Implement Guidance model for ISO 11783 standard

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Abstract: Automatic guidance systems for agricultural tractors are steering only the tractor, not the implement connected to the tractor. In a long trailer type implement, the deviation from the path may become remarkable under lateral forces causing navigation error. The implement steering combined with tractor steering would improve the accuracy remarkably, but there is no standard yet for multi-brand systems to operate as plug-and-play. Current systems are either two independent guidance systems, one for tractor and another one for implement, or the combined solution is provided from the same vendor. In both cases, the implement steering mechanism is usually retrofitted. In this paper, we present a model based on abstract implement to be included in ISO 11783 standard series. This model allows not only the data exchange model between the guidance system and the implement, but also makes the development of a guidance system easier. By using the abstract implement model, the guidance system may rely on a common kinematic model that is suitable for any implement with steering capabilities.

Keywords: tractors, implements, automatic guidance, implement steering, navigation, interfaces, ISOBUS.

1. INTRODUCTION

Automatic guidance systems for agricultural tractors emerged in early 2000. Currently, tractor manufacturers provide embedded guidance systems and various add-on kits are available on the market. Commercial guidance systems handle the steering of a tractor well. The development of guidance systems is steady and more functions are integrated into new versions, like support for automatic turning in the headland.

ISO 11783 (known as ISOBUS products) defines messages to read the current state of the tractor steering as well as commands to actively steer the tractor. To abstract the various kinematics of tractors, like front wheel steered and articulated steered, the signal defined in the standard is the *curvature* of the steering. In other words, a guidance system may give a command for the curvature and the internal system of the tractor realizes that with the actuators it has.

Standalone implement steering or guidance systems are available in the market, e.g. under Trimble, Sunco and Orthman brands. These systems are beneficial if better accuracy is required in large system. Side slope, wheel slip and curves with trailer type result deviation in the path between the tractor and the implement. Implement steering systems can be divided into three categories: laterally movable hitch, carriage with coulter wheels, or steerable tires. The steering action may move also the body of the implement, or just coulters/wheels. (Heraud & Lange, 2009)

A combined navigation system, which commands both the tractor and the steerable implement, requires a mathematical model of the controlled system. For the navigation purposes, various kinematic models have been derived. For tractor-trailer systems unsteered implements are subject to research by Bell (1999), Bevly (2001) and Cariou et. al. (2010). Backman et al. (2009 and 2012) presented a kinematic model with steerable drawbar. Karkee and Steward (2010) studied the characteristics of a tractor and a single-axle towed implement system. They derived three different models for a tractor-trailer system: a kinematic model, a dynamic model and a high-fidelity model.

In another study, Werner et al. (2012) derived kinematic and dynamic models for the tractor and the towed steerable implement. Werner et al. (2013) also developed a custom-made, actively steered implement with a multitude of actuators for field test purposes. The position of the implement could be controlled via actively steered wheels, actively steered coulters or an actively steered drawbar or with a side shift frame, which was connected to a hitch point.

The experiments of Karkee and Steward (2010) showed that the kinematic model described the behaviour sufficiently well when the driving speed was less than 4.5 m/s and the input frequency less than 1 rad/s. Werner et. al. (2012) obtained similar results also with actively steered implements. The dynamic model requires parameters like the mass, the moment of inertia, friction and other parameters that are not required by the kinematic model and are subject to change during the agricultural operation time. However, actuator dynamics has to be modelled in both cases.

So far, ISO 11783 does not support implement steering in any manner. The objective of this paper is to derive the schema for implement steering in ISO 11783. The schema will be based on the requirements that ISOBUS systems and current guidance systems have. The core of the proposed solution is abstract implement that is based on the skeleton structure and that will support implements with different kinematic structure. Finally results show that the derived schema support different guidance objectives.

2. REQUIREMENTS

Like the current interface in ISO 11783 for tractor steering (ISO 2009), the extension to implement steering should provide a clear interface to allow products made of different manufacturers to operate together. The main challenge in ISOBUS systems is the high level of plug-and-play required: the end-user, e.g. a farmer, is the integrator of the system. For guidance, it means that any implement with the steering option could be connected to any guidance system that supports that option. It is not desirable that the guidance system must be configured for any new type of the implement separately and an engineer is required to couple tractor, implement and the guidance system in every farm, separately. Plug-and-play is the customer demands.

Guidance system commanding both the tractor and the implement is desired as the implement only steering would require an operator to use substantial effort to steer the tractor. As the desired path is common for the tractor and connected implement, the standard should support the idea of combined guidance system that commands both the tractor and implement. In ISOBUS systems, this would be realized in multi-brand systems like presented in Figure 1. However, the standard defines only the interfaces, so it does not exclude the pattern of separated guidance systems.

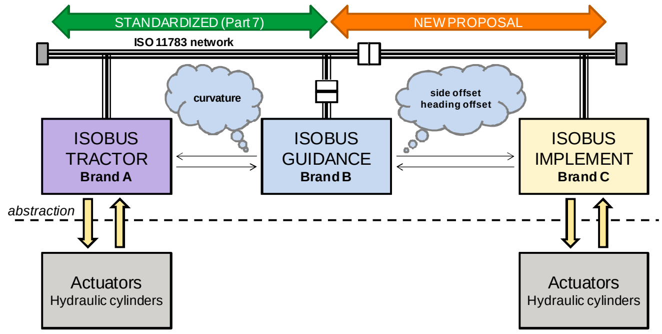

Figure 1. The architecture of combined guidance system.

Controlling both the tractor and the implement in the same guidance system requires more effort compared with single degree-of-freedom (DoF) systems. To control the steering with high accuracy in high velocity might require taking the kinematics and dynamics of the system into account. In addition, the stability of the controlled system must be guaranteed. However, the standard should not force developers to use any specific algorithms or methods in the implementation of the guidance. The same applies to the sensors. We see that the standard should support the algorithms from a simple PID controller to the model based control.

The standard should not limit the kinematics of the implements for any predefined set. However, as a requirement, some typical implement types are presented in Figure 2 that addresses the challenge. Type A is a fully hitch mounted tool. Type B is a trailer type implement with side shift in the joint. Type C is a trailer type implement with a steerable drawbar. Type D is a trailer type implement with steerable wheels. Type E has both a steerable drawbar and wheels for heading control. Type F is like type C but the tool is in the front body.

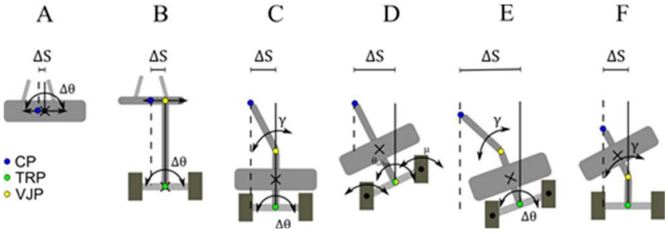

Figure 2. Typical implement types.

As Figure 2 addresses, the implement may have one or two DoF. Type E is used e.g. in some potato harvesters, where the tool must be oriented along the ridges. Therefore, the guidance system must have ability to command up to two DoF of the implement. Real implement moves in 2D world in three DoF: x, y and heading. However, the implement is always connected to the tractor, so the maximum number of DoF is two.

Furthermore, while abstracting the implement, the interface should not lose information that is relevant to accurate guidance.

3. ABSTRACT IMPLEMENT

3.1. The Skeleton of Abstract implement

For tractor steering, the ISO 11783 has defined curvature as a variable for the abstraction of any tractor kinematics. In the tractor, with one degree of freedom, this is an evident choice and easy to interpret. However, in implement, the case is not that trivial, as the implement is always coupled with the tractor (hitch or pin) and DoF cannot be freely controlled.

In this paper, we propose an *Abstract implement* as the base for the abstraction of any implement. The Abstract implement is a skeleton that presents the virtual structure of the implement. The skeleton of abstract implement consists of three joints/coordinates and two links connecting them. The first joint is Connection point (*CP*), the point for connecting the implement to the tractor. True Rotation Point (*TRP*) defines the ground contact for the implement, around which no lateral movement appears. The third is Virtual Joint Point (*VJP*) which defines the location of the guidance actuator of the implement. The VJP usually lie somewhere between *CP* and *TRP*. Using the *VJP* the guidance may take the mechanical structure of the implement into account, e.g. how much the implement length "shortens" while steering. It appears that this skeleton is the sufficient structure definition of any implement, for the guidance system.

Figure 3 presents examples on some selected implement types, how the skeleton is identified. For any implement, the easiest one is to locate *CP* and then *TRP*. An implement with wheels, *TRP* is located on the line connecting wheels. *VJP* can be found in the mechanical structure between *CP* and *TRP*, in the position where the joint is located. In Figure 3, in the third type, *TRP* and *VJP* are collocated. For mounted implement, see Figure 1 (type A): only *CP* is defined and *TRP* is located in the *TRP* of the tractor.

Abstract implement is not limited to the presented examples (Figure 2), the essential points can be derived to any implement type.

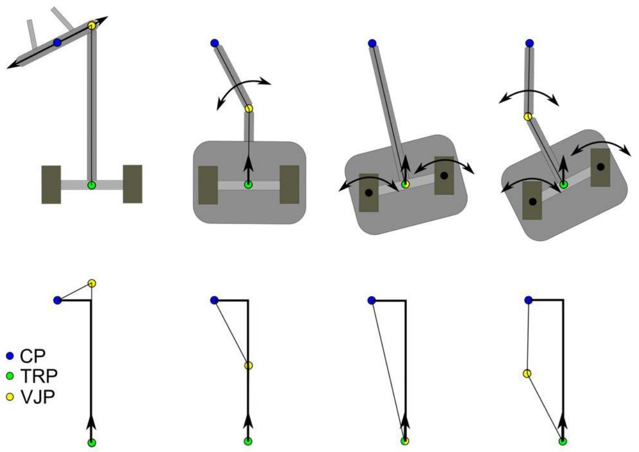

Figure 3. Abstract implement. On top: the skeleton overlaid on various implement types, on bottom: only the skeleton.

The *tool* of the implement may be located in various places in the body of the implement. Here, the tool refers to parts like header, cutter, pick-up, coulters or other functional part of the machine. For any implement, the Guidance Control Point (*GCP*) is defined in the location of the tool, to guide the correct part of the machine along the desired path. In Figure 2, implement types E and F represent cases where the rotation point of the tool in the skeleton is not obvious. Furthermore, to let the guidance know where the point of rotation is located, a Tool Rotation Point (*TORP*) is defined.

3.2. Control variables

After the abstraction phase, the implement has only the skeleton visible to the guidance system. The variables to control the steering in the abstract implement are 1) **side offset** *(ΔS)* and 2) **heading offset** *($\Delta\theta$)*. If the implement has only one DoF (single actuator), the other variable is defined as not available for control.

Side offset and heading offsets are defined for the implement by orienting the wheels of the implement along the vertical axis and placing the *TRP* in origin. The horizontal distance from *CP* to the vertical axis is the definition for side offset. Similarly, the heading offset (for the tool) is defined as the angle between the tool heading and the vertical axis. See Figure 2 for illustration of ΔS and $\Delta\theta$.

To avoid misunderstanding, it is highlighted that the side offset is a measure used in the control interface, it may not be misinterpreted as the deviation from the desired path. Thus, it cannot be used in general for guidance pattern: side offset = - navigation error. The same applies to the heading offset. Even the simplest guidance method must take the parameters of the skeleton into consideration, as will be presented below.

The implement is steered usually with hydraulic cylinders and either the angle of the joint is directly measured or indirectly from the position of the piston. Conversion formulas are required to do transformation between mechanical angles and ΔS and $\Delta\theta$. The standards should include formulas for typical implements, but these conversion formulas are rather easy to derive for any implement. The conversion is done in the implement controller.

3.3. Using in guidance system

The abstract implement allows guidance system developers to create single software that works for any implement. The parameters like the location of *CP*, *TRP* and *VJP* are different in real implements and the *parameter pool* must be transferred from the implement to the guidance when plugging systems together.

The abstract implement supports the utilization of model based control, as the same kinematic model can be used for any implement, just the parameters change. The kinematic model can be derived either in combined form (tractor + implement together) or in separated form.

The actuators of implement steering always incorporate dynamics, like the maximum steering rate and the control delay. These can be either identified by the guidance system by using certain test functions in a safe place, like proposed in Oksanen (2010) for general hydraulic actuators or in Backman et.al. (2011) for guidance systems. The other option is to allow the implement to transmit the parameters from the implement to the guidance system in the plug-in phase.

3.4. Implement Guidance Parameter Pool (IGPP)

To transfer the parameters, constants, from the implement to the guidance system, a standard method is required. The parameter pool consists of a list of parameters. Two schemas are available in the standards for this: to follow the object pool approach used in ISO 11783-6 (ISO 2014) for virtual terminal parameters, or NMEA2000 (NMEA, 2015) or SAE J1939 multipacket (SAE, 2015). Virtual terminal kind of object pool allows hierarchical representation, a tree of parameters instead of a list, while NMEA2000 or SAE J1939 multipacket model is remarkably simpler for the implement.

In spite of the protocol for the transfer, in Table 1 we present a list of parameters to be included in the Implement Guidance Parameter Pool (IGPP). VJP_ROT defines whether the tool rotates with the body of the implement, like for our implement type E this is defines as yes.

In addition to the parameters already discussed above, lag and delay parameters related to actuator the dynamics of steering are included.

Furthermore, the last eight parameters are used to define the maximum control space. In some form of implement the control space is rectangular (e.g. our implement types A to C, all single actuator implements) while in more coupled double actuator steering systems the control space is a parallelogram (e.g. our implement type E). These eight parameters define the corner points of parallelogram/rectangle of the maximum control space.

Table 1. Parameters of IGPP considered as constants.

Name	Abbreviation	Unit
VJP location X in TRP VJP location Y in TRP	VJP_X VJP_Y	m
Is VJP rotating with heading offset	VJP_ROT	yes/no
CP location X in VJP CS CP location Y in VJP CS	CP_X CP_Y	m
Tool Rotation Point X in VJP/TRP Tool Rotation Point Y in VJP/TRP	TORP_X TORP_Y	m
Is TORP in VJP coordinate system (..or TRP)	TORP_ORIGIN	yes/no
GCP location X in TORP GCP location Y in TORP	GCP_X GCP_Y	m
Lag of ΔS (1st order dynamics)	LAG_DS	s
Lag of $\Delta\theta$ (1st order dynamics)	LAG_DT	s
Delay of ΔS	DELAY_DS	s
Delay of $\Delta\theta$	DELAY_DT	s
Control space constraint point 1 ΔS Control space constraint point 1 $\Delta\theta$	CSC1_DS CSC1_DT	m deg
Control space constraint point 2 ΔS Control space constraint point 2 $\Delta\theta$	CSC2_DS CSC2_DT	m deg
Control space constraint point 3 ΔS Control space constraint point 3 $\Delta\theta$	CSC3_DS CSC3_DT	m deg
Control space constraint point 4 ΔS Control space constraint point 4 $\Delta\theta$	CSC4_DS CSC4_DT	m deg

4. RESULTS

4.1. Guidance objective: follow trails of tractor

For some trailer type implements, like sprayers, the desired guidance objective is to steer the implement in a way that the wheels of the trailer follow the trail created by the tractor wheels. It can be assumed that the guidance system contains the actual curvature of the tractor while moving as it is either commanding that or it may access it through methods in the current standard (ISO 2009). The question is how to command the implement ΔS so that the trailer would follow the tractor?

Assuming the hitch length of the tractor is zero, Eq. 1 can be used to do this conversion in feed-forward manner. L represents the total length of the drawbar, or $|CP\text{-}TRP|$, and k_{trac} is the curvature of the tractor. The inverse function is presented in Eq. 2.

$$\Delta S = \frac{1}{k_{trac}}\left(1 - \sqrt{1 - {k_{trac}}^2 L^2}\right) \tag{1}$$

$$k_{trac} = \frac{2 \cdot \Delta S}{L^2 + \Delta S^2} \tag{2}$$

4.2. Double actuator case: potato harvester

Implement type E (in Figure 2) is used e.g. in potato harvester Grimme SE 260 (Figure 4). The trailer type harvester is equipped with both a steerable drawbar and steerable rear wheels. In the basic operation mode, drawbar is used in the mainland to adjust the harvester intake along the ridges and the rear wheels are used in the headland for agile maneuvering. As the intake is a rather long device, the guidance objective is to adjust the intake along the ridges both in the lateral position and orientation. For guidance, the simultaneous use of both actuators would allow this, beneficial especially in curved ridges.

Figure 4. Potato harvester with drawbar steering and steerable rear wheels.

In the potato harvester, GCP is located in the centre of intake. For the particular model, the measures of the skeleton are: $|TRP\text{-}VJP|$=5m, $|VJP\text{-}CP|$=1.5m and VJP is located off-center: Δ_{VJP}=0.85m.

The derived transform from abstract implement variables to mechanical angles is presented in Eq. 3 and 4.

$$\alpha_{wheels} = -\Delta\theta \tag{3}$$

$$\alpha_{drawbar} = -\Delta\theta + \sin^{-1}\frac{(\Delta S - \Delta_{VJP}\cos\Delta\theta - \|TRP - VJP\|\sin\Delta\theta)}{\|VJP - CP\|} \tag{4}$$

The inverse transform, from mechanical angles to abstract implement variables is presented in Eq. 5 and 6.

$$\Delta\theta = -\alpha_{wheels} \tag{5}$$

$$\Delta S = \|TRP - VJP\|\cos\Delta\theta + \|VJP - CP\|\cos(\alpha_{drawbar} + \Delta\theta) - \Delta_{VJP}\sin\Delta\theta \tag{6}$$

These equations are embedded in the implement controller of the potato harvester and only the variables ΔS and $\Delta\theta$ with the skeleton dimensions are visible to the guidance system. The top view of the potato harvester is presented in Figure 5, presenting all variables and their values in the situation.

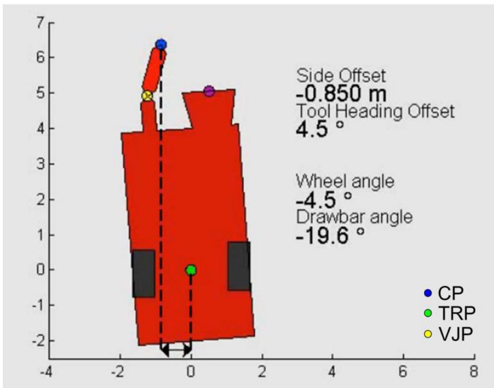

Figure 5. Points of the skeleton in potato harvester.

4.3. Kinematic model of Abstract implement

A more sophisticated guidance algorithm than feed-forward curvature based control, like presented above, would often require a kinematic model of the implement. The kinematic model is not only needed in model based control, or model predictive control methods, but also as a base of LQR type controllers.

In Eq. 7 we present the kinematic model for the abstract implement with a tractor with front wheel steering. (x_{trac}, y_{trac}) represents the location of the tractor in global coordinate system (*GCS*), ϕ is the heading of the tractor in *GCS*, ψ is the heading of *TRP* in *GCS*, v is the forward velocity of the tractor, k is the curvature of the tractor and b is the hitch length. c_{VJP} is a binary variable that defines whether *VJP* rotates around *TRP* with $\Delta\theta$.

$$\begin{cases} \dot{x}_{trac} = v \cos\phi \\ \dot{y}_{trac} = v \sin\phi \\ \dot{\phi} = k\, v \\ \dot{\psi} = \dfrac{-b\,k\,v\cos(\phi-\psi) - v\sin(\phi-\psi) + c_{VJP}\frac{d}{dt}L_2 \sin\Delta\theta + \frac{d}{dt}\Delta S}{(L_1+L_2)\cos(c_{VJP}\,\Delta\theta) - \Delta_{VJP}\sin(c_{VJP}\,\Delta\theta)} - c_{VJP}\dfrac{d}{dt}\Delta\theta \\ where\ L_1 = \|TRP - VJP\|\ and\ L_2 = \sqrt{\|VJP - CP\|^2 - \Delta S^2} \end{cases} \tag{7}$$

5. CONCLUSIONS

The proposed model for the standard way of steering the implement is based on the idea of abstract implement. The Abstract implement is suitable for any type of implement. The core of the Abstract implement model is in the skeleton model representing the essential joints and points of the implement in 2D and the main variables for the interface: side offset and heading offset.

In case of maximum two mechanical DoF in the implement, the transform between the mechanical angles of the implement and the side offset and the heading offset is lossless. In case of three independent actuators for steering the implement, the manufacturer of the implement must add an additional constraint for the transfer.

The proposed model supports a wide range of guidance algorithm levels from simple feed-forward or PID to model based control. While providing a common model for any implement type through abstraction, the standard gives room for algorithm development.

The model supports the idea of chained implements. Another trailed type implement connected on behind the first trailer is possible with this model.

The proposed model tries to solve the plug-and-play challenge of ISOBUS devices, by defining a clear interface between the duties of the implement controller and the guidance system. The conversion from the abstract implement variables to the mechanical angles of the implement is the duty of the implement controller and the guidance system relies on the kinematic model.

REFERENCES

Backman, J., Oksanen, T., Visala, A. 2009. Parallel guidance system for tractor-trailer system with active joint. Eur. Conf. Precision Agric., 6–8 Jul., Wageningen: p. 615–622.

Backman, J., Oksanen, T., Visala, A. 2011. Semi-automatic Tuning of NMPC Based Trajectory Control System in Agricultural Machine. In Proc. 18th IFAC World Congress. Milano, Italy, August 28-September 2.

Backman, J., Oksanen, T. and Visala, A. 2012. Navigation system for agricultural machines: nonlinear model predictive path tracking. Computers and Electronics in Agriculture, 82 (2012), pp. 32–43

Backman, J., Oksanen, T. and Visala, A. 2013. Applicability of the ISO 11783 network in a distributed combined guidance system for agricultural machines. *Biosystems Engineering*, Vol. 114(3), pp. 306-317.

Bell, T., 1999. Precision robotic control of agricultural vehicles on realistic farm trajectories. Ph.D. diss., Stanford Univ., Stanford, CA.

Bevly, D.M., 2001. High speed, dead reckoning, and towed implement control for automatically steered farm tractors using GPS. Ph.D. diss., Stanford Univ., Stanford, CA.

Cariou, C., Lenain, R., Thuilot, B. and Martinet, P. 2010. Path following of a vehicle-trailer system in presence of sliding: application to automatic guidance of a towed agricultural implement. IEEE/RSJ Int. Conf. Intelligent Robots and Systems, 18–22 Oct., Taipei, Taiwan: p. 4976–4981.

Heraud, J., and Lange, A. 2009. Agricultural automatic vehicle guidance from horses to GPS: How we got here, and where we are going. ASABE Distinguished lecture #33.

ISO IS 11783-6. 2014. Tractors and machinery for agriculture and forestry — Serial control and communications data network — Part 6: Virtual terminal. International Organization for Standardization, Geneva, Switzerland.

ISO IS 11783-7. 2009. Tractors and machinery for agriculture and forestry — Serial control and communications data network — Part 7: Implement messages application layer. International Organization for Standardization, Geneva, Switzerland.

Karkee, M. and Steward, B.L. 2010. Study of the open and closed loop characteristics of a tractor and a single axle towed implement system. Journal of Terramechanics, 47 (6), 379-393.

NMEA. 2015. NMEA2000 - Standard for Serial-Data Networking of Marine Electronic Devices. National Marine Electronics Association.

Oksanen, T. 2010. Closed loop control over ISO 11783 network – challenges of plug-and-play. In Proceedings of the third IFAC International Conference Agricontrol 2010, Kyoto, Japan, 6–8 December 2010. pp. 203-208.

Oksanen, T. and Backman, J. 2015. Standardization proposal on Implement guidance for ISO 11783 compatible tractor-implement systems. Aalto University, Aaltodoc series: Working papers.

SAE. 2015. Surface vehicle recommended practice, SAE J1939.

Werner, R., Kormann, G., and Mueller, S. 2012. Path tracking control of tractors and steerable implements based on kinematic and dynamic modeling. In Proc. 11th International Conference on Precision Agriculture. Indianapolis, Indiana USA, July 15-18.

Werner, R., Kormann, G. and Mueller, S. 2013. Systematic model based path tracking control of actively steered implement in simulation and experiment. In Proceedings of the fourth IFAC International Conference Agricontrol 2013, Espoo, Finland, 28–30 August 2013.