Operation in Tunnels Construction Works with Autonomous or Tele-operated Trucks

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Abstract— **It is possible to transfer the technological base of autonomous vehicles to other areas. Such is the case of public works and, specifically, tunnels given their particularities. In this regard, this area is characterized by the fact that work is developed in a limited area, in which vehicles should not be registered for using them in public roads and the presence of human beings is restricted or prohibited. In this context, the implementation of autonomous vehicles in public works can provide significant improvements. For this, it is intended to improve the process of material removal from the tunnel by means of an automation and communication kit for heavy public works trucks. Then, the conventional vehicles can be transformed to work autonomously in a coordinated way between them and with other vehicles that operate also autonomously or manually.**

Keywords-autonomous vehicle; public works truck; V2X communications; teleopration; autonomous guidance.

I. INTRODUCTION

Almost all major car manufacturers, as well as other players outside this industry, are involved in the development of vehicles with a certain degree of autonomy, in addition to driver assistance systems, which, in some cases, take advantage of actuators automation. The results suggest that the automotive industry has opted for this type of technology for the not too distant future, although there is still a long way to go [1].

Autonomous driving is not confined to highways. There are several areas where the use of this technology can be applied, and special applications based on this type of vehicles have been implemented over the years. In this way, there are specific applications for off road environments, military missions, rescue, supervision and surveillance, land exploration, agriculture, etc. In general, all these applications share the fact that some tasks should not be made by a human operator due to the exposure to imminent danger or automation could provide a specific service with better benefits.

This paper presents the implementation of the elements for transforming a set of conventional public works trucks for tunnels construction into a set of autonomous vehicles that could operate both automatically or teleoperated from a control site. The main system architecture is shown, and preliminary results are discussed.

Section II includes a review of previous works on this specific field. Section III presents the specifications required for the system operation. Then Section IV shows the technological solution used for each of the elements that involve the system. Finally, Conclusions and current state of the project and future works are commented in Section V.

II. AUTONOMOUS VEHICLES FOR CONSTRUCTION PURPOSES

In addition to public roads transport, autonomous driving has applications in specific structured scenarios looking for a reduction of the presence of the operator. Now we review some of these areas, such as mining and construction [2].

Mining jobs are highly demanding and workers' conditions can be extreme. In this sense, automation has a clear positive impact and has already been undertaken for a long time, to reduce operating costs and risks for operators. For example, fully autonomous mining trucks complete a set of tasks without the intervention of the operator and, instead, are monitored in a remote-control site by the miners to ensure that the trucks are operating efficiently throughout the mine. This solution increases productivity.

Among other examples, we can mention Sandvik, which has been developing loaders and autonomous trucks for mines over the past 20 years. Sandvik has developed vehicles that can automate the entire production cycle. Sandvik tests its vehicles to ensure they are safe and functional in an underground mine in Finland and also works closely with its customers to ensure that product expectations are met. Also, Autonomous Solutions, Inc. offers autonomous solutions for trucks, excavators, etc. Cyngn is another company that proposes autonomous excavators and loaders. Caterpillar is committed to assisting operator technologies that control specific functions of the machine to increase productivity and reduce costs, remote control systems that keep operators away from the cabins and even, in some cases, by totally autonomous trucks. Another example is the use of remotely supervised trucks at the Pilbara iron mines in Australia. 80 Komatsu trucks are used and each one has worked more than 700 additional hours compared to a conventional driven vehicle.

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The negative aspects are the fact that the configuration, operation and maintenance of equipment without a driver is expensive. In addition to the vehicles themselves, there is the additional cost of mapping the mines to operate the vehicles, as well as the installation of a control center.

In the construction field, using robotic systems is a reasonable option in the short term since construction sites are closed to traffic and people. In addition, construction robots can work independently once guidelines are given. One of the main advantages lies in the fact that they offer safer jobs and less exposed to dust or vibration conditions, by managing the operation remotely. Thus, machines can autonomously perform dangerous and repetitive tasks.

However, complex and changing working conditions can reduce the potential benefit, which, together with the inertia of the sector, means that the presence of autonomous tools is still small, but not non-existent.

In October 2017, Built Robotics developed a loader controlled from an iPad that provides the functionality of entering operating parameters and, through satellite positioning and other sensors, it is able to perform the work. In the same year, Volvo introduced the HX2 electric charging vehicle and the LX1 hybrid loader, which provide considerable savings in energy consumption. Volvo also incorporates autonomous capabilities in the L120 excavator and the A25 articulated truck. In the same line, Caterpillar 793F trucks provided an increase of 20% of productivity in comparison with the one driven manually. Komatsu offers the semi-autonomous D61i-23 dozer, while Caterpillar and John Deere work in similar vehicles, which will start being semi-autonomous to evolve towards full automation.

III. System Specifications

The project presented in this paper corresponds to the technological line of transferring the fundamental knowledge acquired for road environments to scenarios in the industrial sector. This project aims to apply the knowledge of vehicle automation, positioning, obstacle detection and communications to a tunnel excavation, more specifically, in the tasks of extracting material from a tunnel to the area of intermediate discharge near its exit. This operation has a series of safety constraints that limit the human presence, and, on the other hand, the operation is very well defined, so it is susceptible for automation. As main challenges, beyond the type of vehicle, quite different from road vehicles, we could highlight the environment detection (considering light and dust), positioning (because of the lack of Global Positioning System (GPS) signal) and collisions avoidance, as well as the automatic and remote management of the points of material loading and unloading, and the synchronized operation of a small group of vehicles working simultaneously.

The project aims to replace conventional vehicles driven manually by autonomous and connected vehicles, also managed from a control center. Specifically, the aim is to automate 3 Volvo A-25 public works trucks (Figure 1), as well as including communication systems and a user interface to guarantee compatibility with other manually driven trucks, so that they can share the workspace and the operation in a coordinated way from a monitoring and control center. The 6x6 Volvo A25 has great capacity and flexibility in mixed and very difficult terrain conditions.

Figure 1. Volvo A-25 public works truck

Excavation of a tunnel is usually executed by means of different machinery such as a front wheel loader, model Volvo L120 or similar. These machines load the material on articulated trucks such as Volvo model A25D. Once arrived at the end of the tunnel or near crossing zones enabled for it, these trucks will turn around so that their cabin is oriented facing the exit of the tunnel. Then, in reverse gear, they will be properly positioned so that the loading machines can pour the material into the truck's box. Once the load is completed, the truck will move to the corresponding dumping area outside the tunnel. The rest of the trucks of the fleet will be returning and/or waiting inside the tunnel, in the areas enabled for it.

This process can be automatized because of its repeatability. To indicate to the trucks the final stopping points, both inside and outside the tunnel, beacons are placed, which allow the operators to easily modify the collection and unloading points.

We can define 5 specific innovations of the project derived from the development of this project:

- Development of a kit for automation of Volvo A-25 trucks, which will equip them with the ability to operate autonomously. The vehicle will maintain its ability to be driven manually and, in addition, will allow autonomous driving. Furthermore, since automation is provided by a removable kit, it can be installed in conventional machinery that is currently working on the construction site so specific machinery is not required.
- Development of a perception system for operation in off-road environments in tunnel construction without positioning information, and under poor light and dust conditions.
- Development of cooperative capacities, so a set of vehicles can work in the same area at the same time in a coordinated manner. To do this, automation will be carried out in three vehicles and communication systems will be incorporated to enable them to exchange information in real time with each other and with the management and monitoring system.
- Development of a management system for monitoring the fleet of autonomous vehicles during

the operation in the excavation of a tunnel in order to control in real time the development of the same.

- Development of a methodology for the automation of public works vehicles so that the results of this project can be extended to other machinery and other machinery manufacturers.

IV. Technological Solution

The technological solution involves 5 main elements:

- Automation kit for transforming a conventional vehicle into a vehicle with autonomous or teleoperated capabilities (Subsections A and B).
- Low-layer control system. This element involves the steering system automation, speed automation and control subsystem, considering all the information and commands provided by sensors and communications (Subsection C).
- Perception and High-level control system. This system includes the information collection (vehicle positioning, obstacles detection and reference element detection) and processing, as well as the guidance system (Subsection D).
- Teleoperator site from which vehicles are supervised and controlled (Subsection E).
- Communications systems for exchanging information between vehicles, and with the control site in order to achieve a coordinated operation when more than one vehicle is involved (Subsection F).

Figure 2 shows a block diagram with the interconnection of these elements, including a new emergency system to stop the vehicle externally in case of failure or incorrect operation.

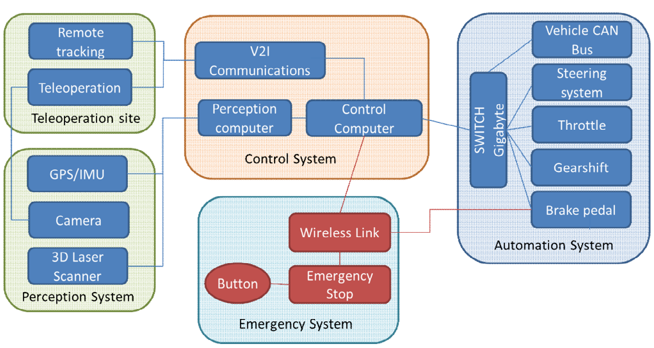

Figure 2. Device for controlling the steering system

A. Steering automation

The Volvo A25 truck has articulated steering, with an exclusive Volvo steering system that is self-compensating hydromechanically and with re-coupling between the rear axle and the steering slide from the steering and tilt valve. The steering system is coupled in parallel with the tilt system, with which it has common hydraulic pumps.

There are two ways to act automatically on the steering system: 1) act directly on the hydraulic cylinders, inserting a bypass on the current hydraulic circuitry with solenoid valves controlled from the computer; 2) attach an actuator on the steering column that is capable of moving the steering wheel, not modifying the pre-existing equipment of the truck.

The second one is chosen. To do this, a motor must be attached to the steering column in such a way that it exerts the same effect that human drivers do when moving the steering wheel. Additionally, an absolute encoder must be added to the steering bar indicating the angle that the steering of the vehicle is turned, in order to be able to close the control loop.

The solution adopted is based on the patent ES 2516568 B2, "Equipment to automatically control the steering system of a vehicle", property of the Technical University of Madrid [3] (Figure 3). It includes the following features [4]:

- The device is independent of the type of vehicle and the type of steering assistance system (electric or hydraulic), including the presence or absence of such assistance, unlike other previous developments that require a specific type.
- The assembly of the device does not imply any permanent modification of the vehicle, nor does it eliminate the steering column.
- Orders through the vehicle internal communications bus are not required for the vehicle control, which allows the use of the device in every type of vehicle.
- The coupling or decoupling of the autonomous mode is controlled automatically and not manually, so it could be carried out while the vehicle is moving and instantaneously, using the same microprocessor that controls the rotation angle of the steering wheel.
- The driver does not lose control of the vehicle.
- It is not visible and does not interfere with the driving task.
- The device is removable.

Figure 3. Device for controlling the steering system

With the solution used, in normal driving, the driver acts on the steering wheel, the electric motor is stopped and an electromagnet, which acts as a clutch, is deactivated so no effort is transmitted. When it is decided to change to autonomous driving, the electromagnet is activated, and the rotation of the electric motor is transmitted to the steering column. This connection can be made at any time and with any position of the steering wheel. On the other hand, if the vehicle is in autonomous mode and the driver wishes to perform different actions than the ones intended by the system, the system could be deactivated as soon as the driver acts. The device performance has been tested on other vehicles types [4] with satisfactory results. The electric motor, gears and mechanical parts have been designed in this case considering the measured forces involved.

B. Speed automation

The throttle of the Volvo A25 is electronic. In this case, in order to automate it, it is necessary to transmit the analog signal proportional to the angle of the accelerator pedal from an external source. Then, it is necessary to send an alternative analog signal generated by a computer that emulates the one generated by the original potentiometer and allows its operation from the automation system.

On the other hand, the Volvo A25 is equipped with a classic brake assist system with hydraulic assistance. This implies that access to related electronics is not enough for its automation, so it is necessary to act mechanically on some of its components in order to obtain the desired action.

Finally, the Volvo A25 equips an automatic gearbox with a torque converter, where the driver can select from 6 different positions. The action of the gear selector on the Electronic Control Unit (ECU) is totally electronic, activating each selection according to a series of 8 bits that correspond to the electronic outputs of the selector itself. In order to proceed with the automation of this element, it is necessary to bypass the outputs of the gear selector in order to emulate them from an electronic digital output card.

C. Control architecture (low-level control layer)

The control scheme must define the necessary equipment requirements to carry out the automation of the vehicle's actuators: throttle, brake, steering wheel and gearshift, as well as their interconnection and operation from a centralized on-board computer.

In this way, the control architecture has been designed in a distributed manner, where each actuator constitutes a subsystem and all components are interconnected in two levels. On the one hand, all the components of each subsystem will be connected through a real-time Controller Area Network (CAN) bus line. This architecture simplifies the electronic layout and centralizes all the commands in the same protocol for all the actuators. In case any modification would be introduced in the future, it is much simpler and modular. On the other hand, each subsystem will be interconnected and connected to the central computer by a TCP/IP network. Then, the malfunctioning of one of the subsystems will not cause the global system to fail, since the architecture makes it tolerant to failures in its components.

In this way, we define 3 subsystems:

- Subsystem of access to vehicle information. Access to the data of the internal bus of the vehicle, in order to obtain the data of vehicle speed, engine speed and change of gears. An Ethernet/ CAN card, connected to the local network of the vehicle, is used for this purpose.
- Subsystem of actuators driven by motors. In this case, this subsystem controls the steering wheel and the brake, two elements with the same configuration: they are driven by DC motors mechanically connected to the controls. These motors will receive orders directly through a CAN line through CANOPEN protocols. An Ethernet/CAN card is used for this, connected to a second ad-hoc bus, which will not interfere with the original CAN bus of the Volvo A25.
- Electronically controlled actuator subsystem. In this case, the throttle and the gearshift of the vehicle will be controlled by means of this subsystem, which obeys the analog electronic signal protocol. To do this, these signals will be generated by an analog output card, which is connected to the Ethernet network through another Ethernet/Serial card.

All subsystems are linked by a Gigabit switch, which ensures the maintenance of real time in the global system. In case this switch fails, the system detects that no more new data is received so a stopping command is sent automatically to the brake pedal, whose actuator receives power directly from the vehicle battery. This control system is implemented in a box containing all the electronic devices, bus interfaces and communication antennas inputs (Figure 4).

Figure 4. Electronic and communication control box

D. Perception and autonomous guidance system (high-level control layer)

The fundamental objective of the autonomous guidance system is to take control of the different actuators of the vehicle and provide them the appropriate commands to perform the desired tasks. In order to achieve this objective, the vehicle equips a GPS receiver for using this signal when available and installs 2 different perception systems:

- a 3D laser scanner sensor
- a camera placed near the human driver point of view

As GPS signal is quite poor or unavailable in tunnels, positioning and autonomous guidance is performed be means of the laser scanner. So, this sensor is used for improving positioning accuracy detecting the walls of the tunnel in order to follow the path safely. It is also used for obstacles detection [5]-[8] to stop the vehicle in case the path is blocked and send a warning to the teleoperator. The camera sends images to the teleoperation site in order to take control decisions. Then, this high-level control layer can work in two operating modes:

- Autonomous mode: a trajectory or a reference element is followed without human actions. For this purpose, previous algorithms as presented in [9] are used to improve accuracy and robustness.
- Remote control: commands are sent from the teleoperation site and they are translated to be transferred to the low-level control layer. In both cases, obstacles detection is active and impose its

decisions on the other commands because of safety reasons.

E. Teleoperation site

The tele-operator site is responsible for monitoring the trajectory and operation of all vehicles that circulate in the construction area [10]. It includes devices for controlling trajectory and speed of the vehicle in the tele-operated mode. Furthermore, one of the screens shows the images from the cameras placed on the vehicles near the driver position and the other screen presents operation data of the vehicles. Finally, in case the autonomous mode is activated, the mission tasks are stored in the control computer and sent to the vehicles. These missions could be updated in an easy way by the operator.

F. V2X communications

Communications allow the exchange of information between the teleoperated or autonomous vehicles and the teleoperator site. For this purpose, Vehicle-to-X (V2X) standard communications systems are used. The requirements that these communication systems must comply with are the following ones.

- Desired range: 1 km with direct line of sight
- Bandwidth of at least 1 Mbps
- Operation in broadcast mode.
- UDP/IP communications protocol in order to guarantee the robustness of the operations.

In this way, INSIA-ITS communications modules are used, which comply with the current standards to support communications in road vehicle environments and can be used with any type of IP protocol. In order to extend the range of these modules, they are equipped with signal amplifiers. These modules have been satisfactory tested in road scenarios [11][12] and trials in tunnels are expected for the near future.

V. Conclusions

This project aims to develop a cooperative work between autonomous trucks in a complex environment such as tunnel construction in order to limit human intervention in a highly aggressive environment. In addition, it has the particularity that autonomous vehicles are obtained transforming conventional manual driving with non-permanent nor intrusive adaptations, thereby respecting the possibility of dual operation, which represents a clear competitive advantage.

The project is a challenge for autonomous driving given the environment in which the work of the vehicles must be developed, which negatively affects perception and positioning, as well as having a very restricted space. On the other hand, communications between the vehicles and with the infrastructure and a control site allow the coordinated management of the vehicles to achieve greater productivity and anticipate potential dangers.

At the current stage, subsystems have been tested independently. In this sense, vehicle automation lower control layer has been tested, as well as the internal communication bus that provides control commands. Furthermore, the teleoperation site for controlling and supervising the vehicle operation is finished and communication with the vehicle has been tested. Perception algorithms are now under modification in order to adapt them to the specific scenario that can be found in a tunnel. As a final stage, coordinated operation between different trucks managed from the same teleoperation site is expected to be implemented.

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