Hose Laying for Umbilical Slurry Spreaders: Modelling and Control

Authors: C. Auclaire[1], M. Favier[1], S. Feick[1], T. Fischer[1], Mark Hruszczak[1], V. Michael[1], Y. Su[1],
lgam@mv.uni-kl.de
[1] *Technische Universität Kaiserslautern*

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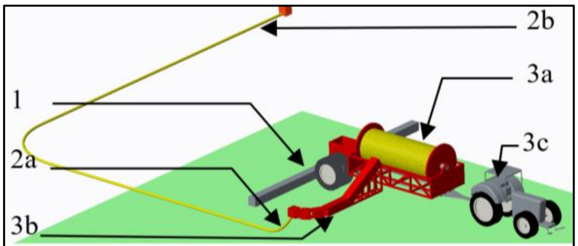
Abstract: Umbilical slurry spreaders are increasingly used by farmers having to spread annually a large amount of manure. To make these machine user-friendlier, the actual tether handling system has to be improved. The design of the new control system starts with the development of kinematic and dynamic models. The simulation work can be divided into three phases: kinematic simulation and control engineering in Simulink, a fast and plausible dynamic simulation in a physics engine and finally a precise but computer time consuming multibody Simulation (MBS) in a dedicated software. Results are encouraging since the developed models permitted the authors to design and to test a new tether handling concept.

1 INTRODUCTION

Despite the fact that umbilical slurry spreaders (Figure 1) are a marginal slurry application method compared to tanker spreaders, they are increasingly used by farmers who want to spread a large amount of manure in a short time, whilst avoiding compacting the soil. (Thirion & Chabot, 2003).



1. Tractor & slurry spreader
2. Tether:
   2a. Hanging tether; 2b. Laid tether
3. Tether Management System:
   3a. Tether storage; 3b. Boom;3c. Control terminal

Figure 1: 3D CAD model umbilical slurry spreader from WM Innovations (Ruen, 2010)

Currently the tether management is controlled by the operator. Besides driving the tractor, the operator has to control the winding of the hose, depending on the position of the spreader on the field. Therefore, new control approaches are required to improve the user friendliness of these machines and to extend the service life of the hose. This work shows how kinematic and dynamic multibody simulations are involved in the control prototyping.

2 IMPROVED HOSE LAYING CONTROL

The two main requirements of a hose laying control is to assure that the umbilical slurry spreader (hereafter called spreader) has enough degree of freedom to accomplish its work and to protect the tether from being damaged. To accomplish its function, the control system or tether management system (TMS) is divided into a logic control and a feedback control module.

2.1 Logic control

The state machine of the tether management system decides whether the hose has to be reeled or unreeled and sets the position of the tether arm depending on the position of the machine on the field. (Figure 2)

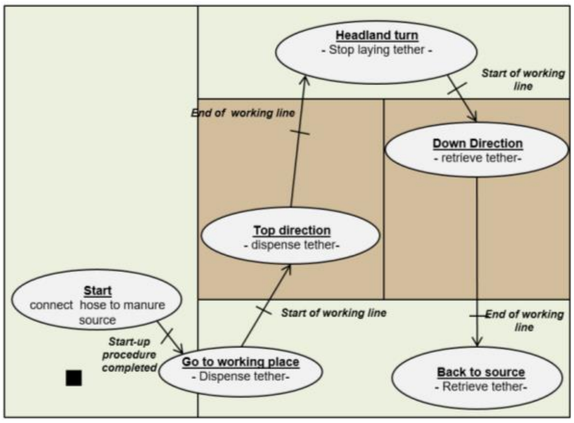


Figure 2 State machine of the tether management system implemented in Simulink

2.2 Feedback control

The feedback control of the TMS is a multivariable PID control which controls the torque of the hydraulic reel taking into account not only the speed of the vehicle but also the driven distance of the vehicle. (Figure 3)

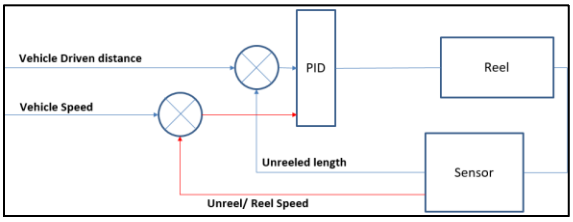


Figure 3 Multivariable PID control implemented in Simulink

3 MODELLING AND SIMULATION STRATEGY

To optimize the use of the available computational resources, dynamic models are only used for the tether and tether handling system. The motion of the rest of the agricultural machine is set by kinematic constraints. To model and to analyze the tether management system of spreaders three software are used depending of the required accuracy.

The kinematic simulation and the visualization software SimMechanics Explorer permit to evaluate and improve the tether handling strategy by modifying the path of the vehicle, the lay speed and/or the position of the boom. (Figure 4-1)

Physics engine based simulation permits to get plausible and rendered results of tether handling scenarios. The physics engine model runs approximatively in real time. (Figure 4-2)

Co-simulations between Simulink and a MBS software permit to tune the tether handling control accurately. The results can be obtained after few days of simulation. (Figure 4-3).

The reason why physics engine based simulations are less computer time consuming as MBS software lies in the way contacts are modelled. Whereas MBS software use a penalty based contact model, physics engines are constraint based. (Bender, 2007), (Trinkle, 2010)

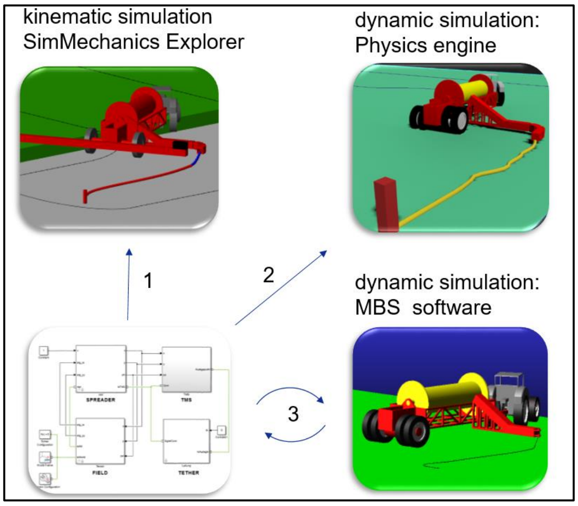


Figure 4 Modelling and Simulations strategy

4 KINEMATIC MODEL

The kinematic model of the umbilical slurry spreader includes:

- a tractor-trailer model
- a hose model (1250 m long, 0.1 m diameter, 30 kg/m)
- a tether management system model

4.1 Kinematic model of the Tractor/Slurry Spreader combination

The tractor/spreader combination can be described by the model shown in Figure 5

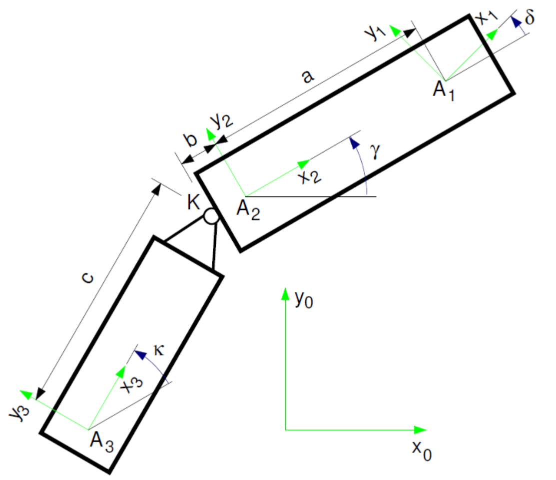


Figure 5: Kinematic model with trailer (Rill, 2006)

Table 1: Mathematical symbols used in the description of the tractor trailer model.

Description	Symbol
Tractor wheelbase	a
Tractor Steering angle	δ
Tractor Heading angle	γ
Vehicle velocity	v
Distance between Tractor rear axle and the coupling point	b
Distance between the coupling and the trailer axle)	c
Coupling angle between tractor and trailer	κ

The equations of motion for the towing vehicle model are:

$$\dot{\gamma} = \frac{v}{a} \cdot \tan(\delta) \quad (1)$$

$$\dot{x} = v \cdot \cos(\gamma) \quad (2)$$

$$\dot{y} = v \cdot \sin(\gamma) \quad (3)$$

Then the equation of motion for the trailer is:

$$\dot{\kappa} = -\frac{v_H}{a}\left(\frac{a}{c}\sin(\kappa) + \left(\frac{b}{c}\cos(\kappa) + 1\right)\tan(\delta_v)\right) \quad (4)$$

4.2 Kinematic Model of the Tether

4.2.1 Hanging line model

Since the spreader moves at a speed of approximatively 4 km/h in a low acceleration range, the dynamic loads on the tether can be neglected and the hanging line can be modelled as a catenary under static load. The tether –boom interface is modeled by a pivot joint.

In the vertical plane the hanging tether is modeled as a catenary hanging from the point A1 of the spreader boom, 0.7 m above the ground, and touching the soil at point P1 (Figure 6).

In the horizontal plane the model describes the movement of the last laid point P1 as a tractrix of the leaving point A1.

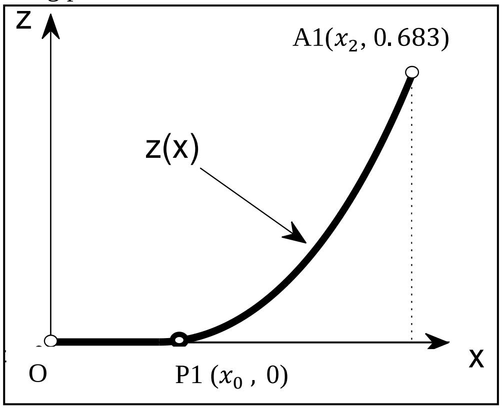


Figure 6 Mathematical Model of the hanging tether

The hanging tether represented in Figure 6 is described by the following equations. (Feldhusen, 2007)

$$z(x) = \begin{cases} -a + a * cosh\left(\frac{x - x_0}{a}\right), & x \geq x_0 \\ 0, & x \leq x_0 \end{cases} \quad (5)$$

$$L(x) = x_0 + a * sinh\left(\frac{x_2 - x_0}{a}\right) \quad (6)$$

Where a is the scale factor of the catenary.

With $q = 30\,kg/m$, the horizontal tension in the tether is defined as:

$$F_H = a \cdot q \qquad (7)$$

Depending on the new positions of the point A1 and P1, a new hanging line is computed at every simulation step.

4.2.2 Model of the laid tether

The laid tether is mathematically represented with a Last In First Out (LIFO) table whose elements are deleted depending on the horizontal length of the hanging tether (catenary). As a simplification, the friction coefficient between the laid tether and the terrain are considered as infinite.

4.2.3 Visualization in SimMechanics explorer

Figure 7 and Figure 8 show a view of the moving spreader at time t=21.77 and at time t=22 sec. The hanging line changed because at time 21.9 s the reel was stopped. $(v > -v_t)$. The horizontal tension of the tether F_H increased from 42 N to 108N (equation 7)

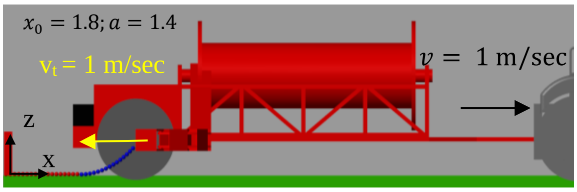


Figure 7 Spreader at physical time 21.77 s

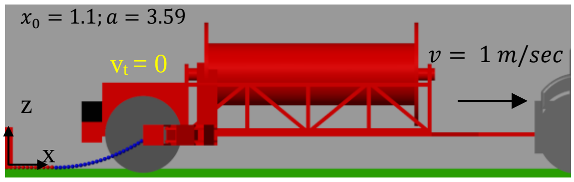


Figure 8: Spreader at physical time 22 s

5 DYNAMIC MODEL

After using a continuous static model for the hanging tether in section 0, a discrete dynamic model for the whole tether will be now defined. As mentioned in (Dreyer & Van Vuuren, 1998), the lumped masses tether model and the hinged rods model are the most used discrete dynamic models. The rod model was chosen since it permits an easy implementation of the bending behavior. Then it will be run in the physics engine and in the MBS software.

5.1 Tether Model in physics engines

In physics engines the tether is modelled as a series of rigid links connected by a frictionless spherical joint. Each element has a length of 0.2 m and a mass of 6 kg.

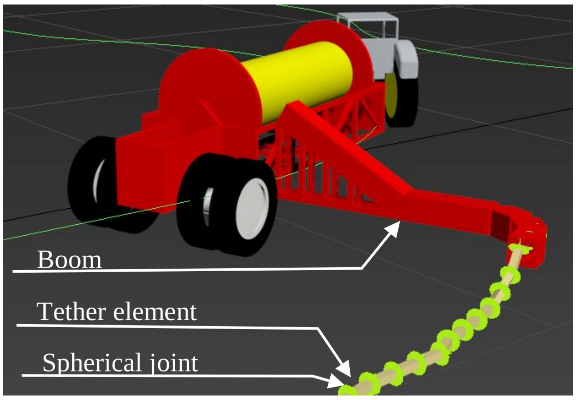


Figure 9: Model of the spreader in physics engines

5.2 Modeling of the Tether in MBS software

Unlike the model implemented in the physics engine, in the MBS software each element is connected to its neighboring elements by a dynamic bushing joint. By using this 6DOF spring damper systems to link the tether elements, a more realistic representation of the tether is achieved. The same number of rods is used as in Figure 9.

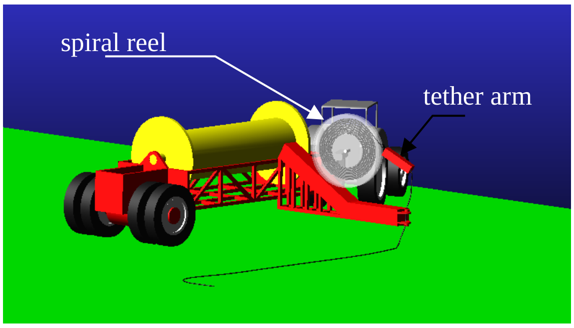
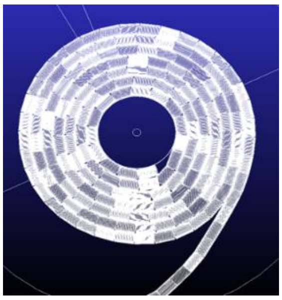


Figure 10 spiral reel and tether arm models connected to the spreader.

For simplification a spiral reel model describes the long reel of the spreader (Figure 10).

To obtain the reel as represented in Figure 10 and Figure 11, a pre-simulation step is required. At the beginning the tether must be namely in static equilibrium with motionless reel.

The tether arm connected to the reel has two passive rolls. The position and the number of rolls of the tether arm can be adjusted for test purposes in order to find the best way to guide the tether. (Figure 12)



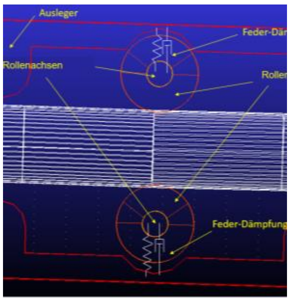


Figure 11: 75 m tether rolled on a reel (left)
Figure 12: Dynamic model of the tether arm (right)

6 SIMULATION

The following simulations help the control system designer to test the control strategies explained in section 2. The state machine (Figure 2) and the laying feedback control (Figure 3) can be firstly tested with the kinematic simulation and the physics engine. To tune the feedback control accurately the Co-simulation between Simulink and the MBS software is necessary.

5.1 Tests with kinematic simulation

The kinematic simulation permits to ensure that the hose laying control requirements mentioned in Section 2 are respected in straight lines and during headland turn maneuvers.

a) Straight lines

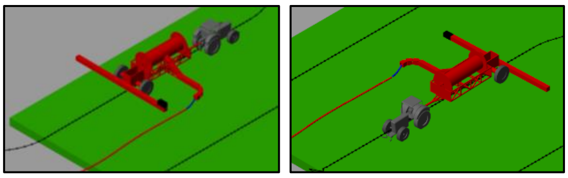


Figure 13 –Slurry spreader dispensing and retrieving the tether: no collision and tension seems no to be too high

b) Turn Maneuvers

During headland turn maneuvers, the hanging line should be kept tight in order to avoid that the implement collides with the tether. Figure 14 shows on the left a spreader dangerously colliding with the tether. On the right the tension applied to the tether permits to avoid a collision.

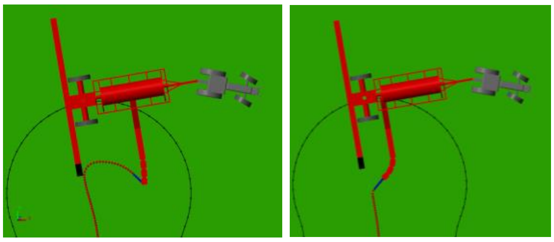


Figure 14 Umbilical Slurry spreader during headland turn maneuver (left: collision; right: no collision)

5.2 Tests with dynamic simulation in MBS software

A co-simulation between Simulink and the MBS software permits to test precisely the feedback control mentioned in Figure 3.

If the speed of the reel is not adapted to the vehicle speed, the tether gets tight or loose (Figure 15)

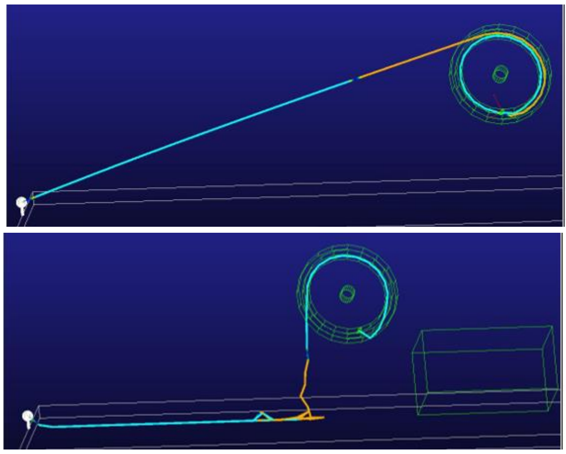


Figure 15:Co-simulation without optimized control: reel speed<vehicle speed (top), reel speed>vehicle speed (bottom)

The first results show how a multivariable PID control of the reel reduces tensions in the tether (Figure 16) compared to the original control strategy (Figure 15)

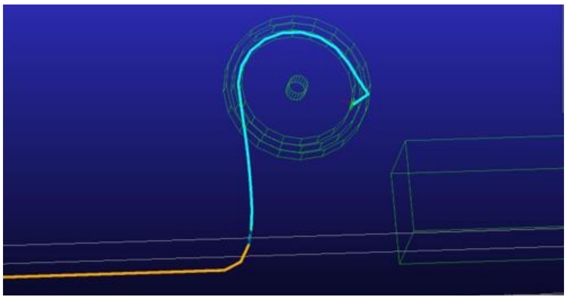


Figure 16 Cosimulation with Multi Variable PID Control

The simulation is computer time consuming since 1.5-day are necessary to complete 11 s in physical time of simulation. (Figure 17)

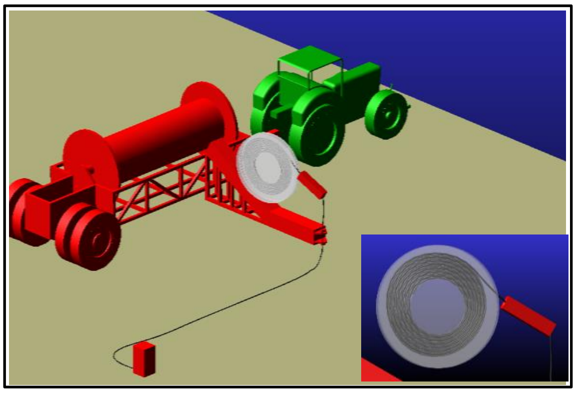


Figure 17: MBS software: spreader at physical time 11 s

7 CONCLUSION AND OUTLOOK

This work demonstrated how kinematic and dynamic simulations assist in prototyping new control strategies for umbilical slurry spreaders.

The theoretical simulation results and the experimental results are comparable. Further investigation of mechanical properties of tether should be done to improve the accuracy of the tether model.

To assess the scalability of the developed solution. It is necessary to run the developed model with other parameters corresponding to a different umbilical spreader or to any other kind of tethered mobile machines.

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