Master-Slave System Design for Tractor Field-Testing

Audrey Guillet[1]
[1]*AGCO, 41 avenue Blaise Pascal 60026 Beauvais, France*
audrey.guillet@agcocorp.com

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Abstract: The design process of new tractors includes extensive tests of all functions in real-life conditions. To increase the validations, a new system has been designed. This system is embedded in a tractor and permits to automate this one in order to follow autonomously the trajectory of a master, human-driven, tractor and apply commands from this latter and test cases scenarios. The first tractor's driver supervises the behaviour of the autonomous follower tractor and defines the mission objectives. The safety of the system has been considered both by systemic procedures to inform the supervisor of the working state of the application and apply stopping protocols in case of failure, and by external procedures for out-of-the-loop emergency stopping.

1 INTRODUCTION

Nowadays, modern tractors are technological products offering a lot of advance functions which are more and more electronically controlled. Each and every one of these functions needs to be tested and validated in order to guarantee optimal performances to the client in its daily use of the machine.

These functions (transmission, PTO, hitch…) are validated in their performances (in all modes of use), in their interaction with the other functions, as well as in durability in a wide range of real-life conditions. As a result, this validation process is time and resource consuming. In order to improve validation productivity, a new system has been designed to make a tractor autonomous under human supervision.

This work is included in a global framework about the future of agricultural vehicles, studied by a many industrials and institutions (Blackmore, 2005) (Berducat, 2009). Agricultural work indeed presents specific conditions about the environment (off-road context), the machine architectures (powerful vehicles carrying an implement) as well as the performances expected. In this context, the input of electronic is a global trend started in the 1960s that has permitted to develop more precise control of the functions (engine speed for the PTO for instance), and the development of new functions. Now, with development of automation, the focus is set on the control of the driving of the machines (Edan, Han, & Kondo, 2009) (Mousazadeh, 2013). The path of the vehicle in the field consist usually in covering all the field area in successive working lines with the fewest overlapping or missing spots due to positioning errors. Taking into account these specifications, industrials have developed auto-guidance systems now integrated in the tractors (Heege, 2013) (Massey Ferguson). These systems mainly rely on GPS positioning sensors to provide absolute positioning with a precision ranging from sub-metre to a few centimetres pending on the potential correction system (EGNOS, RTK…). The control of the steering angle permits then to position the tractor along the desired line during working phases while transient phases (during headland) are not handled.

On another hand, tractors are usually used as machines carrying and powering an implement, this latter being the one effectively performing the working action. The development of the ISOBUS standard now permits to have a common framework for the communication and interface between tractors and implements (ISO, 2007). This makes the tuning of implement parameters from the tractor and feedback of data a common process.

The system presented in this paper aims to integrate both aspects of the tractor use in order to make a test platform capable of driving the tractor and sending controls to the implement in order to test the standard functions of the tractors. The designed system is adaptable to commercial on the market Massey Ferguson tractors; it does not modify the architecture (mechanics and software), only add a software layer that interacts with the tractor as a virtual driver.

Dealing with autonomy, safety procedures have to be thoroughly taken into consideration. To design entirely autonomous system, a complete understanding of the environment must be developed through different sensors to guarantee that any event occurring is correctly detected and interpreted, and that the system can handle it and react in a safe way. This usually implies the use of numerous and expensive sensors (lasers, cameras…) with important computation times for scene understanding in real-time (see for instance (Hussein, 2016) (Manduchi, 2005)). The system presented in this paper has few sensors; it is designed for semi-autonomy or shared autonomy, with human kept in the loop. In order to have good performances and a safe running of the application, capabilities and limits of the system should be clearly identified so that allocation of tasks between the human supervisor and the autonomous system are clearly defined.

The definition of the system, its framework of use and the role of the supervisor in safety protocols are presented in the second part of the paper. The third part is dedicated to the presentation of the applications carried out. This system has been tested in field with different tractors and is also applied to in-site endurance testing for a couple of tractors running on a circular track with bumps. The automation of a tractor driving let the test supervisor focus on the evaluation of the test, analysing data in real-time and evaluating the behaviour of the tractor.

2 SYSTEM DEFINITION

Automation of some working operations performed by a tractor becomes possible considering the sensors embedded, the electromechanical actuators allowing external control and on-board computation capabilities in real-time. Nevertheless, the capabilities of such automated system needs to be precisely evaluated in order to define its context of use and the role of the human supervisor in the loop: what are its actions during the autonomous part and when does he have to take back control of the system? This should permit to ensure not only the good fulfilment of the operation but above all the safety and security of the machines and the environment.

2.1 Positioning safety

To do so, a first step is to set evolution zones. These areas define the actions allowed. For instance, total automation will be permitted in the working zone (in the field) while partial automation and/or special human supervision will be advised in a warning zone (in the border), and no automation should be possible outside these zones (forbidden zone), as illustrated in Figure 1. The limits of these zones can be marked out either physically by a mechanical link preventing or informing of its crossing, or in the system software. In this case, the border are defined off-line as limit positions and the system must verify in real-time its position provided by its sensors lies inside the borders. A failure of the sensors should be identifiable and handled as the position integrity then cannot be guaranteed.

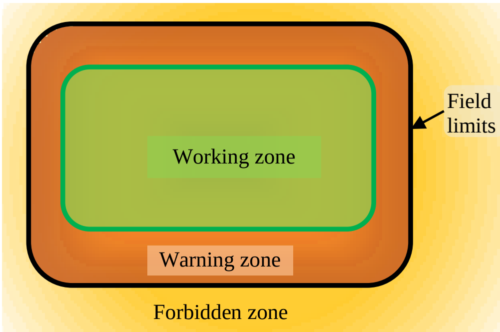

Figure 1. Evolution zones in the field.

In the system we designed, tractors are equipped with RTK-GPS providing absolute positioning with 2-cm accuracy. The borders are then defined as a set of GPS positions recorded beforehand and describing a closed (convex or non-convex) area. The control of data reception rate permits to detect loss of positioning integrity.

2.2 Autonomous control

Within the borders, the tractor can be automated.

In the scenarios considered, the working setup is made of two tractors. The first one, called the *master*, is human-driven while the second one, known as the *slave*, is the autonomous one which goal is to follow the path of the master. The setup of the system is depicted in Figure 2.

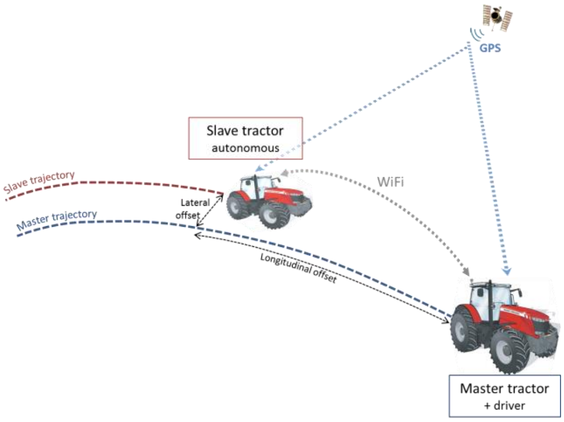

Figure 2. Master-Slave system description.

The system, embedded in the autonomous tractor, computes actuators commands to drive the tractor and fulfil the objective. To do so, it needs to be fed with real-time data. First, it gets its position from the GPS mounted on the tractor and checks its integrity.

Positioning and velocity data from the master vehicle are sent over a wireless connection. Similarly to its own positioning data, the integrity of master data received by the slave is verified.

Other proprioceptive data from the slave's state are also collected by the system over the CAN bus of the tractor. All data integrity is verified in order to guarantee the values used by the system reflect the actual working state of the machines. The autonomous control of the slave tractor is also subjected to the verification that no failure or error is identified on the vehicle.

When all these conditions are satisfied, the system exploits the collected data for the autonomous control. Given the application objective, the current position of the master is recorded and added to the reference trajectory to track. Then, using its localisation data the system derives the slave's positioning distance to the trajectory. This relative position is compared to a desired position, tuned by the supervisor as a set of desired offsets to the master tractor. These tuneable parameters allow the supervisor (usually the driver of the master tractor) to define and adjust on-line the configuration; pending on the application, the slave will be lined up with the master, shifted of one implement width or even ahead of the master so that the driver can visually inspect the performance of the slave work.

The control laws will then derive commands, a velocity command and a steering command, regulating the actual positioning of the tractor in order to make it converge to its desired position and hold it during the path tracking, whatever the trajectory shape (straight lines or curves).

These commands are applied to the tractor, if they do not exceed the mechanical limitations of the actuators or software limitations set in the warning zone (in order to stay away from the forbidden area).

Finally, data of the system are communicated to the master over the wireless connection for display on the man-machine interface in the master's cabin.

This process for the control of the autonomous master's driving is summarized in Figure 3.

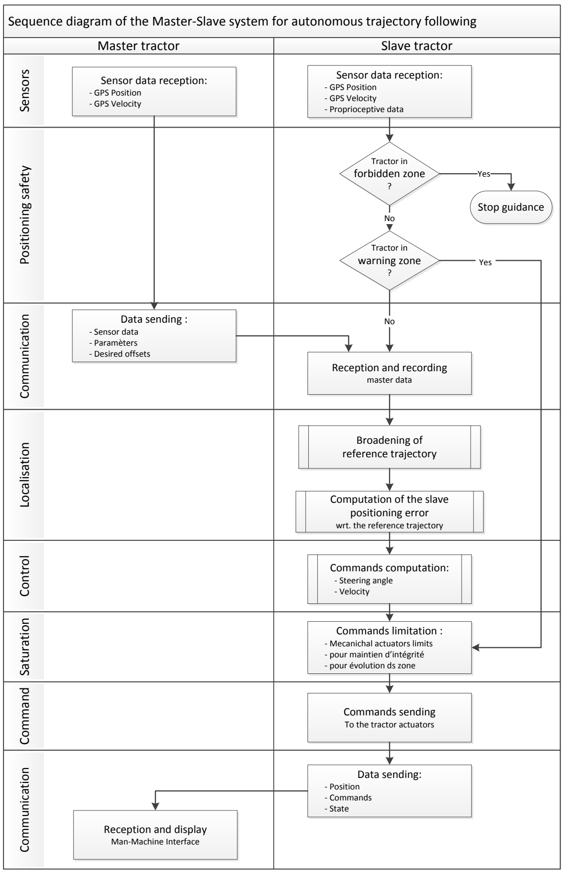

Figure 3. Sequence diagram of the control system.

2.3 Additional safety procedures

The human supervisor of the application oversees the smooth running of the system. He starts and stops the autonomous following and adjusts the configuration parameters (desired distances) via the Man-Machine interface set in the master tractor cabin. On this terminal are also displayed data from the system, its working state and performances.

Besides these systemic actions, other manual safety devices are provided with independent out-of-the-loop emergency stops. These emergency switches must permit to stop the autonomous tractor in any evolution condition. To be always reachable, two types of devices are set up. One remote control is always carried out by the driver. It can send an emergency signal to a receptor over an independent radio link. Another couple of wired switches are added on the wings of the slave tractor. They permit to keep a physical stopping connection which can be triggered in last resort by an operator outside the tractor.

3 APPLICATIONS

This system has been applied to two aspects of the validation process.

This system of automation of a slave tractor with respect to a master vehicle has been implemented to two validation works. The design of new tractor indeed requires different validation steps, from the tests of the functional developments to durability verification. Among this process, two stages require driving the tractors over long periods to check their behaviour consistency and are therefore opportune for automation.

3.1 Master-slave path tracking in field

New tractors designed are extensively tested in their real-life conditions of use: in fields using a wide range of implements with different weather conditions. These tests entail functional and durability validation of the tractor behaviour (itself as well as its interaction with the implements). They consist of long runs of driving, controlling the tests conditions, tuning the parameters and evaluating the resulting behaviour. With the system presented above implemented on a slave tractor referencing to a master one, the driving part of the test is handled autonomously by the system. It lets the human supervisor change the parameters of the test and communicates back enough data so that the supervisor can evaluate the performances of the run.

It has been applied to test runs for durability validation of tractor parts and software subject to off-road conditions: vibrations, dust, mud… The test field is depicted in Figure 4. It is an 8 hectare agroforestry plot. It is lined with trees marking out working lines 30-meter wide and 300-meter long. The limit of the evolution zone (exterior border of the 3 working lines defined) is recorded off-line during a previous drive. The tree lines position is also recorded and integrated in the system as static obstacles. A safety zone around these known obstacles is defined and the distance of the slave position to the trees is calculated in real-time. Similarly to the in-field positioning verification, if the slave enters the tree safety bubble, it stops and the system is disconnected.

Multiple validation runs have been performed with the driver of the master tractor supervising the proper functioning of the autonomous slave tractor, as illustrated in Figure 5. During each run, several kilometres were covered and the supervisor was modifying on-line the formation configuration so that the slave came back behind the master for the headland half-turn, in the warning zones, before setting back the working configuration. Additionally, the slave driver was setting the slave ahead of the master at times to make complementary visual checking of the tractor implement from behind.

Figure 4. Map of the test field with its evolution zones.

Figure 5. Master (right) and slave (left) tractors in a side-by-side configuration.

3.2 Autonomous bump track test

A circular track, tarred and equipped with small bumps, is used to validate the tractors and implements parts breaking strength over deformation and shocks during repetitive bump crossings, as illustrated in Figure 6. The tractors to validate are equipped with sensors and driven on this track during a few hundreds of hours.

Figure 6. The circular track with bumps.

During the tests, two tractors are running autonomously on the track of 32 metres in diameter. The track is physically limited with fences on which emergency stop buttons are put. The tractors and implements are also fastened with cables to the track centre to make sure that they stay on the track lane. The run is started by an operator outside the track on a dedicated terminal that communicates with the tractors over the wireless connection. Both tractors steering angle is mechanically set through the steering wheel according to the track curvature. On the master tractor, the travel speed is set as constant and defined by the test parameters. A light version of the system presented above is embedded on the slave tractor for the control of its velocity. On the track centre, an angle sensor gives data about the tractors positions and the system velocity command is derived to maintain the slave tractor opposite to the master, at a 180° angle. Systemic safety procedures are added on both tractors so that they do not collide on the track. Indeed, if the slave tractor stops, the master must also stop so as not to catch up with it (and vice versa). This is implemented through the interpretation of the angle between the vehicles, known by both tractors. Consistent behaviours are planned to derive tractor commands when they digress from their desired respective positions, with a complete stop of both tractors implemented if they become too close from each other.

These specific safety procedures added to the master-slave system with an autonomous master have permitted to carry out autonomous driving of two tractors on the circular bump track.

4 CONCLUSIONS

The validation process of new tractors applied in Massey Ferguson aim to verify the behaviour of the machines in a wide range of real-life conditions of use and durability, in order to guarantee the best product quality to the clients. These in-field tests are therefore time-consuming and a new dedicated system has been designed to delegate the driving part of the test to the autonomous system, so that the human supervisor can be focused on the interpretation of the data and the resulting behaviour in real-time. In details, the presented system works in a master-slave framework. The system is implemented in a slave tractor and drives it autonomously to follow the trajectory of a reference master vehicle.

Regarding the safety of the application, field limits are defined in the system so that the autonomous tractor cannot get out of the desired evolution zone. Position integrity and sensor failures are also checked to guarantee the proper functioning. In case of failure, the system and the tractor stop. Static obstacles, such as trees, can be integrated in the system to define a safety zone around it. As for dynamic obstacles, the few sensors used cannot give a good detection so their processing (should the slave tractor stop or is it ok to continue) is left to the supervisor.

Indeed, the supervisor has different controls on the system. Mainly, a Man-Machine Interface permits to start and stop the system, as well as adjust test parameters (slave desired position…) and get real time data about the functioning of the system. In case of danger, the supervisor also has an independent emergency stop remote control and additional wired emergency switch are also placed on the wings of the slave tractor.

This master-slave system has been applied to in-field validation tests were the autonomous slave tractor was successfully following a human-driven slave during runs of several kilometres along a trajectory of any shape with on-line modification of the configuration. It has also been implemented in a related application on a circular bump track on which two tractors are running autonomously to test durability over deformations and shocks. The system has been adapted to guarantee no collision between the tractors can occur and it has permitted to double the validation capacity of the track.

Future work will focus on a more advanced management of the implement in order to control multiple functions in synch, autonomously according to set points or triggered by the supervisor. Integration of other sensors such as cameras or lasers will also be studied in order to get a better understanding of the environment in real time.

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