Simulation Environment for Testing Guidance Algorithms with Realistic GPS Noise Model

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Abstract: This paper presents a simulation framework and realization for a tractor-trailer system with an active joint in an agricultural field setting. In addition, all real system measurements are also provided for hardware-in-loop testing. In the simulator, the kinematics and dynamics of the tractor and the trailer are modelled, as well as noises related to each measurement. The noise statistics and typical amount of wheel slip were identified from field tests. For hardware-in-loop testing the simulator provides the measurements in CAN-bus (ISO 11783 standard) and the commands to the steering valve are also received via the bus. CAN-bus is the only link between the guidance system under test and the simulation environment. In addition, the simulation environment contains a graphical front end, where the trajectories of the vehicle can be observed and analyzed.

The most challenging noise related to the simulation of an environment is related to the GPS and its inaccuracies, as the noise properties are far from Gaussian white noise. In this paper an error model for GPS noise is presented as a position measurement and noise range statistics to the measurement. The simulation environment is tested with nonlinear model predictive control algorithms.

Keywords: simulation, agricultural machines, trajectory control, navigation, GPS, CAN bus

1. INTRODUCTION

Commercial guidance, or auto-pilot systems that are marketed mainly for tractors have become possible due the improvements in GPS-positioning and embedded systems. Some tractor manufacturers have pre-embedded guidance system in the tractor, but also generic retrofit systems are available. Almost all guidance systems rely on GPS-positioning with some correction system, like a local base station or correction from a special satellite. However, the commercial systems today usually rely on rather simple navigation algorithms, and the goal is to keep the tractor in the driving lane, however, not necessarily the trailing tool (called 'implement' in agricultural engineering) connected to the tractor. As the field operations are done with fixed-width implements, usually the goal of navigation is to keep the swaths side-by-side. Therefore some also use a term "parallel guidance". Bell (2000) evaluated the control system’s accuracy by the mean and standard deviation of the GPS-measured tracking error from the desired trajectory.

There are many researches about navigation algorithms for vehicles, and the most interest has been for car-like kinematic systems. Most agricultural tractors share this kinematics, as the steering wheels are in the front. More challenging trajectory control case is the so called tractor-trailer system.

The more degrees of freedom and inputs the system has, the more challenging the tuning procedure becomes. Also the nonlinear nature (non-holonomic, trigonometry) of kinematics leads to situation that linear control theory does not necessarily give analytic results for control law. Development and testing advanced navigation algorithms and navigation systems is challenging, as it requires realistic environment and repeatability is required to test accuracy related to control actions itself. Therefore it is important that the developed algorithms can be tested hardware-in-loop with realistic signals. Also with the simulator the tuning or optimization of the algorithms can be made within certain limits.

1.1 Navigation system state of the art

A recent survey has extensively compared different existing path tracking methods (Snider 2009). In the survey, none of them was found to be practical for every situation. Instead they all have some characteristic advantages.

The most commonly used and simple path tracking method is based on the geometric approach. The geometric relationship between the path and the vehicle is exploited in these control laws. Often a look-ahead distance is used to measure error ahead of the vehicle. Such a geometric path tracking algorithms are for example the Pure Pursuit (Amidi 1990) and the Vector pursuit (Wit 2004).

More advanced path tracking methods utilizes the kinematic model of the vehicle. The kinematic model is transformed into a chained form and basic control theory methods are used (Morin 2008). The drawback of this approach is that it has more complex implementation and not so intuitive tuning.

The most advanced path tracking methods are based on the vehicle dynamic model and utilize optimal control theory. The usage of Nonlinear Model Predictive Controller (NMPC) is one of the most recent research topics in path tracking methods. By using these kinds of methods more accurate path tracking is possible. However, the model is have to be perfect and the controller properly tuned.

1.2 GPS noise

Common sources of errors in GPS positioning are ionospheric and tropospheric effects, errors in satellite orbits and clocks, multipath effects, receiver noise and clock error, and calculation errors. Also the geometry and the amount GPS satellites cause GPS errors. These errors are attributed to various factors. Total error at time instant t is a sum of all of these errors. Different real time correction methods can reduce these errors, but they can hardly eliminate any of the error sources thus complicating the structure of the GPS noise.

Mobile tractor in a changing environment sets challenges for the GPS noise definition. This is because the determination of GPS positioning quality, a static performance of receivers might not be indicative of dynamic performance (Stombaugh et al. 2002). Pirti (2008) found that tree canopy on one side increased the standard deviation around 40% for both baselines and height differences. Min et al. (2008) made dynamic GPS tests in citrus orchards. They found that receivers performed differently under various test and orchard conditions. Also the type of receiver and mounting height had significant effects on accuracies.

There are only a few GPS error generation studies dealing with GPS output messages. Rankin (1994) constructed a simulator that models the error statistics for various receivers. The simulator had a model of GPS satellite orbits, which were used to create dilution of precision (DOP) values that translated pseudo range errors to XYZ errors which the simulator outputted. Oksanen et al. (2005) presented a noise model for a low-cost GPS. For a guidance algorithm testing and development, there is a need for a more realistic and controllable noise model. This paper presents a controllable noise model for NMEA (National Marine Electronics Association) -type GPS-messages for guidance algorithm tests.

2. METHODS

As it was described earlier, the goal of the control is to keep the tractor-trailer system (with an active joint) in a trajectory, which is generated from the previous swath. To simulate a vehicle, typically the following have to be modeled: the kinematics of the vehicle, the dynamics of the system, random type noises related to inputs and outputs, and movement based noises like wheel slipping.

In the development of embedded systems, simulation can be used in two ways: in software-in-loop to test algorithms or software against the test model in different runtime environment (usually development PC, with emulation), or in hardware-in-loop, where the software is run in the actual hardware, and the interface to sensors and actuators is simulated. In this case, the communication is crucial for the navigation system, as the commands and measurements are delivered over the network (ISO 11783). Therefore the objective was to develop a hardware-in-loop simulator.

2.1 Simulation model

The simulator uses the differential equation of the bicycle kinematic model:

$$\begin{bmatrix} \dot{x}_R \\ \dot{y}_R \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \delta_v v \cos\theta \\ \delta_v v \sin\theta \\ \delta_v v \frac{\tan(\delta_\alpha \alpha)}{a} \end{bmatrix}, \tag{1}$$

where (x_R, y_R) is the coordinates of the vehicle rear axle centre point, θ is the heading angle, v is the speed of the vehicle, α is the front wheel angle, δ_v is the slipping factor of the speed, δ_α is the slipping factor of the front wheel angle and a is the wheelbase. The difference from the basic model is the added slipping factors. These are parameters which can be changed during the simulation.

The trailer is modelled using the freely moving joint angle of the trailer. The differential equation of the trailer angle is:

$$\dot{\beta} = \frac{-av\sin(\beta+\gamma) + v(d + c\cos\beta + b\cos(\beta+\gamma))\tan\alpha - ad\dot{\gamma}}{a(d + c\cos\gamma)}, \tag{2}$$

where β is the angle between the tractor and the trailer, γ is the angle of the controlled joint and $\dot{\gamma}$ is the time derivative of that, d is the distance to the seed coulters from the drawbar, c is the length of the drawbar and b is the distance to the attachment point from the rear axle.

The dynamics of the actuators is modelled as a first degree low pass filter:

$$\begin{bmatrix} v_t(k+1) \\ \alpha_t(k+1) \end{bmatrix} = \begin{bmatrix} k_v v_t(k) + (1-k_v) v_d(k) \\ k_\alpha \alpha_t(k) + (1-k_\alpha)\alpha_d(k) \end{bmatrix}, \tag{3}$$

where v_t and α_t are modelled "true" control values and v_d and α_d are desired control values. k_v and k_α are parameters to modify the dynamical behaviour. In this model, it is assumed that the actuators are eventually able to realize the desired control values.

2.2 GPS-noise model

There are two main procedures for constructing a realistic and controllable noise model. The first is to try to separately simulate all of the error sources and their respective errors. Unfortunately, this would require absolute knowledge of the error structure for each factor, which is most likely impossible. The second, which was employed in this paper is to try to simulate the errors themselves. The key is to define the phenomena which causes the changes, and gives a structure for the noise. To find out these phenomena and to build up a noise model, four separate data collections were performed.

For the data collection, three GPS receivers were used. Two of them were Trimble 5700 receivers, which were used autonomously and with RTK-VRS correction. The third receiver was NovAtel with a decimeter level Omnistar high performance (HP) differential GPS correction, as being quite typical for the guidance usage. For each test, GGA, VTG and GST messages were collected. Message fields of interest were the coordinates, horizontal DOP, correction status, number of satellites, speed, direction, standard deviation (SD) of the error ellipse and SD of the coordinates. For each receiver, elevation mask was selected to be a 13° and the DOP was not limited.

In the first test, static GPS measurements with 1 Hz interval were collected during a 24 h period. The data was used to determine typical variation with daily satellite constellations. Then two autonomous Trimble 5700 receivers collected 10Hz data for one hour. The data was used to determine white noise by removing other detected appearances from it. White noise was determined by comparing data from the two identical autonomous GPS's.

The third test was a dynamic test adapting horizontal positioning test parts from a forthcoming dynamic GPS test standard ISO/DIS 12188-1. The RTK-GPS was used as a reference, driving speed was 10 km/h and the driving path was driven only three times. Dynamic tests were applied to determine rapid changes, effects caused by the movement and changing environment. In the fourth test, GPS antenna was covered for a while, and the recovery time was examined.

When examining the 24 h and the dynamic data, significant correlations were found only between latitude and longitude and the estimated errors for all of the axis. However, north DOP is larger than east DOP at least in a mid-latitude area (Wu et al. 2006). In the dynamic test, which was done in the 60° latitude, 52% of the horizontal error was caused by the north axis.

Examining closely, a correlation between changes in the number of satellites (SV) and the rapid error changes was found from the autonomous data. The situation was similar with HDOP values, but they were found to be very unstable with dynamic tests (Figure 1). Standard deviation in figure 2 was a calculated horizontal error based on the SD fields on the GST message. The presented error was the difference between the HP corrected data and the RTK data.

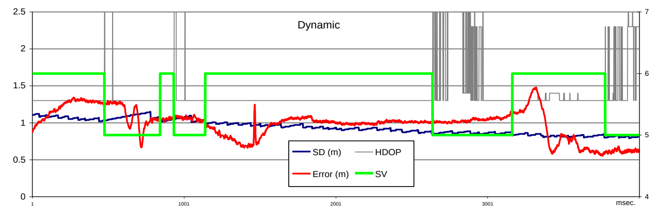

Figure 1. HDOP, the number of SVs and the accuracy.

Direction and speed were calculated from the coordinates. The results were found to correlate with the VTG message, although there were some inaccuracies caused by the projection and the delay was 15 milliseconds.

2.3 Interface

The ISO 11783 network is used to communicate within the tractor-trailer system. The ISO 11783 standard defines an open communication to be used between a tractor and implements connected to that. The standard defines messages for the communication and specifies ECU roles in the system. The specific ECUs are Tractor-ECU (interface to the resources of a tractor), Virtual Terminal (HMI device), GPS (positioning) and Task Controller (a link to management system), and one or more implement ECU's. The physical and data link layers of ISO 11783 are based on CAN-bus, in a sense of OSI-model.

The ISO 11783 defines three classes for the tractor (Tractor-ECU): in class 1 and 2 the tractor serves certain state and sensor information via the bus on request, and in class 3, the implement or other client can command tractor's resources. To realize control-over-network, a Class 3 compatible Tractor-ECU is required. For navigation purposes, an additional letter 'N' is used.

The simulator is intended to emulate ISOBUS Class 3N Tractor and ISOBUS implement (Figure 2). By this way, the interface of the Guidance-system needs not to be modified when changing the simulation environment to the real system.

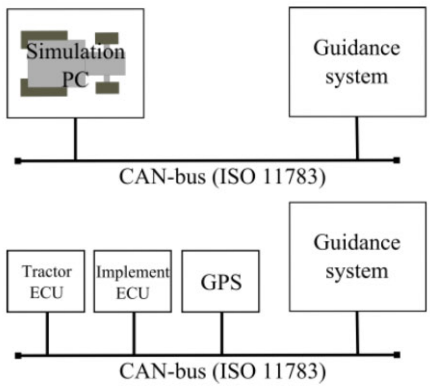

Figure 2. The simulation environment and the real system

3. REALIZATION

3.1 Simulink-model

The simulator was realized completely in Matlab Simulink -environment. The overall structure of the simulator is constructed in modules (Figure 3). There are five different module groups: *Kinematic and dynamic model* (blue), *environment model* (green), *error models* (red), *interface* (yellow) and *auxiliary* (gray).

The measurement information flows from the environment model to the kinematic and dynamic models and from there to the error models and finally with added noise to the external interface. Also, the control information flows from the interface modules to the kinematic and dynamic model.

The environment model is basically a map, where different conditions in the field are described. The condition vector can be basically anything, which is required in kinematic and dynamic models or GPS-noise model. Basically, this means the field conditions and available satellite configuration.

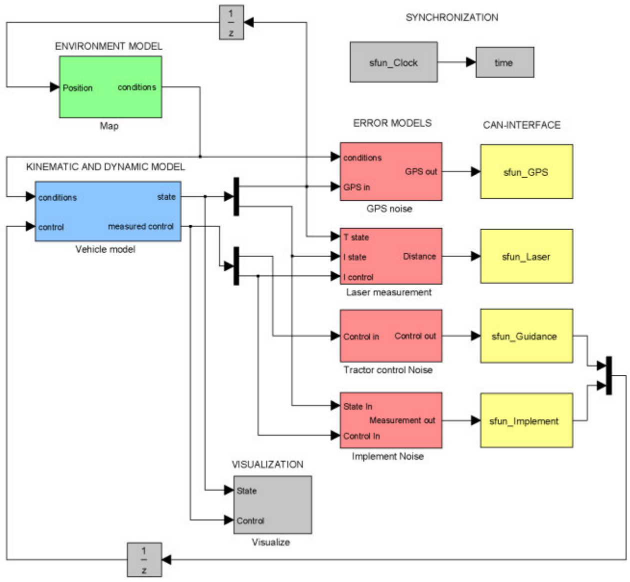

Figure 3. The overall structure of the simulator in Matlab Simulink - environment.

The kinematic and dynamic model is also modular. It contains separate models for the tractor and for the trailer. The models for the tractor and for the trailer are further separated to the actuator dynamic models and system kinematic models. By this way, it is easy to change the controlled system without major modifications to the simulator itself.

The error models are separated to *GPS-noise*, *Laser measurement, Tractor control noise* and *Implement noise* modules. The GPS-noise model is an important part of the simulator and therefore discussed separately in the next subchapter. Laser measurement is local auxiliary position measurement, which was used to track the previous driving line (Backman et al. 2009). This is case-specific and therefore omitted here. The Tractor control noise and the Implement noise modules include the added noise of the tractor and that of the implement measurements. The noise intensity is identified from the real system and modelled as a white noise with the same intensity in the simulator measurements.

The interface modules are *GPS, Laser, Guidance* and *Implement* modules. These represent different physical devices in the real system. The measurements are packed in the CAN-messages according to ISO 11783 specifications. Also control messages from the CAN-bus are read and transferred to Simulink. These modules are realized with a C-code and compiled as S-functions in Matlab.

The auxiliary modules are used to control and visualize the execution of the simulator. Because the simulator is connected to the real guidance device, the simulation is updated according to a real-time clock. Also the movement of the simulated system is visualized in real time.

3.2 Realization of GPS-noise model

The amount of SVs was selected as a basis for the noise model (Figure 4). The effect of poor DOP was included into the daily variation equations (skyplot and positioning error). Error dynamics are characteristic for each receiver type.

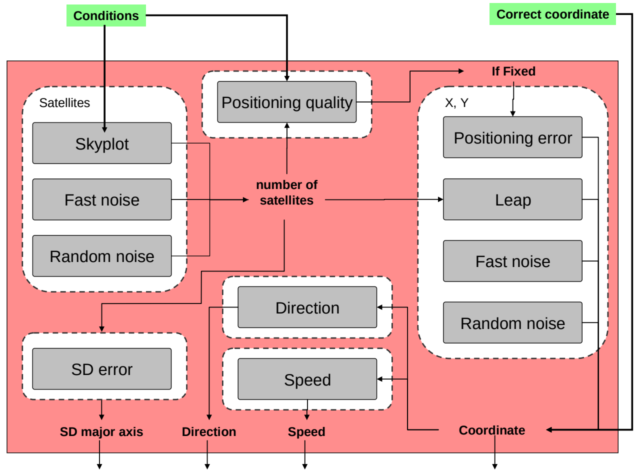

Figure 4. The structure of the GPS-noise model

Environment model gives correct coordinates, the level of obstructions for the satellites and the correction status information (Figure 4).

Skyplot represents the daily variation in the number of satellites. It was constructed from the 24 h measurements so that the rapid changes lasting less than 5 seconds were removed from the data (0.64%) and an equation was fitted to it with Matlab's Identification Toolbox. If requested, the level of obstruction decreased the amount of SVs. Best fitting model was a discrete-time polynomial in the delay operator q^{-1}:

$$A(q) = 1 - 0.9837q^{-1} - 0.004885q^{-2} - 0.0115q^{-3} + 0.002606q^{-4}, \quad (4)$$

Fast noise for the satellite amount was based on the dynamic tests so that the effect that comes from the movement could be captured. The results of the 24 h tests were removed from the dynamic test results. The fast noise drops out only one SV at the time. The time of the effect was determined by first summarizing the drop out times from the data and then randomly selecting one.

Finally the random noise was added to the number of satellites. It temporally removes one SV with a random 0.64% occurrence.

The error models for the coordinates X and Y, variables direction, speed and a standard deviation of semi-major axis of error ellipse were then identified. In addition to the inputted absolute GPS coordinates, the position error equation generates an error (Figure 4). The positioning error equation was generated similarly to the skyplot generation. Independent equations were constructed for the autonomous and HP-corrected messages. For the HP positioning error model, errors measured in the dynamic tests were exploited as a source data. First a leap equation effect (which is presented in the next paragraph) was removed from the data.

With the static 24 h tests, there was not found any significant errors or drifting in the HP data. State-space models were constructed for the HP positioning errors for the coordinate values. Numerical values and equations for the Y-error are presented in Equation 5, where *x(t)* is the state vector of the noise model, *e(t)* and *v(t)* are white noise with variance 1 and *y(t)* is the error in the position measurement. The resolution was 1 mm.

$$x(t+1)=\begin{bmatrix} 0.997 & -0.036 & 0.018 & -0.059 \\ -0.014 & -0.458 & -0.900 & -0.144 \\ -0.001 & 0.755 & -0.307 & -0.578 \\ 0.013 & 0.020 & -0.318 & -0.113 \end{bmatrix} x(t) + \begin{bmatrix} 0.072 \\ 0.150 \\ 0.182 \\ -0.302 \end{bmatrix} e(t), \quad (5)$$
$$y(t)=\begin{bmatrix} 13.502 & -0.063 & -0.129 \end{bmatrix} x(t)+v(t)$$

As the changes in the amount of satellites were observed to correlate with the rapid error changes, a leap equation was constructed. If the amount of satellites decreases, the leap equation adds an error. This error fades within the time identified in the 24 h tests. With Y-error, leaps in the elevation data found to be 1-5 cm lasting 0.5-2 seconds.

The fast noise was then constructed. Rapid changes that were filtered from the positioning error were used to determine the fast noise and the occurrence was then randomized. Finally a random noise was added. The random noise was based on the white noise of the source data. The sign of the random values was kept constant for a random time period to bring a small detail drifting effect. Figure 5 shows the generated error by each component for the Y-axis.

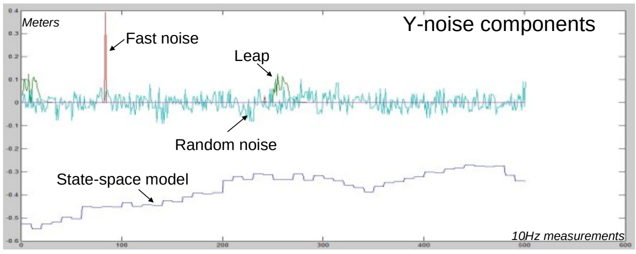

Figure 5.Y-axle errors caused by different components.

Direction and speed were calculated from the noised coordinates. The number of satellites was an input for a state-space model for the semi-major axis of the error ellipse.

Finally a delay was added for each of the component. The delays for the coordinates were one measurement and 3 measurements for the other components.

4. RESULTS AND DISCUSSION

The simulator environment was successful in the sense of that it is full replicate of the real vehicle. Physically, the same navigation equipment can be tested with both the simulator and the real vehicle. With the simulator, all internal data can be recorded and analyzed afterwards.

It is very hard to show that the simulated vehicle and measurements behaves equally to the real vehicle because of the random nature of many internal factors. There is no sense to analyze all measurements of the test drives and corresponding simulations numerically, because the disturbance conditions can be different. However, it can be shown that the simulator behaves similarly to real world. In many cases this is sufficient. In this case, the purpose of the simulator is to validate the correctness of the developed navigation algorithm and the stability of the estimation and control. For the purpose, a simulator worked well (Backman et al. 2010).

4.1 Kinematic behaviour

In the current state, the simulator has only the kinematic model of the vehicle and the trailer. The dynamics of the actuators are modelled, but some important properties like slipping is not modelled realistically in the simulator. That is the most important reason why the kinematic behaviour in the simulator is not equal to the real world. By setting constant slipping factors 0.75 and 0.9 to the front wheel steering angle and to the speed respectively, the simulated trajectory corresponds to the real one when using same control inputs in simulation that was used in real test drive (Figure 6). The driving speed was 8 km/h and the tractor was guided with automatic steering system in a real test drive. The real trajectory was measured by RTK-GPS with 2 cm accuracy. Controls were recorded from CAN network during test drive and later fed to the simulator. It is noticeable that these slipping constants (0.75 and 0.9) are not identified from the same data as is used in the simulation. However, it is important that the data used to identify these constants is collected from the same field conditions.

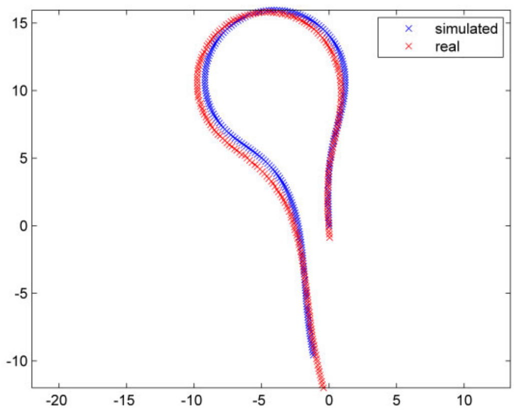

Figure 6. The recorded trajectory of the real vehicle and the simulated trajectory with the same control values.

4.2 GPS-noise

For the corrected GPS data, the noise is very random since the correction method evens the effect from different sources. Correction signal dropouts and huge skyplot changes are key roles in dynamic positioning.

The simulation result gave a 12.9 cm SD and 33 cm mean error for the Y-axis, while the SD of the source data was 12.1 cm and the mean was 63 cm. Figure 7 shows a short driven path which was collected with RTK and HP systems. The simulated data was added on top of the RTK data. From the start the accuracy of the both systems was good. After the turning loop, the simulated and the HP data drifted away from the returning driving path.

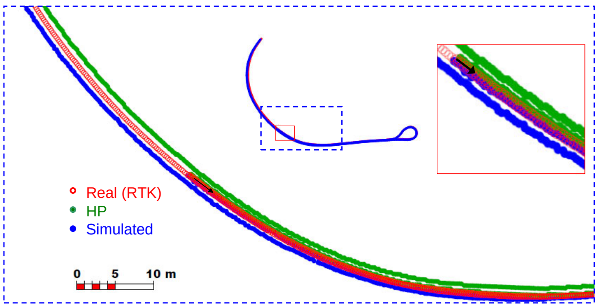

Figure 7. The recorded trajectory of the real vehicle and the simulated trajectory with the same control values.

5. CONCLUSIONS

In this paper, a simulation system for testing positioning and motion control algorithms is introduced. All the measurements of a real system are provided for hardware-in-loop testing. The noise statistics and typical amount of wheel slip were identified from field tests. The simulator provides the measurements in CAN-bus (ISO 11783 standard) and the commands to the steering valve are also transmitted via the bus. The CAN-bus is the only link between the guidance system under test and the simulation environment. In addition, the simulation environment contains a graphical front end, where the trajectories of the vehicle can be illustrated and analyzed. An error model for the GPS was been identified. Position measurements and the related noise range statistics was presented. The simulation environment was successfully tested in connection with nonlinear model predictive control algorithms.

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