TOWARDS A METHODOLOGY FOR MODELLING AND VALIDATION OF AN AGRICULTURAL VEHICLE'S DYNAMICS AND CONTROL

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ABSTRACT
A model-oriented approach aimed at cost-effective development of autonomous agricultural vehicles is presented. Here a combination of discrete-event modelling of a digital controller and continuous-time modelling of the vehicle is used for co-simulation. In order to have confidence in the simulation results it is paramount to be able to relate the simulation results to the behaviour of the real system. The cost of physical tests is high and we argue that using such collaborative models is a cost-effective way to experiment with the most significant design parameters influencing the optimal system solution. The suggested methodology is exemplified on a Lego®Mindstorms®NXT micro-tractor. Testing is performed based on measurements from a localisation system and internal sensors on the tractor. Our tests show that we are able to predict the performance with a high accuracy indicating that this is worthwhile for a full-scale model.

Keywords: Auto-steering, Bond graph, Lego Mindstorms NXT, Vienna Development Method

1. INTRODUCTION
Modern agricultural machinery is gradually moving towards a higher degree of autonomous operation (Grisson et al. 2009). Global Navigation Satellite Systems (GNSS) in combination with other sensors are used to estimate the position of the vehicle. Operational tasks like ploughing, spraying and harvesting are commenced by the autonomous vehicle. A pre-planned route for the agricultural vehicle to follow for a specific broad-acre field is supplied in advance. The onboard auto-steering system then aims to adjust the current position so it gets as close as possible to the pre-planned route. The ability to automatically correct the position helps deal with physical conditions, such as the terrain (Fang et al. 2005), which may affect the vehicle's movements in unpredictable ways.

Methods to determine the precision of the vehicle's control equipment have been proposed in a ISO test standard (DS-F/ISO/DIS 12188–2). Testing is performed over a period of more than 24 hours, repeating the testing scenarios multiple times. Full-scale testing of performance and operation is both time-consuming and very costly. Utilising a simulated model of an agricultural machine and auto-steering system, could lower some of these costs. Relevant testing scenarios can be determined based on flaws found through evaluation of the simulations. These scenarios could then be tested to determine if they would produce similar results as in the real physical system.

The aim of this work is to develop collaborative models of agricultural vehicles and their auto-steering systems, combining discrete-event models of control elements with continuous-time modelling of the physical elements and the surrounding environment. The Vienna Development Method (VDM) is utilised for discrete-event modelling of the vehicles control equipment and 20-sim is used as the continuous-time framework for modelling the tractor. In this paper collaborative modelling (co-modelling) is used to model a concrete physical system and its controller.

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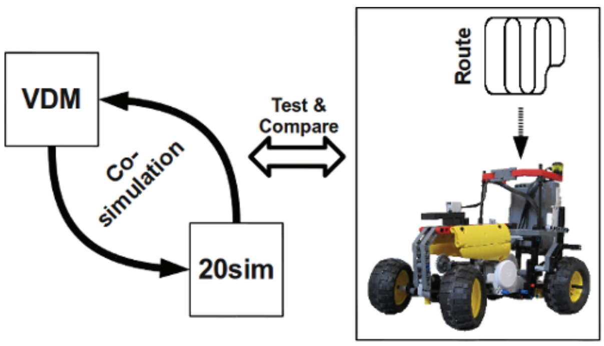


Figure 1: Overview of the micro-tractor and the co-modelling method. 20-sim models the vehicle and VDM the control part

An agricultural tractor system is a complex system to model, simulate and test. Many of the parameters in such a complex system are unknown, making it difficult to verify the complete model based on testing and analysis. To simplify the process, a model and co-simulation based on a Lego®Mindstorms®NXT tractor (micro-tractor) has been developed. The micro-tractor is a representative scaled model of agricultural machinery used to test and demonstrate autonomous operations.

This prototype model of the autonomous vehicle is intended to provide an abstraction with key components in autonomous vehicle steering and explore alternative requirements and design decisions.

The model of the system will provide the functionality to control the motors for the front and back wheels, using the inputs from motor encoders and Inertial Measurement Unit (IMU) in VDM. Subparts of the 20-sim model were modelled separately and combined after verification of each subpart (component). The output from the co-simulation model is the dynamic movements of the vehicle while commencing a pre-planned route.

The article is structured as follows: a short presentation of the underlying method and technologies used for co-modelling and co-simulation is given in section 2. The case study with the scaled-down tractor and a short description of the proposed development process is provided in section 3. The verification and validation of the model in relation to the real physical system is found in section 4. Finally section 5 provides concluding remarks together with directions for future work.

2. TECHNOLOGIES APPLIED

Models of control systems can be complex when they account for many different scenarios. Testing the final model to determine the sources of a specific problem is complicated and time consuming. The work presented in this paper uses a methodology that integrates tests as an essential part of the development process.

The idea is to discover errors and faulty assumptions at an early stage in the development process. It is expected that combined analysis and testing throughout the development will provide a good methodology for developing the multi-domain models.

In the initial part of the development phase a subcomponent of the system is selected. This subcomponent is analysed and an initial sub-model is created. A test scenario will then be created to determine the sub-model's accuracy compared to the actual setup. If flaws are found in the sub-model, extensions and improvements are made until the model represents the actual sub-component.

After the subcomponents have been modelled independently they are put together as a first version of the system intended to be modelled. This model will then be tested using the same process as the sub-models. The process is an iterative incremental development process that improves and extends the model.

2.1. DESTECS and Co-simulation

This paper is based on the DESTECS ("Design Support and Tooling for Embedded Control Software" (see www.destecs.org).) co-simulation technology (Broenink et al. 2010) that supports a model-based approach to the engineering of embedded control systems. Models are built in order to support various forms of analysis including static analysis and simulation — the latter is our focus here.

The technology supports models where the controller and plant or environment is modelled using different specialized environments and tools. In particular, it supports co-simulation by allowing the collaboration of two simulation engines in order to produce a coherent combined simulation of a co-model of a digital controller expressed in a Discrete-Event (DE) formalism and a model of the plant/environment expressed in a Continuous Time (CT) notation.

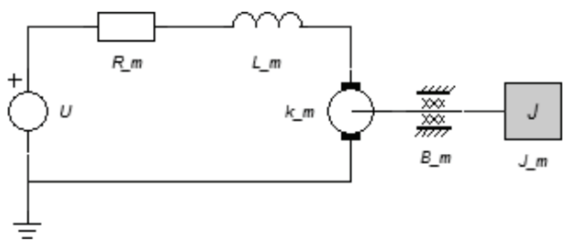
In order to link the DE and CT models together, a contract is established between them. The contract includes information about the shared design parameters as well as monitored and controlled variables exchanged between the two simulators. Once co-models have been constructed, they can be evaluated by co-simulation. Evaluation is done using criteria's chosen by the developer, intended to select the best candidate co-model termed Design Space Exploration (DSE).

VDM is used for modelling DE controllers, and 20-sim as the CT framework for modelling the environment. VDM Real Time (VDM-RT) is the dialect used in DESTECS (Verhoef et al. 2006; Verhoef 2009). Both VDM and 20-sim are well-established formalisms with stable tool support and a record of industry use.

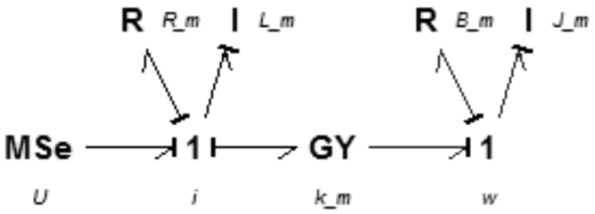
2.2. 20-sim and Bond graph modelling

20-sim is a modelling and simulation tool, developed by Controllab Products in the Netherlands. The tool is able to model complex multi-domain dynamic system, such as combined mechanical, electrical and hydraulic systems. 20-sim models (Kleijn 2006) may use iconic diagrams, Bond graphs and equation models. Iconic diagrams generally contain a sub-model based on equations or Bond graph models. In this context a sub-model means a part on the overall model describing a dynamic system.

Bond graphs are a type of directed graph representing the idealized power flows in a dynamic system (van Amerongen 2010). Every element in a Bond graph is represented by a multiport, describing a subpart (sub-model) of the system. The connections between sub-models, called bonds, represent the exchange of energy. Each port element describes the energy flow, using the product of the variables effort (*e*) and flow (*f*). The meaning of different ports elements changes based on the current system domain. In an electrical domain (*e*) and (*f*) could represent voltage and current and in a mechanical domain torque and angular velocity. This abstraction of ports provides a huge advantage, in terms of reuse and movement between different physical domains.



(a) Iconic diagram representation



(b) Bond graph representation

Figure 2: Motor representations using iconic diagrams.

An iconic diagram representation of a DC-motor can be seen in Figure 2(a). In a Bond-graph terminology voltage source would mean an effort source for the motor system. In Figure 2(b) the bond-graph represents the Direct Current (DC)-motors mechanical and electrical domains. In the electrical domain the I-element represents the inductance L_m and R the resistance R_m connected to the electrical 1-junction. The gyrator GY relates the effort and flow between the electrical and mechanical domain. In the mechanical domain the R-element represents the internal friction B_m and the I-element the moment of inertia J_m. In the bond-graph model *i* represent the current and *w* the rotational speed of the DC-motor.

2.3. The Vienna Development Method

The 20-sim tool environment also provides techniques to allow for mixed modelling and simulation of digital controlled physical systems. Using the equation models different discrete-event scenarios can be simulated and tested. This provides the ability to simulate both continuous and discrete time events of a dynamic system. Most modern digital control systems are complex and hard to model in a single model block. The 20-sim tool provides the ability for external software to connect and communicate with a specific model. An external environment could therefore be used to model the discrete time event parts of a dynamic model (Fitzgerald et al. 2011).

VDM is a formal method for specification, analysis, modelling and identification of significant features in a computer system. VDM originate from work done at IBM's Vienna Laboratory in the 1970's on semantics of programming languages (Bjørner and Jones 1978). VDM provides the ability to model at a level higher of abstraction, than is realizable in a normal programming language. Validated models can then be turned into a concrete implementation in a programming language. The current tools focus are to provide modelling and analysis techniques used for simulation rather than proof checking. VDM tool support is provided by the open-source Overture tool (Larsen et al. 2010).

The demands and assumptions about the system intended for modelling is a significant part, when describing the functionality of the system. Functionality is performed on different data types, ranging from basic type like Booleans, tokens, integers and real numbers and collections such as sets, mappings and sequences. Functions can be either implicit or explicit specified in VDM, for a modelled system in terms of describing the relations. The VDM functionality has been extended to include the Object-oriented structuring (Fitzgerald et al. 2005) using the VDM++ extension. For VDM to be used in a real-time embedded system context, it requires explicit modelling of computation time. The capabilities to describe real-time, asynchronous, object-oriented features are provided in the VDM-RT extension. Using the VDM formalism for both control and modelling of the environment is not an ideal solution, since the CT environment would be expressed in DE formalism based on simplifying assumptions. A co-simulation with a CT event tool would be a significant improvement, in terms of simulating the VDM controller.

3. THE MICRO-TRACTOR CASE STUDY

The micro-tractor was developed to represent an average 150 bhp tractor. A scale ratio of 1:14 was used. The micro-tractor is described in (Edwards et al. 2012).

The micro-tractor's steering range was between +/-30 (degrees) and controlled by an NXT servo motor and gearbox.

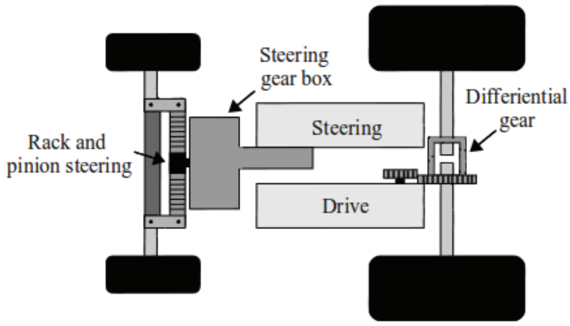


Figure 3: Sketch of the micro-tractors steering and drive components.

The rear wheels were powered by another NXT servo motor. A differential gear was used on the drive axle to allow the wheels to turn at different speeds and reduce slip (see Figure 3).

The navigation sensor is the CruizCore R XG1300L IMU. The IMU measures heading of the micro-tractor based on relative initial heading. The IMU contains a single axis MEMS gyroscope and a three axis accelerometer. The signals from these sensors are processed onboard the IMU.

3.1. Co-simulation

A co-simulation engine is responsible for exchange of shared parameters and variables between the CT and DE models. The co-simulation engine coordinates the 20-sim and VDM simulation by implementing a protocol for time-step synchronisation between the two simulation tools. A contract defines the parameters and variables to be exchanged during simulation as illustrated in Figure 4. Here the start and stop times of the co-simulation are shared, to ensure common reference. The micro-tractor (CT Model) updates the shared angle parameters of the motor encoders and IMU and the controller (DE model) drives the shared input parameters the motors.

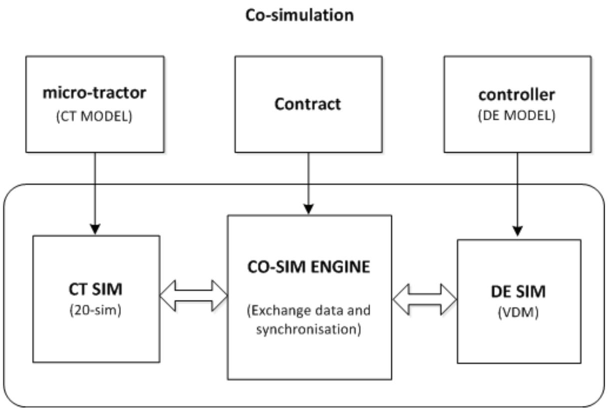


Figure 4: Co-simulation engine and synchronisation of the CT and DE simulation.

3.2. Bond graph model

The motor is modelled as the first component of the vehicle model, since it is used for control of both drive and steering.

To exemplify the development method, the motor subpart will is described in detail. The NXT controls the average voltage output to the motors using Pulse Width Modulation (PWM). This makes it possibly to compare input/output between model and actual Lego DC-motor: A representation of a bond graph DC-motor model can be seen in Figure 2(b).

To test if the model works as intended, the bond graph is supplied with motor parameters for the Lego DC-motor. An impulse-function (0V-7.4V-0V) is used to apply a voltage to both Bond graph and real DC-motor.

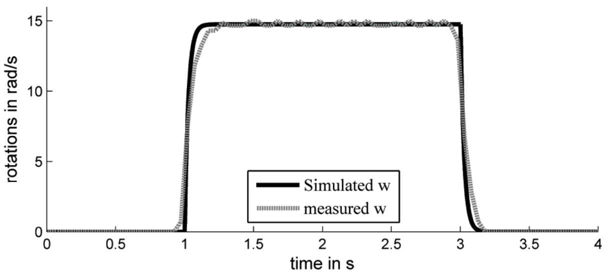


Figure 5: Impulse test of DC-motor model and real system.

From the plot in Figure 5 it can be seen, the plots correlate to a high degree. Based on these findings, the DC-motor bond-graph is accepted and development on other subparts is initiated.

A similar methodology is applied when modelling the remaining components in 20-sim.

The controller is connected to the DC-motor implementation, providing the interface for communication with VDM. Gearing for steering and drive components are modelled using Transformer TF elements. Each TF element corresponds to a gearing ratio effort with effort out causality. A Bond-graph equivalent of a spring damper (C_g , R_g) system is used to model the effects of rotating gears using a 0-Junction.

Change in angle of the front wheels are represented using a friction and moment of inertia (B_{fwheel}, J_{f_wheel}). Interactions between wheels and ground plane are only considered for a smooth surface to keep the complexity of the model down.

Only the longitudinal effects on the wheel are considered, since tire-road normal effort (Merzouki et al. 2007) is expected to be minimal. Effects of the wheels moment of inertia is represented with a 1-junction and an I-element J_{b_wheel}. A TF-element converts between rotational and linear speed. A spring-damper system (C_{b_wheel} , R_{b_wheel}) is used to represent the longitudinal surface interaction with the wheel contact-point.

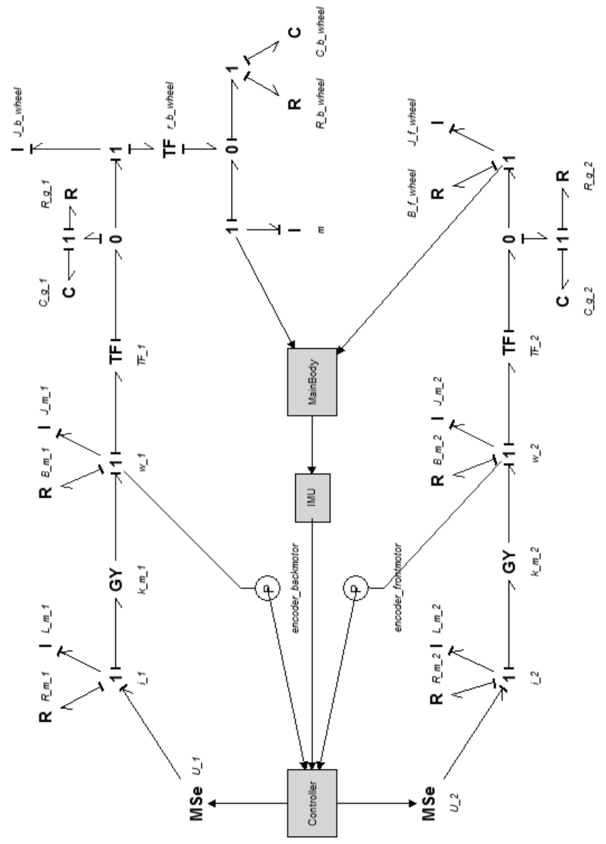


Figure 6: The micro-tractor model in 20-sim. A combination of bond graphs and iconic diagram blocks are used for modelling the micro-tractor.

To combine the dynamic effects of the back and front wheels a first order bicycle model (Figure 7) has been chosen. The first order bicycle model is a pure kinematic model (Rovira M Rovira Más et al. 2011) of the chassis movements, without regards for the forces acting on the body.

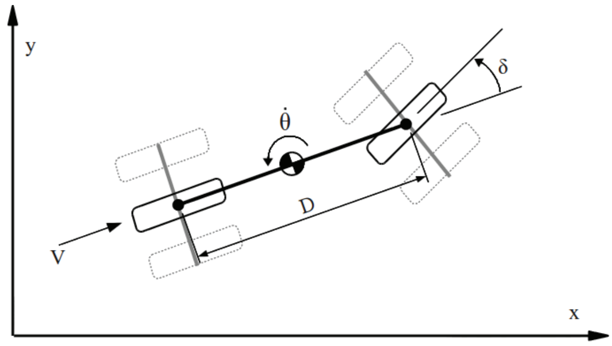


Figure 7: Bicycle vehicle model used to model the body of the micro-tractor.

Translational speed (V) from the back wheel in combination with the rotational speed (δ) of the front steering system is used as input for the model.

Equation (1), (2) and (3) are used to calculate the vehicle rotation and speed in x,y direction in a global reference frame.

$$\dot{x} = cos(\theta) \cdot V \tag{1}$$

$$\dot{y} = sin(\theta) \cdot V \tag{2}$$

$$\dot{\theta} = (tan(\delta)/D) \cdot V \tag{3}$$

D represents the distance between front and back wheels, δ the orientation of the front wheels. To represent backlash in the steering system Gaussian noise is added to the rotational change.

A Bond graph model of backlash in the front wheel orientation is not incorporated, since modelling of the external forces on both front wheels would be needed. Position and orientation of the vehicle over time is calculated using numerical integration of equation (1), (2) and (3). The positioning and orientation of the vehicle is the intended output from the model.

3.3. VDM model

The discrete event control system modelling the NXT's steering of the micro-tractor is modelled in VDM-RT. A pre-planned route is given to the autonomous system. This route is used when the micro-tractor commences its task in an area.

The route is based on a collection of continuous curve elements. Each continuous path element is either a line segment or circular arc with constant radius, containing a start and stop waypoint (Bevly 2009).

The micro-tractor is aware of its current position and is able to use this information when following the route. A route-manager ensures that each route segment is performed in the order described in the route. The VDM model uses invariants and pre and post-conditions to ensure only a viable route and route segments are commenced. The description is given to provide the reader with a perspective of what the VDM capabilities could be used for. Details of the route-manager will not be given in this paper but similar systems can be found in (Fitzgerald et al. 2005).

When a route element is commenced a control loop is needed to keep the micro-tractor on track. In this model the inputs from the back-motor encoder and the IMU is used to determine the current position and orientation. The model for executing a line function segment can be seen in Listing 1.

```
class controlStraight

instance variables
public rotations: real; -- 20-sim variable
public ImuOrient: real; -- 20-sim variable
P: real; --proportional control factor
MotorOutput: real; -- output value in %
distance: real; -- distance to travel
wOrient: real; -- Wanted orientation

operations
public ControlStep: () ==> ()
ControlStep() ==
( if abs rotations >=
distance/(2*MATH‘pi*R_BACK_WHEEL)
then drivingMotor := 0.0;
else driveMotor := MAX_OUTPUT*MotorOutput;
steerMotor := MAX_OUTPUT*P*(ImuOrient-
wOrient)
);

thread
periodic(10E5,0,0,0)(controlStraight); -- 100Hz
end controlStraight
```

Listing 1: VDM++ model of control loop for driving a straight.path.

A line segment is followed until the distance between start and stop point is reached. The control loop allows the micro-tractor to steer off track, since any positioning error is accumulated. A more advanced control system could compensate for this and is intended for the future.

4. MODEL VERIFICATION AND VALIDATION

Measurement data from the testing of the micro-tractor is compared against the vehicle co-model to determine the accuracy of the co-model. To accomplish this task measurement data from an external source is compared against data from the co-simulation. The testing, measurement method and results thereof are presented in this section.

4.1. Test scenario

The testing will determine the difference between the actual system and the co-simulation, in terms of position and orientation. Running the same route-scenario in will make them comparable and provide a means of comparing different parts of the route. Testing is performed on a route with 3 straight segments of 2-3 meters and 2 circle arcs in opposite direction. A more complex route with more route-segments could introduce larger accumulative errors in terms of position.

Since this is not taken into account in the current co-model, comparison would clearly fail. The selected route ensures the testing is done for movements with different rotational speeds θ of the micro-tractor body, which is a major part of the micro-tractor dynamics. The model parameters used in the co-simulation of the bicycle vehicle model are given in Table 1.

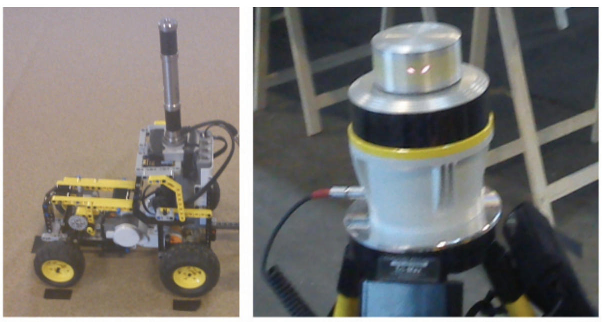
Table 1: Testing and co-simulation parameters

Sub-system	Parameter Values	
Motor:	$R_m = 5.2637(\Omega)$ $k_m = 0.4952$ $J_m = 0.0013(kgm^2)$	$L_m = 0.0047(H)$ $B_m=6^{-4}$ Nm/(rad/s)
Gearing:	$TF_{g1} = 20/28$ $Cg = 10^{-5}$	$TF_{g2} = 3/70$ $Rg = 10^{-5}$
Back-Wheels :	$J_{wheel} = 3.67^{-6}$ $C_{b\_wheel} = 1.1\mu$	$r_{b\_wheel} = 0.0408(m)$ $R_{b\_wheel} = 0.3$
Body:	m = 2.2374(kg)	D = 0.175(m)

Parameters with the equal value in Figure 8 like k_m_1 / k_m_2 is represented with same symbol (ex k_m).

4.2. Testing equipment

To determine the position of the micro-tractor over time the iGPS system from Nikon is used. iGPS measurement technology is a laser-based indoor system with optical sensors and transmitters to determine the 3D position of static or moving objects. The iGPS technology is based on internal time measurements related to spatial rays that intersect at sensor positions in the measuring area. The iGPS measurement system has been evaluated in experimental studies (Depenthal, 2010) of the capabilities for tracking applications.



(a) (b)

Figure 8: Nikon iGPS receiver mounted at the micro-tractors CoR (a) and transmitter used in the testing (b).

The intention is to use the iGPS technology to evaluate full-scale autonomous agricultural vehicles based on the ISO. The system is able to measure the micro-tractor position over time to provide capabilities for direct analysis of auto-steering system.

The iGPS sensor is mounted on top of the micro-tractor close to the Centre of Rotation (CoR) (see in Figure 8(a)). Using the CoR as measurement point ensures measurement data is comparable directly with co-simulations. The vehicle was driven at 20% of full motor power output when running the pre-planned route. The low motor-output was chosen to ensure safe driving, when using the iGPS sensor system.

The testing was repeated 10 times to account for any variation in performance.

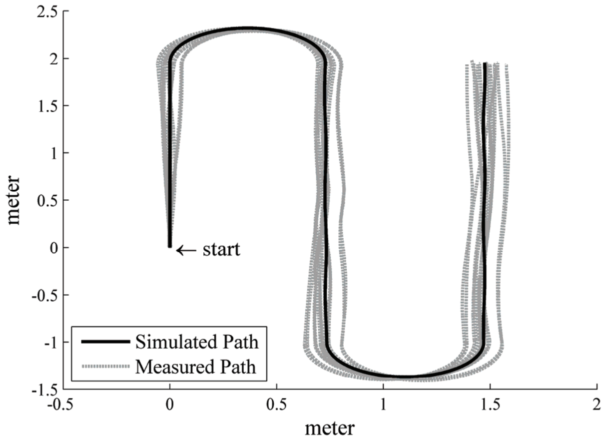


Figure 9: Measured and simulated path of the micro-tractor. Measured path shows the variation in 10 runs.

Figure shows the micro-tractor drifts in position but keep it's heading throughout the path. The small variations in angle can mostly be described to variation in initial placement, since the IMU is a relative sensor any misalignment is kept throughout the path. These initial misalignments are not part of the simulation, resulting in a path moving in the middle of the actual measure paths.

Position measurements are determined to have a precision of 0.4-0.5 mm, based on estimates provided by the iGPS system.

5. CONCLUDING REMARKS AND FUTURE WORK

Based on testing of the current co-model it can be concluded, that the model can emulate the basic performance intended for the micro-tractor. Visual presentation of results and comparisons show a high consistency between actual system and co-model. The current model can be seen as a first step towards a full scale co-model of an autonomous agricultural vehicle. Different routes can be tested in the co-model, to determine their efficiency on the actual system. The co-model will allow for detailed analysis, without the need to start the process of the testing each time.

The need for testing can be diminished significantly and thereby saving development costs. The development process has shown exemplary initial results, to produce dynamic models. Splitting design of the model into smaller steps helps ensures sub-part errors could be determined easily throughout testing. Experience from this project has indicated an iterative modelling method with testing to be a beneficial development and modelling approach.

Continuing to use the current approach to model development is therefore seen as a promising way of continuing the development.

The current version of the co-model is used to test and develop more advanced control algorithms for the micro-tractor driving and steering system. Only selected versions of the control system need to be tested on the actual system, to confirm any improvements. Obtained measurements could be used to improve the model, should a different result be produced in the testing from simulation using the co-model. Many errors and shortcomings in the control loop can also be tested using the co-model to determine their source and provide the mean to test solutions to the problems.

The co-model currently has a number of shortcomings in terms of describing the dynamics between the front and back wheels. At the current state, a kinematic description is used to describe the overall changes to the vehicles placement and orientation. Forces acting on front and back wheels need to be described in more detail in the co-model to account for their interaction. The forces introduced by the back wheels when rotating and thereby driving the vehicle forward influences the front wheels and the backlash introduced in the orientation. Occurrences of backlash are seen when the micro-tractor is moving in a straight line in figure 9 as small changes in orientation over time. Body rotation of the vehicle introduced by the front wheels will introduce forces on the back wheel and the differential gearing drive. Accounting for these factors is expected to provide a model able to run more complex route scenarios and provide a reliable estimate of the real system.

These improvements to the model are planned to be part of the next stage of the co-model development. Later versions should also account for the external factors like uneven terrain and 3-dimensional movement.

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