathrm{I}$ and step size μ, is added to the calculated controls, (28).

$$\boldsymbol{\theta_{a,k+1}} = \boldsymbol{\theta_{a,k}} + \mu\cdot\boldsymbol{J_I}\boldsymbol{e}_{a,k}, \tag{28}$$

where $\boldsymbol{\theta_{a,k+1}}$ is the augmented control vector at iteration k+1. The calculation is carried on until the difference between desired pose **t** and calculated pose differs less than by a predefined margin $\boldsymbol{\epsilon}$. Calculation of the weighted difference $\boldsymbol{e_W}$ is presented in (29).

$$e_W = \sum(e_a \, W e_a^T), \tag{29}$$

where **W** is a weighting matrix.

3.5 Workspace restrictions

To prevent damage to the tractor the workspace of the hitch had to be restricted. The stabilizer movement was restricted at the controller level with strict limits to the allowed cylinder length. Another important limiting factor was the upper link attachment which did not allow very much sideward movement. The upper link also risked collision with the external hydraulics block. The workspace was restricted by monitoring the horizontal and vertical angle of the upper link and restricting the movement of the hitch in a direction that would violate the restriction. Land collision of the lower links was not limited as it was not deemed harmful to the tractor.

3.6 Unit controllers

Tuning of the unit controllers for each cylinder follows a procedure initially described in (Eriksson & Oksanen, 2007) and as applied to this particular case in (Matikainen, et al., 2013). Therefore the details are omitted.

4. RESULTS

In this chapter the parameter values used and test results are presented. Results related to unit control of the cylinders as well as physical measurements of the hitch configuration, as well as the target pose test sequence used, are presented in (Matikainen, et al., 2013). The step size μ used was 0.9 and value of ϵ was 1. The diagonal weighting matrix **W** had gains of 1000 for the angular values and 1 for translational values.

Absolute positioning accuracy was calculated from the whole test data. Average of the positioning accuracy was also calculated to see if the error was biased or not. As a measure of repeatability the standard deviation of individual measures from the same point on different runs was used. In this analysis only the first part of the test sequence was used.

The positioning errors are depicted in table 1, where E is the average error, |E| is the average of the absolute errors, $|E|_{MAX}$ largest absolute error and RA repeatability accuracy.

Table 1 Errors for each degree of freedom

Degree of freedom	E	|E|	$\|E\|_{MAX}$	RA
X	3.45mm	8.9mm	30mm	13.4mm
Z	-5.01mm	9.8mm	35mm	5.7mm
Roll	-0.00016rad	0.0145rad	0.047rad	0.0112rad
Pitch	-0.017rad	0.0176rad	0.033rad	0.0047rad

5. DISCUSSION

The rear hitch is a quite challenging structure from a modeling point of view: it includes both serial and parallel kinematic structures. With the tractor and implement used the available workspace was intuitively thinking quite restricted, especially for x- and roll-motion. The required workspace, as well as required precision, is naturally highly application-specific. For applications like road conditioning with a leveling drag, harrowing a paddy field or plowing, the authors believe the accuracy to be sufficient. The range of the tilt cylinder did not result in a symmetrically adjustable roll-angle, which could be mechanically balanced by adjusting the left lift rod.

Comparing to the Stewart-Platform hitch (Berhardt, et al., 2003) the system has less degrees of freedom but also doesn't require quite as large modifications to the tractors existing rear hitch. Also the lower links are rigid which means that when doing work which requires a large draft force, there won't be extra strain on the cylinders and valves.

Compared to the method presented in (Matikainen, et al., 2013) the maximum absolute errors were smaller or equal. The average absolute errors were quite similar and repeatability accuracy was actually better in the geometric solution than in the DLS. However, the parameters of the DLS-method were not optimized but values that gave a reasonable solution were used. Also comparison to other Jacobian-based methods, Jacobian transpose and Pseudoinverse, would be worth researching.

A probable source of error was the tape measure used to measure the mechanical parameters of the hitch as well as the real-world position. Having an accurate CAD-model would likely result in better results. In addition to measurement inaccuracies especially the stabilizers have notable mechanical backlash which makes high-precision positioning challenging. The unit controllers did not reach the desired set-points exactly, error being a few millimeters.

6. CONCLUSION

The system presented provided the user with means of controlling a hitched implement in Cartesian coordinates which was the goal of this research. The interface was simple, one button enabling control of translational degrees of freedom and another enabling the control of the rotational degrees of freedom. The DLS-method was well suited for solving the rear hitch kinematics. Performance of the system was sufficient for foreseeable applications.

7. ACKNOWLEDGEMENTS

This research was conducted in project Agromassi which is part of FIMECC-program EFFIMA. FIMECC is Finnish Metals and Engineering Competence Cluster whose aim is to increase and deepen the cooperation between companies, universities and research institutes in the area of top quality research.

8. REFERENCES

Ahamed, T., 2006. *Navigation of an Autonomous Tractor Using Multiple Sensors.* Tsukuba: University of Tsukuba.

Berhardt, G., Fedotov, S. & Rudik, R., 2003. *Hitch for a Work Vehicle.* Moline, IL, Patent No. US 2003/0217852 A1.

Bernhardt, G., Fedotov, S., Rudik, R. & Weiss, H., 2002. *Vehicle/implement coupling system.* US, Patent No. 6,581,695 B2.

Buss, S. R., 2009. *Introduction to Inverse Kinematics with Jacobian Transpose, Pseudoinverse and Damped Least Squares methods..* [Online] Available at: http://www.math.ucsd.edu/~sbuss/ResearchWeb/ikmethods/iksurvey.pdf
[Accessed 24 7 2013].

Coulter, C., 1992. *Implementation of the Pure Pursuit Path Tracking Algorithm,* Pittsburgh: Carnegie Mellon.

Douglas, D. & Peucker, T., 1973. Algorithms for the reduction of the number of points required to represent a digitized line or its caricature. *The Canadian Cartographer,* 10(2), pp. 112-122.

Eriksson, L. & Oksanen, T., 2007. *PID Controller Tuning for Integrating Processses: Analysis and New Design Approach.* Sharjah, ISMA.

ISO, 2004. *ISO 11783 Part 6: Virtual terminal.* Geneva: International Organization for Standardization.

ISO, 2005. *ISO 11783 Part 1: General standard for mobile data communication..* Geneva: International Organization for Standardization.

MathWorks, 2013. *Simulink - Simulation and Model-Based Design.* [Online] Available at: http://www.mathworks.se/products/simulink/ [Accessed 15 4 2013].

MathWorks, 2013. *Stateflow.* [Online] Available at: http://www.mathworks.se/products/stateflow/ [Accessed 13 6 2013].

MathWorks, 2013. *System Identification Toolbox - MATLAB.* [Online]
Available at: http://www.mathworks.se/products/sysid/ [Accessed 15 4 2013].

Matikainen, V., Backman, J. & Visala, A., 2013. *Cartesian Control of an Advanced Tractors Rear Hitch - Geometric Solution.* Espoo, AgriControl 2013.

Nakamura, Y. & Hanafusa, H., 1986. Inverse kinematics solutions with singularity robustness for robot manipulator control. *Journal of Dynamic Systems, Measurement and Control,* Volume 108, pp. 163-171.

Öhman, M., Kalmari, J. & Visala, A., 2008. *XML Based Graphical User Interface Editor and Runtime Parser for ISO 11783 Machine Automation Systems.* South Korea, IFAC World Congress.

Oksanen, T., Kunnas, A. & Visala, A., 2011. *Development and Runtime Environment for Embedded Controller supporting ISO 11783 Standard..* Milan, IFAC, pp. 2895-2900.

Ramer, U., 1972. An iterative procedure for the polygonal approximation of plane curves. *Computer Graphics and Image Processing,* 1(3), pp. 244-256.

Rice, R. & Cooper, D. J., 2003. *Practical Model Predictive Control Structures for Non-Self Regulating (Integrating) Processes.* Houston, TX, ISA.

Snider, J. M., 2009. *Automatic Steering Method for Autonomous Automobile Path Tracking,* Pittsburgh, Pennsylvania: Carnegie Mellon University.

Wampler, C. W., 1986. Manipulator inverse kinematic solutions based on vector formulations and damped least squares methods. *IEEE Transactions on Systems, Man and Cybernetics,* Volume 16, pp. 93-101.