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Lateral Power Controller for Unmanned Vehicles

***Abstract**. This paper deals with autonomous vehicles. This could be considered a utopian goal nowadays but recent advances bring it closer than ever. Automation of the actuators involved in the management of a car, and control of the steering wheel constitute two of the most complex issues involved. We here describe an automatic power steering architecture to manage the steering wheel via an Ethernet controller. An on-board PC is connected to the controller to permit handling by computer generated signals. An electric car has been equipped with the system, and we present the results of tests of the behaviour of the system in real situations on the private driving circuit at the IAI facilities.*

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Keywords: Autonomous vehicles, Power control, System analysis and design, Intelligent Transportation Systems.
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Introduction

The increase in the number of cars in the last two decades has been a cause of preoccupation for most governments. Solutions such as building new transport infrastructures or increasing fines for inappropriate driving have not achieved the goal of reducing the number of fatalities on highways or the traffic congestion in urban areas.

Intelligent transportation systems (ITS) [1] focus on improving road safety by acting on two possible aspects: on the one hand, the infrastructure and the possibilities of optimizing traffic flow, and on the other, acting on the cars and the actuators involved in the tasks associated with driving, i.e., steering wheel, brake, and throttle.

The idea of driverless cars traveling around cities is today still a utopia. However, some advances in this sense have been achieved in the last few years. The automobile industry has implemented various aids to the driver in their mass-produced vehicles. Two examples are warning systems to alert the driver about risk situations such as blind angle detection through infrared cameras, and adaptive cruise control through long-range radar sensing technology which tracks information up to 150 metres ahead in all weather and road conditions.

In the research field, the US Department of Defense organizes the DARPA Urban Challenge [2] event, which required teams to build an autonomous vehicle capable of driving in traffic, performing complex manoeuvres such as merging, passing, parking, and negotiating intersections. In Europe, there stand out the Lara project [3] of INRIA in France with a focus on the development and experimentation of techniques for new forms of urban transport, and the Argo Project [4] of the University of Parma in Italy whose goal is to develop active safety systems for vehicles of the future.

The guidance of autonomous vehicles is one of the most important research topics in the intelligent transportation systems field. The main actuator involved in this task is the steering wheel, whose position at every moment needs to be known in order to obtain a good controller.

The difficulty of manually turning the steering wheel has led to the appearance of two kinds of system to aid the driver. In a hydraulic power steering (HPS) system, an engine-driven hydraulic system is used to aid the movement of the steering wheel. And in an electric power steering (EPS) system, an electrical motor is used.

A model of an EPS system is presented in [5] where the inputs are the motor torque, the driver steering torque, and the front wheel aligning torque, and the output is the steering angle of the front wheels. With respect to HPS systems, Ferries [6] models the behaviour of such a system during low speed steering manoeuvres, and Gao [7] presents a low-order linear model to emulate an HPS system for heavy duty vehicles.

With respect to experimental results, Graovac [8] designs a method to choose the optimal PWM method for driving a 3-phase inverter in automotive EPS and HPS applications, and Rhyu [9] presents a hybrid electro-hydraulic power steering (EHPS) system for a 42-V car.

We here present the automation of the steering wheel in an electric Citroën Berlingo van. This model, whose production stopped in 2005, is similar to the petrol version. The main characteristic in the steering is the inclusion of an electric motor to supply the power steering hydraulic pump.

There is a system installed to switch between automatic and manual driving, and a DC motor governed via an Ethernet controller is used to determine the position of the steering wheel from the feedback of an encoder. A laptop, in which the control software is installed, is connected to the Ethernet controller. There is a test-bench to show the behaviour of the system, with comparisons between the straight stretches and right and left curves. After installation and testing, the system is incorporated into the fuzzy logic based AUTOPIA control architecture, and a final demonstration of the automatic steering wheel control while driving along a real road is performed.

In the follow sections, we describe the system's design, its assembly, and implementation in the electric Citroën Berlingo van. The results of different experiments to show the behaviour in real situations are presented. Finally, the adaptation of the system to the AUTOPIA control architecture is described.

Automation of the Steering Wheel

Design of the autonomous system

The decision to implement an automatic steering wheel system was taken conditioned to keeping the original steering wheel system of our electric car. For this reason, we opted for using a gear pulled by a lever to select between the two systems. This lever allows one to switch easily between the two steering systems: in the low position using the standard car system of manually regulating the position of the steering wheel, or in the high position using the automatic steering controlled by the designed system.

Before proceeding with the design, the expected requirements of the automatic system were established. The first step in the design of the steering wheel control was to take into account the limitation set by the power supply: all the power has to come from the vehicle's 12-volt battery.

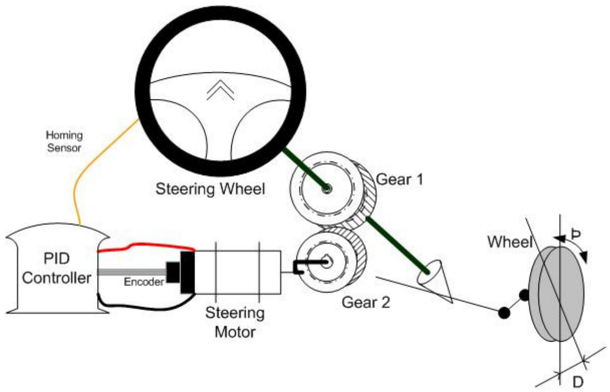

Fig.1. Steering axle actuation system

When the alternative automatic system is selected, a 12-volt DC motor is needed to automatically move the steering wheel. The system is organized as a DC motor connected to the steering bar through two gears, one in the motor rotor and the other in the shaft. The motor can be controlled in different ways. In our case, a discrete PID controller is used. The control loop is closed by an incremental 500 pulse per turn encoder. The system is shown in Fig 1.

One of the goals of the AUTOPIA project is to try to mimic human behaviour in driving situations. Given this premise, the time needed for driver to turn the steering wheel from the leftmost to the rightmost position was determined experimentally. This time (8 seconds) was used to calculate the steering wheel turning speed, resulting in a value of 22.5 rpm.

Another important parameter influencing the choice of motor is the torque. The situation which requires the greatest torque is when the vehicle is stationary and the four wheels of the vehicle are in contact with the ground. A torque wrench on the central axis was used to determine the torque needed to move the steering shaft. To this value, 5 Nm, a security factor was added to obtain a final torque of 7 Nm.

The power for the motor is critical because it is provided by the battery of the electric car, and the more power is required by the motor the more charge is demanded from the battery. For this reason, the maximum current was fixed at 8 amps. The motor used is a FaulHaber model 3863012C, with a 66:1 reduction stage to permit a reduction in the angular speed of the motor (from 6500 rpm to 98.49 rpm) and increase the nominal torque (from 110 mNm to 7.26 Nm).

After designing the automatic steering wheel system, it was necessary to determine how to gear it to the steering bar. An optimal gearing ratio between the motor and the steering bar would be 5:4. But, because of market availability and the size of the diameters, we had to use a ratio of 4:3, with 120 and 90 teeth respectively. This ratio fixes the final angular speed at 73.86 rpm (greater than 22.5 rpm) and the final torque at 9.67 Nm (greater than 7 Nm), fulfilling the design conditions.

The next step in the design was the choice of controller. Previously, an older motor steering system had been implemented with an ISA bus card inserted into the backplane of the main PC, which emulated a discrete PID (based on an LM628), and the power stage had been implemented with another custom-made card with a typical H-bridge, controlled by a PWM signal sent from the aforementioned ISA bus card.

The older controller system had a major problem: its dependence on a backplane PC with ISA cards. This kind of card is falling into disuse, thus making it difficult to replace the computer. Therefore, the main prerequisite for the choice of the power controller was for it to be a peripheral controller fully independent of the on-board PC technology. A homing sensor was needed to determine the position of the steering wheel at initialization.

Current DC motors control technology permits the use of a power stage of small size which includes easy to implement systems of communication with the main PC controller (via Ethernet, USB, or serial port). The new controller used is an Fmod-IPECMOT 48/10 made by FiveCo which provides motion control with Ethernet connection, and with the capacity to control a brushless motor through a discrete PID, in addition to the homing

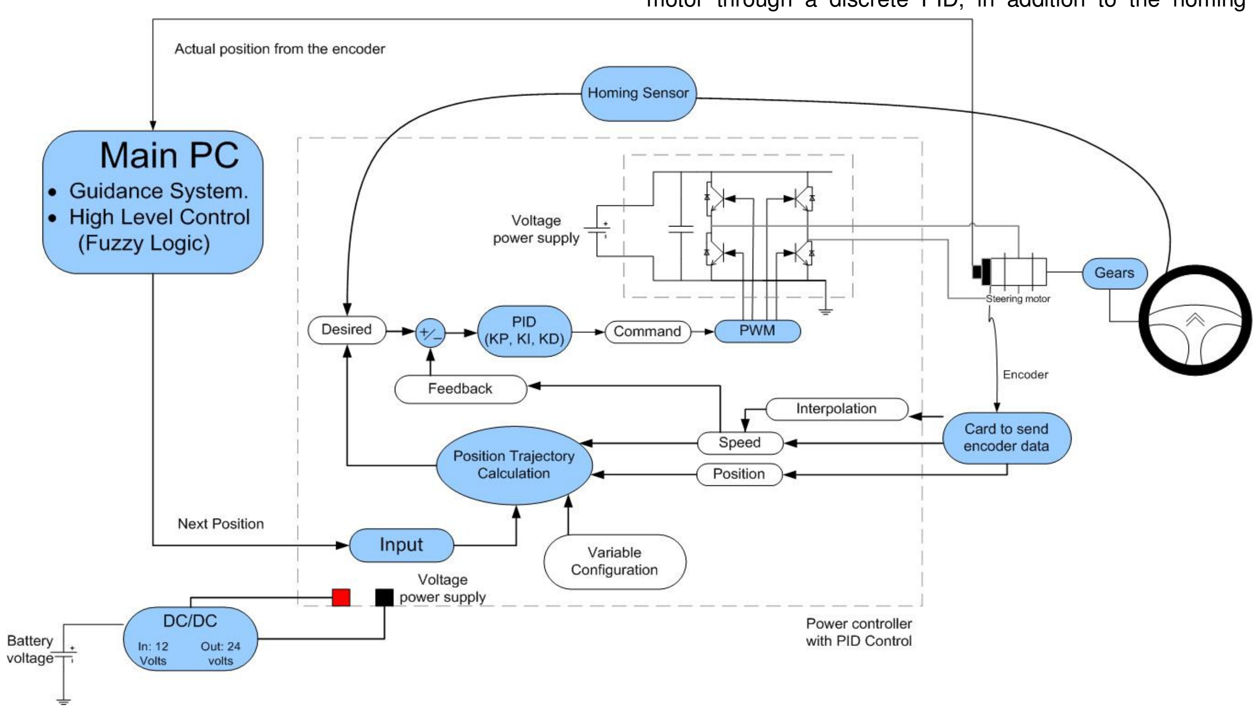

Fig. 2. Design of the electric steering wheel power controller.

sensor.

This controller needs a power voltage of between 15 and 48 volts. To ensure its correct supply, a 12-24 volt DC-DC converter is used to feed it. Fig 2 shows the scheme of the steering wheel controller. The bottom left part of the figure shows the power supply for the system which is taken from the lighter socket and connected to the DC-DC converter. The converter feeds the power controller which has three inputs: one from the laptop executing the fuzzy controller that commands the system; another from the homing sensor; and the last from the 12-volt DC motor encoder used to inform, after the initialization, of the position of the steering wheel.

The next position reference value is sent from the laptop, and is the new target for the PID controller which drives the DC motor through a PWM governed H-bridge.

Assembly in Rocinante

Once the control system for the steering wheel had been designed, the next step was its location and assembly in the electric car ("Rocinante"). Thanks to the small size of the motor, it is possible to place it close to the gear that moves the automatic system. The power for the motor is supplied by the power controller that is fixed near to the automatic gearbox and (in the same location) the DC-DC converter. The converter is connected to the electric car's lighter to provide the system's power.

Finally, an Ethernet cable connects the power controller to the laptop that is located in front of the copilot's seat. Fig 3 shows the location of all the components in the electric Citroën Berlingo van.

Tuning the PID controller

The steering wheel control system used is a classical cascade control, with two feedback loops. The primary or main loop is controlled by a fuzzy logic system in the central PC. This loop is closed by the GPS, which is used to calculate the angular error (in degrees) and the deviation (in metres) with respect to the pre-defined trajectory. As was mentioned above, the inner or secondary loop uses a PID controller and is closed with the incremental encoder.

It is important to make a good estimate of the PID parameters. The first step is to identify the system. In order to do this we coupled the motor to the steering wheel, and then set the system in open loop, i.e., without feedback, and with an excitation pulse from an external source. For this test, we set the steering as far to the right as possible. Since the steering wheel can make three full turns, this position is located 540 degrees to the right of the centre. We then sampled the response of the system to the pulse.

With the data collected, and using the ident tool of Matlab, the second-order transfer function was identified, and is given by equation 1.

$$H_{(s)} = \frac{0.8866 * e^{-0.5}}{(S+3.9609)(S+4.005)} \quad (1)$$

Finally, using the Ziegler-Nichols tuning method, we obtain the PID gains (KP: 2.6003, KI: 0.4333, and KD: 3.90045). These values correspond to a non-interactive PID which is tuned to the sampling frequency.

The frequency in the secondary loop is faster than in the primary by a factor of 10. The GPS sends the data at a 5 Hz rate (200 ms), and the PID controller receives the data from the encoder at a 50 Hz rate (20ms).

Fig 4 shows the simulation results of the system for the step input represented in the figure by the black line. The green curve indicates the response of the system in open loop, the blue curve in closed loop without the PID controller, and the red curve with the PID controller estimated by (1). One observes that in open loop the system is incapable of reaching the steady-state due to the absence of feedback, and that without the controller the response is incapable of reaching the reference value. With the PID controller, the response presents an overshoot that was adjusted manually in the experimental tests.

Test-bench in the Laboratory

Before mounting the designed system in the electric car, the system was subjected to various laboratory tests. The goal was to observe the system's response while performing curves to the right and to the left. To this end, the target turning speed of the controller was set to its maximum value, and different references were tested for the steering wheel position.

The test shown in Fig 5 was made to take two possible situations into account. The first part of the test consisted of a turn of 100 degrees to the right and 200 degrees to the left, the aim being to emulate the driver's reaction in the case of a pronounced bend in a realistic driving situation.

The second part of the test represented another typical situation in driving: the movement of the steering wheel for the car to drive round a tight traffic roundabout. In this case, the movement demanded of the steering wheel is a full turn. First, this is 540 degrees to the right, and then three full turns to the left.

Fig.3.The assembly of the designed system in Rocinante.

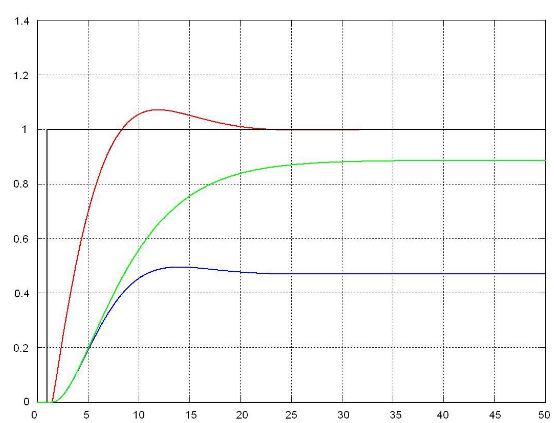

Fig.4. Step response of the PID controller.

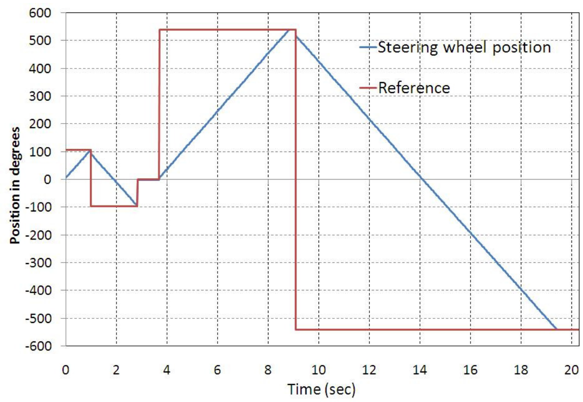

Fig.5. Laboratory test-bench results.

In both cases, the blue line represents the actual position vs time, and the red line the target reference at each instant. One observes that the system's behaviour was perfectly linear.

Experimental Result with AUTOPIA Control Architecture

The AUTOPIA group

AUTOPIA is a research group with more than 10 years of experience in the design, development, and implantation of control systems for the guidance of autonomous vehicles. This experience derives from more than 30 years working in the field of autonomous robots and the adaptation of this know-how to vehicles. The premise has been to avoid significant modifications to the original systems of the vehicles. Various automatic systems have been developed, and the experiments conducted to confirm the designs have given good results.

For these experiments, a private driving circuit was constructed at the IAI facilities to represent an inner city area. It consists of four "city" blocks with one of them finishing in a traffic roundabout. With this circuit, real situations in urban areas can be readily simulated, allowing the autonomous vehicles to be tested in a safe environment.

Each car is equipped with a Real Time Kinematic - Differential Global Positioning System (RTK-DGPS) that is responsible for the guidance of the vehicles. This positioning system is capable of providing a maximum error with respect to the position of a fixed base station of less than 2 centimetres. In this way, we know the position of each car in a global coordinate system with great precision. An Inertial Measurement Unit (IMU) is used in the case of GPS outages that is capable of maintaining the vehicle on the road for up to five minutes [10].

Communication between the base station and each car as well as between the cars is through a wireless LAN. All this equipment is governed by an on-board PC that carries out the control of the vehicles by means of fuzzy logic rules.

The AUTOPIA fleet consists of two Citroën Berlingo vans and a Citroën C3 Pluriel that are fully automated, and a Citroën C3 that is equipped with a DGPS and a wireless LAN but is managed manually. The automation of the two Berlingo vans was based on an ISA power controller. Since this kind of bus is currently falling into disuse, it is mandatory for us to up-date the controller. A peripheral controller to make it independent of the on-board PC allows straightforward replacement of the hardware components of the AUTOPIA architecture.

Experimental results

Managing the steering wheel of a car can be a very complex task, since it can depend on a large set of variables and circumstances. Some of these can be measured or prevented, such as deviation from the lane, current speed, etc., but most are unpredictable or very difficult to measure, such as tyre pressure or road irregularities. Such irregularities mean that the steering wheel has to be managed with high error tolerance.

Also, however, the accuracy and response time of the system can not be neglected, because these can be vital if the system is handling a vehicle with persons inside.

The trade-off between accuracy, complexity, and response time is the main design factor in this kind of system. A well-tried way to resolve these problems is to use artificial intelligence techniques. These methods are especially indicated when one is trying to emulate human control actions, such as a person driving a car. A particularly well known methodological approach to these tasks is the use of fuzzy logic [11], which began in this field with the work of Sugeno [12] on vehicle control in the early 1990s. In the present work, during the experiments a fuzzy controller fed the PID controller with the desired reference positions for the steering wheel and the appropriate turning speed to reach it in order to test the accuracy of the PID controller in real driving situations [13].

A route actually tracked by the vehicle is shown in Fig.6. During the route, the fuzzy controller sends information about the desired steering wheel position to the PID controller. This was done attempting to reach the desired position as fast as possible. The goal during this experiment was to follow the centre of the road. The route comprises six bends, the first three to the left and the second three to the right.

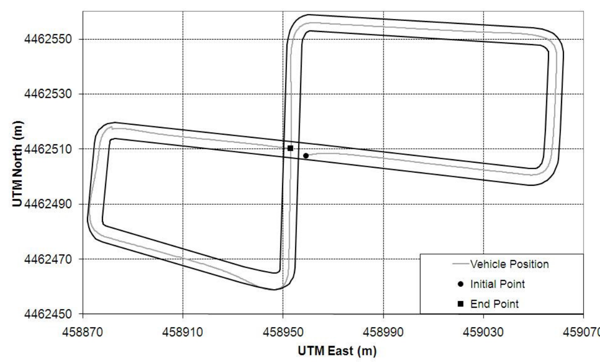

Fig.6. Route followed by the vehicle.

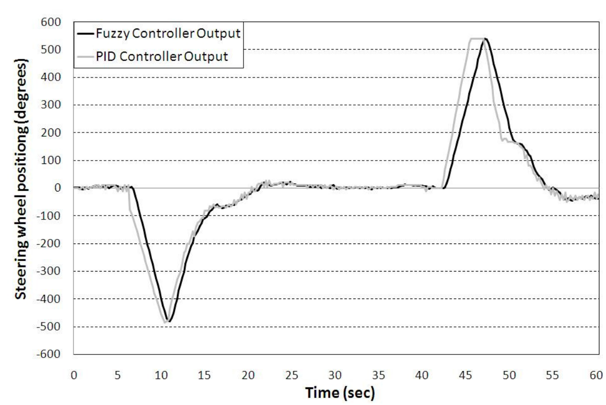

Fig.7. Experimental results of the outputs of the fuzzy controller and the PID controller.

The greatest problem arises at the fourth bend, where an angle of over 100 degrees forces the car to make a large movement of the steering wheel. The designed power controller was able to keep the car on the road and, via the fuzzy logic, return it to the centre of the road.

The results of monitoring the third and fourth curved segments are shown in Fig 7. This figure shows the comparison between the output of the fuzzy controller for the steering wheel position and the output of the PID controller that is sent to the DC motor. The PID controller introduces a short delay, but contributes decisively to stabilizing the input of the DC motor.

Conclusions

As of today, automatic car driving across cities is still an unreachable target. However, advances in this field contribute to reducing the number of road fatalities, or at least to mitigating their consequences. When one considers automatic vehicles, the transfer of the steering control to an automatic system needs to be approached with care because the risk involved can be very great. In this communication, we have described the development of a steering wheel controller.

Automatic systems ought to allow switching between the manual and the automatic system. The system we have developed based on engaging two gears through a lever is a good solution with which to choose between manual and automatic control. For the automatic system, we installed in the test vehicle a 12-volt DC motor controlled through an encoder by a power electronics controller. A laptop located in the electric car sends the commands to manage the controller via Ethernet.

An identification of the system and a simulation to estimate the PID controller parameters in order to close the control loop were carried out, and comparisons were made with the system in open loop and without the PID controller.

The tests showed the behaviour of the designed system to provide a good reaction in situations of sharp bends both to the right and to the left, and to be capable of tracking paths in real driving situations.

The system has now been implemented within the AUTOPIA control architecture. Various experiments were performed to study its autonomous operation. The results showed that the structural design allows the new control system to be installed with only minor changes.

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