ENVIRONMENT MAPPING ENABLING SAFETY AND USABILITY OF AN ELECTRONIC TOW BAR

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Abstract. Cost efficiency and productivity as well as drivers comfort and usability are significant innovation drivers for agricultural machinery. The proposed electronic tow bar system for tillage processes consists of two vehicles, coupled by wireless data connection. An unmanned slave tractor follows a master tractor with a position dependent lateral and longitudinal offset. Operating two tractors with one driver only, increases productivity and improves the capacity load due to higher flexibility in fleet management. In return, the usability and safety of the tow bar becomes a major concern, which is addressed by an elaborate safety concept enabled by sensor based obstacle detection and mapping. Web-based geo-information, are used to support proactive path planning.This paper presents a solution to achieve both, safety and usability, for a complex platoon system. The interaction of the operator with the local and global obstacle map is designed to meet the requirements of both target functions.

Keywords: Platoon, safety, usability, mapping, environment sensors, electronic tow bar, obstacle detection, geo-information

1 Introduction

Today’s agriculture underlies a long term structural change. Driven by the international aggregation of agricultural markets since the 1950s, cost pressure increases and the consolidation of farms and fields in central Europe improves the economies of scale [1]. In compliance with the needs of today’s farming, agricultural machinery manufactures place increasingly powerful machines equipped with various electronic assistance systems on the market [2]. While the engine power of the machinery merely addresses productivity and thereby cost efficiency, electronic assistance systems can be designed, not only to target productivity and machine efficiency [3,4], but as well to improve safety [5], the usability of a rather complex control system, the driver’s comfort and to support the overall farm management [6].

The electronic tow bar features an assistance system, facilitating the operation of several machines by a single Driver thus increasing efficiency of scarce human resources.

1.1 Tow Bar System for Semi-Autonomous Tillage

In a precedent research project, the functional concept of an electronic tow bar has been developed and validated [7]. The electronic tow bar comprises an unmanned slave tractor following a manned master tractor with a predefined longitudinal and lateral offset. The parameter settings of the master tractor are continuously being transmitted to the slave by means of a wireless connection to be copied when reaching the corresponding master track position. A set of four different drive modes has been defined to guide the slave agent in dependence of the master GNSS track through a generic tillage process. Due to the software architecture, the system is restricted to a pair of two identical tractors using identical implements.

The improved tow bar system (EDAUG) as presented in this paper is based on the above concept. The objective of EDAUG is to add an appropriate safety concept maintaining optimal usability. Environment sensors are applied to gather obstacle information in a close range surrounding the slave vehicle to prevent collisions, while geo-information are downloaded in real-time via a mobile internet access on the slave for proactive calculation of obstacle avoidance paths.

Enhanced assistance systems for agricultural machines usually comprise a considerable set of parameters that are configurable via a human machine interface (HMI). For the platoon system, the complete interaction between operator and slave tractor during operation needs to be embedded into the HMI menu. Hence, the development of an easy to use, intuitive HMI is an essential part of the project.

1.2 Safety in Agricultural Machines

During the development process of a safety relevant embedded electronic assistance system several standards and methods need to be met to ensure functional safety of the system. The effort for a series development exceeds the resources and capabilities of a research project. Still, a safety concept may be proven suitable by means suggested in these standards.

2 Functional Safety

The IEC defines functional safety in accordance with IEC 61508 and ISO 25119 as “[…] the detection of a potentially dangerous condition resulting in the activation of a protective or corrective device or mechanism to prevent hazardous events arising or providing mitigation to reduce the fight consequence of the hazardous event.” [8]. Hence, a safety concept is crucial to an electronic tow bar system, keeping or leading the system into a safe state in any critical situation at runtime. ISO 25119 demands the calculation of agricultural performance levels (AgPL) based on a risk analysis for all safety functions of the E/E/EP system to deduce requirements for the system architecture, the components and for the development and validation process.

2.1 Functional safety concept for an agricultural platoon system

Safety is a matter of the interaction between a system and its environment. Hence, the safety requirements for a tow bar system considerably depend on the operation scenarios. Road traffic is characterized by a high density of dynamic obstacles and static obstacles to be passed at close distances. However, the operation of the tractor platoon is restricted to agricultural fields, characterized by a low and usually previously known number of static obstacles. Additionally sporadic occurrences of dynamic obstacles like animals or persons must be considered. Within a dynamic speed dependent safety zone, determined by the stop distance of the tractor and implement combination and by the maximum expected approach speed of an obstacle, obstacles need to be reliably detected by environment sensors. As the postulation for the platoon system is not to harm by action [9], the shape and range of this safety zone is conform, if in a worst case scenario, the elapsed time between obstacle detection event and standstill of the vehicle does not exceed the time to collision. The most critical scenarios appear, if the platoon either moves alongside or orthogonally approaches a field boundary next to a public road. Hence, a high AgPL needs to be achieved for all safety functions that prevent the slave agent to leave the field boundary, since the simplification of the considered scenarios offside of road traffic, are no longer valid. A safety corridor within and alongside the field boundary can be applied to monitor this constraint based on the GNSS position. As a consequence, the precision of the field boundary coordinates and of the GNSS measurement becomes part of a relevant safety function. Due to the absence of fast moving obstacles, the immediate reduction off drive speed to zero and the immediate arrest of all linear and rotational actuators of the tractor and all mounted implements is, as long as all system modules are faultless, a suitable and sufficient response to any critical scenario. This state offers the possibility to maintain a running platoon system until the hazardous scenario clears and operation can be continued or a malfunction forces the system into a further safety level. In case of any component or communication malfunction, an immediate engine shutdown on the slave coherent with the application of the stop brake is supposed to prevent any harm against persons, environment or the machine. After a shutdown, the system needs to be restarted and initialized.

According to the above, a safety concept consisting of three safety levels with the following set of validity conditions unfolds.

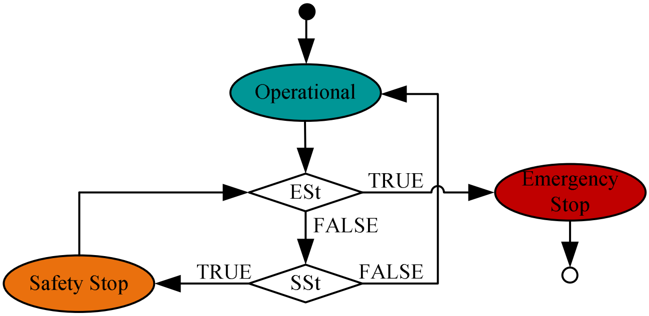

Fig. 1. Decision process of the safety concept of the semi-autonomous platoon.

Validity conditions:
C1 = All subsystems and components work properly
C2 = Internal data communication is not distracted,
C3 = External data communication is not distracted,
C4 = Sufficient quality of absolute position measurement,
C5 = Sufficient signal quality of environment sensors on slave,
C6 = Absolut and relative vehicle positions in range,
C7 = Valid path existent,
C8 = No risk of collision detected

Safety level condition composition:
Operational: Op = AND(C1…C7)
Safety Stop: SSt = AND(AND(C1…C4),OR(NOT(C5…C7)))
Emergency Stop: ESt = OR(NOT(C1…C4))

The composition of the safety level conditions for the safety levels is unambiguousness. During each program cycle the above decision process (Fig. 1) is passed to determine the safety level for the following time step.

2.2 State Model

The safety concept is being transferred into software code, via a state model. A state model consists of system states, connected by transitions.

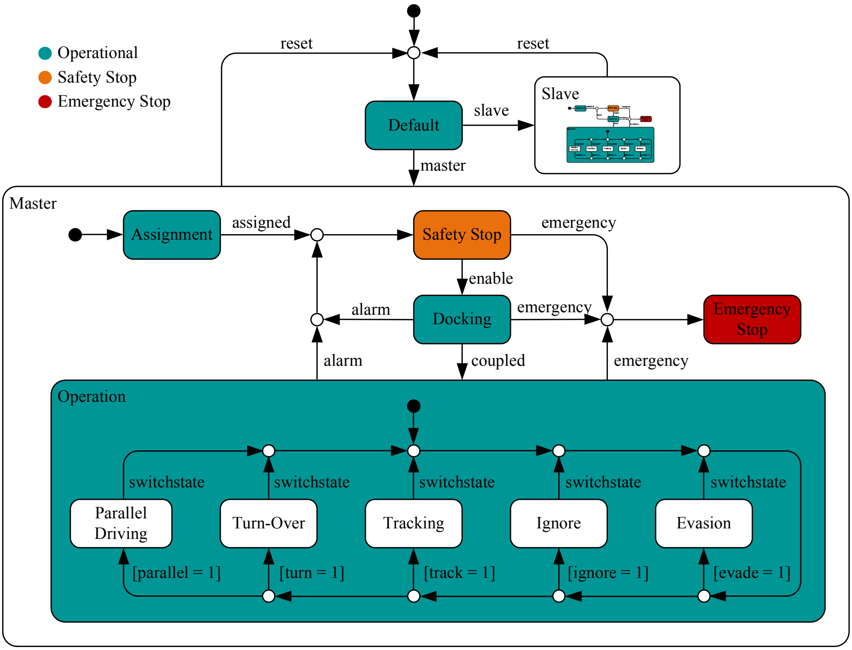

Fig. 2. State model of the platoon system.

If a transition condition becomes true, the system state changes accordingly. Each state contains a set of functions being executed as long as the state is active.

In order to develop a safe system behavior, the anticipation of all safety critical scenarios that may appear at runtime and the determination of critical thresholds for the related diagnoses parameters as transition conditions are essential. The behavior of the tow bar system is shown in the above state model (Fig. 2). The fill colors of the boxes correlate with the three levels of the safety concept (Fig. 1).

Table 1. Functions in Master/Slave sub-states.

State	Tractor Role	
	Master	Slave
Assignment	- monitor hardware alive - send “alive” with system state - send initialization code - receive GNSS position	- monitor hardware alive - send “alive” with system state - receive GNSS position - wait for initialization code - verify initialization code
Safety Stop	- monitor hardware alive - send “alive” with system state - receive GNSS position - monitor wireless slave alive - monitor error codes - send master parameter set - send master position - wait for operator input “enable”	- monitor hardware alive - send “alive” with system state - receive GNSS position - monitor wireless master alive - monitor error codes - send slave parameter set - send slave position - short range obstacle surveillance - download geo-information - wait or “enable” message
Docking	- monitor hardware alive - send “alive” with system state - receive GNSS position - monitor wireless slave alive - monitor error codes - send master parameter set - send master position check couple distance	- monitor hardware alive - send “alive” with system state - receive GNSS position - monitor wireless master alive - monitor error codes - send slave parameter set - send slave position - monitor safety distance to master - short range obstacle surveillance - wait for couple message
Operation	- monitor hardware alive - send “alive” with system state - receive GNSS position - monitor wireless slave alive - monitor error codes - send master parameter set - send master position	- monitor hardware alive - send “alive” with system state - receive GNSS position - monitor wireless master alive - monitor error codes - send slave parameter set - send slave position - path planning - monitor safety distance to master - short range obstacle surveillance
Emergency Stop	- send wireless “emergency” message - send “alive” with system state - reset to default state	- send wireless “emergency” message - send “alive” with system state - shut down engine

The system starts up in a default state, in which the tractor control interface remains passive, waiting for the operator to set the tractor role as master or slave via the HMI. The sub-state architecture of the Master and Slave state as shown in Fig. 2 is identical.

The system state of a master and slave vehicle is synchronized via the wireless connection and can be monitored as a safety function to ensure a consistent state interpretation in the overall system.

The functions to be executed during a certain system state depend on the role as master or slave (Table 1). The “Operation” state incorporates five sub-states featuring the different drive maneuvers. While “Parallel Driving”, “Turn-Over”, “Tracking” and “Ignore” implicate a deterministic predictable path for the slave vehicle, the “Evasion” maneuver implicates a dynamically fitted path, avoiding the mapped obstacles.

2.3 System architecture and data communication

The prototype platoon is being developed at three different locations. Hence, a modular software architecture has been chosen (Table 2).

Table 2. Software modules on master and slave tractor.

Abr.	Description	Master	Slave
EXT	Tractor main ECU – tractor communication interface	X	X
HMI	Human Machine Interface – operator interface	X	X
STM	State Machine – system state decision, wireless/CAN gateway	X	X
NAV	Navigation – path planning, GNSS reception	X	X
ENS	Environment Sensors – dynamic obstacle detection, Safety Zone		X
GIS	Geo-Information – download of static obstacles		X

Each Software module sends a cyclic alive message (see “hardware alive” in Table 1) containing the acknowledgment of the current system state set by the STM module, a specific error code and other useful information. The alive messages are monitored by the STM module to ensure proper functionality. The STM alive message however is monitored by the EXT, switching directly into emergency stop in case of an interruption.

3 Obstacle mapping - Safety vs. Usability

The presented platoon system has access to two different sources for obstacle information. Static obstacle coordinates as well as field boundaries can be obtained from a customized web-server via a mobile internet access on the slave tractor. Previous knowledge of static obstacles is essential to a proactive calculation of efficient obstacles avoidance maneuvers at maximized speed. If the precision of field boundaries is guaranteed, a field boundary enables the safety function not to leave the restricted operation area as described in chapter 2.1. The environment sensors monitor the safety zone to prevent a collision. Obstacles detected by environment sensors are assumed to be potentially moving and therefore called dynamic obstacles. The chosen sensor concept comprises two 2D-laser scanners for distant obstacle detection ahead of the slave tractor and four 3D-ToF cameras for close surround viewing obstacle detection. One laser scanner is mounted on an active 3D levelling fixture, scanning the outer boundary of the safety zone. The 3D fixture adjusts the pitch angle to meet the speed dependency of the outer boundary, while the roll angle is adjusted in case of a changing lateral slope ahead of the slave. The other scanner is adjusted to measure straight horizontally to detect distant obstacles beyond the safety zone for proactive path planning. This measurement is not part of a safety function.

More sophisticated sensor fusion has been developed in the QUAD-AV project [10]. Here, the objective however is a sophisticated integration of static and dynamic obstacle information into the safety and usability concept of the tow bar system.

3.1 Environment Mapping

To communicate obstacle information between the master HMI and the software modules on the slave, a 16 bit identifier is assigned to each obstacle. While the static GIS-obstacles are administrated in a list, dynamic obstacles are administrated using a local map centered at the position of the slave. The local map features an orthogonal histogram grid containing a detection event counter for each square and the assigned identifier. Each sensor provides data to an obstacle detection algorithm. The map operates as data fusion layer on object level. Objects are not further classified. If a detected obstacle overlaps a previously traced object, it copies the existent ID. Otherwise a new ID is assigned. Once an obstacle ID has been assigned, state changes of the related obstacle are recorded in an obstacle event protocol and communicated to all relevant software modules. The event protocol on both tractors is updated via the wireless connection. A set of events is coded within the event protocol (Table 3). After an obstacle has vanished from the field of view, the ID is released again, which is communicated by sending a zero as event code. A time stamp supports retracing the system behavior and debugging.

The default response to an obstacle detected within the planned path of the slave, is to approach until the obstacle enters the safety zone and then switch into safety stop. The safety concept requires an operator interaction to trigger a state change into “Evasion” mode navigating along the suggested avoidance path or to maintain the current drive mode ignoring the obstacle taking full responsibility, if overrunning causes damage.

Table 3. Obstacle Events.

Bit	Obstacle Event	Module
0	Obstacle detected by ENS	ENS (Slave)
1	Obstacle detected by GIS	GIS (Slave)
2	Obstacle ignored by operator	HMI (Master)
3	Evasion maneuver for this obstacle approved by operator	HMI (Master)
4	Obstacle vanished from ENS tracking before passing	ENS (Slave)
5	Evasion maneuver started	NAV (Slave)
6	Obstacle has been passed	GIS/ENS (Slave)
7	Obstacle has caused Safety Stop	ENS (Slave)

This preserves the desired conservative safety gained by the obstacle detection. Still, a manual overwriting of the automatic system behavior is permitted for usability.

4 Summary and Outlook

The presented platoon system innovatively combines a fully automated tractor implement combination, remotely controlled from another vehicle, with a dynamic sensor based obstacle mapping algorithm and static geo-information. The objection of merging safety and usability has been met by the development of a conservative default system behavior, which can be intentionally manipulated by the operator to preserve usability via a flat and intuitive HMI navigation menu.

During the final phase of the project, the concept is validated on a prototype. The robustness and the self-diagnosis capabilities of the obstacle detection algorithm will be validated; latencies for state changes will be measured and the correct layout of the safety zone considering sensor update rates, stopping distances and data communication.

Acknowledgments

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