# DESIGN AND IMPLEMENTATION OF AN X-BY-WIRE AUTOMOTIVE PROTOTYPE

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## ABSTRACT

The concept of electric vehicle as a fully automated mobile robot (a.k.a. X-by-wire, or Drive-by-Wire (DbW) concepts) is becoming more and more attractive in the modern automotive industry. This idea is based on replacing a mechanical subsystem by its electronic equivalent, which includes sensors and actuators, with a computer in-between. Three of the components, namely Throttle-by-Wire, Brake-by-Wire, and Steer-by-Wire, are the most complex and risky elements of the X-by-Wire technology. Moreover, these elements constitute the inherent part of the general DbW paradigm. This paper reports work-in-progress on the design and prototyping of a scaled-down 1:6 proof-of-concept model of a vehicle with an integrated X-by-Wire system. The control for its components is discussed, while emphasizing the Steer-by-Wire actuator based on the Ackermann condition. The concept targets the Toyota Tacoma, as a benchmark. The influence of heading velocity and turning angle on the slipping angle and path error of the model is analyzed. The performance of the dynamics of the prototype is assessed over prescribed paths; deviations from the no-slip condition are evaluated.

**Keywords:** X-by-Wire; Drive-by-Wire (DbW); Steer-by-Wire; Throttle-by-Wire; Brake-by-Wire; Ackermann condition; electric vehicle..

## RÉSUMÉ

Le concept d'un véhicule électrique en tant que robot complètement automatisé (c.f. X-par-câbles ou conduite-par-câbles) devient de plus en plus séduisant dans l'industrie automotive moderne. L'idée est basée sur le remplacement de chaque système mécanique par son équivalent éléctronique, incluant des capteurs et des actionneurs, avec un ordinateur placé entre eux. Trois composants en particulier, le pédale-par-câbles, le freins-par-câbles, et direction-par-câbles, sont les éléments les plus complexes et les plus risqués de la technologie X-par-câbles. De plus, ces elements constituent une partie inhérante du paradigme DbW général. Cette communication porte sur les résultats préliminaires d'un projet dédié au désign et à la construction d'un prototype de preuve à l'échelle 1 :6 d'un véhicule avec un système X-par-câbles. La commande de ses composants est traitée, tout en mettant l'accent sur le mécanisme de direction-par-câbles basé sur la condition d'Ackermann. Les concept utilise les proportions de la Toyota Tacoma en tant que banc d'essai. L'influence de la vitesse de conduite et de l'angle de rotation sur l'erreur du parcours et l'angle du glissement est analysée. La performace de la dynamique du prototype est évaluée en terme des trajets préscrits, ainsi que la condition de non-glissement.

## NOMENCLATURE

| | |
|---|---|
| $a$ | wheelbase (m) |
| $b$ | track (m) |
| $r_s$ | scrub radius (m) |
| $r_\omega$ | diameter of the wheels (m) |
| $r$ | radius of the prescribed arc (m) |
| $\phi$ | steering angle (of the steering wheel) (rad) |
| $v$ | heading velocity (m/s) |
| $\phi_1$ | angle of vertical rotation of the left front wheel (rad) |
| $\phi_2$ | angle of vertical rotation of the right front wheel (rad) |
| $\phi_3$ | angle of vertical rotation of the left rear wheel (rad) |
| $\phi_4$ | angle of vertical rotation of the right rear wheel (rad) |
| $\tau_t$ | maximum torque applied to a rear wheel (Nm) |
| $\tau_{1rm}$ | maximum continuous torque produced by a rear motor (Nm) |
| $r_{gh}$ | speed ratio of the gear heads |
| $\eta_{gh}$ | efficiency of the gear heads |
| $m$ | total mass of the vehicle (Kg) |
| $a_v$ | norm of the maximum acceleration of the center of gravity |
| $g$ | gravity constant (m/s$^2$) |
| $\theta$ | maximum slope (rad) |

## 1. INTRODUCTION

Since the time when automotive vehicles became widespread with the creation in 1908 of the first commercial model, the famous model T, by Ford, only one architecture has been widely used so far. Despite the appearance of electric vehicles on the market simultaneously with their gasoline counterparts, and even their prevalence in the early 20th century, eventually the internal combustion engine (ICE) pushed back all competitors; until the end of the last century the ICE was the only marketable motor in the car world.

In standard architectures there is one main motor providing the torque that propels the automotive vehicle. The motor is connected to a gear box that is connected to a differential mechanism. The gear box reduces the angular velocity from the motor, while the differential mechanism uses the output of the gear box to create two different angular velocities. Most of the time, in rear-drive vehicles, the differential mechanism is connected to the two rear wheels, one transmitted directly to each traction wheel. These angular velocities are different when the automotive vehicle is turning.

Standard architecture implies that mechanical and hydraulic connections are the dominating types of connection between both moving and fixed vehicle components. For example, the steering wheel is mechanically connected to the front wheel steering mechanism; braking is accomplished by the driver pushing a pedal and transmitting force to the brake pads via the hydraulic line; adjustment of speeds of the wheels during vehicle cornering is carried out with the help of an epicyclic gear differential; etc.

However, in recent decades, and especially with the resurrection of electric vehicle technology in the automotive market, new vehicle control concepts have become more and more widespread in the industry. X-by-wire is a generic concept that refers to one of several different technologies: Steer-by-Wire, Throttle-by-Wire, Brake-by-Wire, Differential-by-Wire, Shift-by-Wire, Suspensions-by-Wire, and Steering-mechanism-by-Wire [1]. For any function that used to be implemented via a purely mechanical system and can be replaced by an electronic equivalent, there is a "by-wire" equivalent. Each by-wire technology provides a new opportunity for research, as shown by Kelling and Leteinturier [2].

With Throttle-by-Wire being the first implemented by-wire function in the Chevrolet Corvette series in 1980 to replace the cable-based throttle, today the embedded electronics and software-based systems are increasingly replacing the mechanical and hydraulic connections.

In this paper an X-by-Wire architecture is considered, using most of the above-mentioned by-wire technologies, namely Throttle-by-Wire, Steer-by-Wire (with the integrated Steering-mechanism-by-Wire), Brake-by-Wire, and Differential-by-Wire. The goal is to substitute every mechanical subsystem by its electronic counterpart. An X-by-wire prototype of an electric vehicle was designed and built, along with its control system, as reported in this paper.

## 2. STEER-BY-WIRE AND DIFFERENTIAL-BY-WIRE

One of the key sub-systems of the prototype is the Steer-by-Wire. Along with the Differential-by-Wire sub-system it allows to build a fully functional model of the X-by-Wire vehicle. Therefore, our focus is these two sub-systems.

The use of the Steer-by-Wire technology allows one to completely dispense with as many mechanical components of the conventional steering system (steering shaft, column, rack and pinion, gear reduction mechanism, etc.) as possible, as discussed by Wong [3]. Such replacement allows for significant space saving and better arrangement of the engine compartment. The removal of mechanical components also improves vehicle safety, since there are no mechanical links forcing the steering wheel to intrude into the cab in case of a frontal crash. The absence of mechanical and hydraulic parts and linkages seriously reduces the weight of the steering system, while its electrical parts allow for the optimization of the steering response and driver's feel.

Another important sub-system is a Differential-by-Wire. Practical implementation of these sub-systems is based on the use of two independent electric motors directly attached to the driving axles, and two motors responsible for independent front wheel steering. The same motors which actualize the functions of the Steer-by-Wire and Differential-by-Wire, at the same time may implement main features of the Throttle-by-Wire and Brake-by-Wire technologies.

## 3. ACKERMANN STEERING

### 3.1. The Ackermann Principle

In order to drive a vehicle safely on a predefined trajectory, both wheels should turn at different steering angles. Good steering kinematics is achieved if perpendiculars to the velocity vectors of all wheels meet at a single point [4]. Usually in the automotive industry the extensions of the wheel axes are taken to determine the optimum steering angle for each turning radius. This approach contains some simplification, under the conditions of low lateral acceleration and small lateral forces during cornering, thereby resulting in small slip angles. A geometric relation of such steering kinematics was first described by the German carriage builder Georg Lankensperger in Munich in 1817, and then patented by his agent in England, Rudolph Ackermann (1764–1834) in 1818 for horse-drawn carriages.

The concept of Ackermann steering [5] is crucial to this discussion. An Ackermann steering mechanism, be it mechanical or electronic, must satisfy the Ackermann geometric conditions.

This Ackermann conditions are illustrated in Fig. 1. This figure shows a simplified top view of a rear-drive and front-steered automotive vehicle, obeying the Ackermann steering conditions, the labels denoting: 1 - the rear left wheel; 2 - the rear right wheel; 3 - the front right wheel; 4 - the front left wheel; and 5 - the chassis.

The relations of the Ackermann principle for the current application were developed for the case of a strictly positive angle $\phi$, when the vehicle is turning left. They also hold for $\phi = 0$ and $\phi < 0$, when the vehicle either travels on a straight course or, correspondingly, turns to the right. Furthermore, steering angles smaller than $-70^\circ$, or greater than $70^\circ$, are not considered here. For the control system of the full X-by-Wire proof-of-concept prototype, the Ackermann conditions take the form:

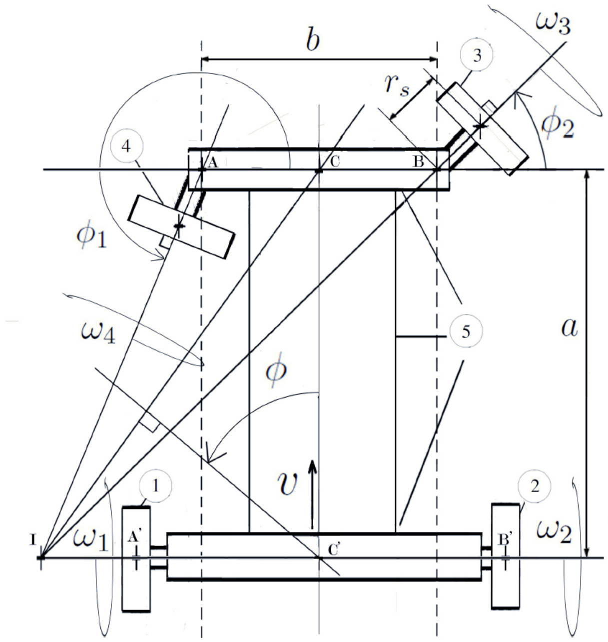


Fig. 1. The Ackermann steering conditions

$$\phi_1 = \pi + \tan^{-1}\frac{\tan\phi}{1 - \frac{b\tan\phi}{2a}} \tag{1a}$$

$$\phi_2 = \tan^{-1}\frac{\tan\phi}{1 + \frac{b\tan\phi}{2a}} \tag{1b}$$

$$\omega_1 = \frac{v}{2\pi r_\omega}\left[1 - \frac{(b+2r_s)\tan\phi}{2a}\right] \tag{1c}$$

$$\omega_2 = \frac{v}{2\pi r_\omega}\left[1 + \frac{(b+2r_s)\tan\phi}{2a}\right] \tag{1d}$$

### 3.2. Ackermann Approximation and Alternative Strategies

As a matter of fact, standard mechanical steering mechanisms, including four-bar linkages, cannot satisfy the Ackermann conditions as Xiaoping and Jinming showed [6]. Equations (1a)-(1d) are only approximated by means of the standard mechanisms. Due to wheel deformation, however, the Ackermann conditions need not be exactly satisfied. For the purposes of improved dynamics at high speeds, a common and smart strategy consists not in satisfying the Ackermann conditions, but rather in implementing alternative equations for the front wheel angles and rear traction angular velocities [7]. Indeed, at high speeds and high steering angles the influence of the centrifugal forces becomes significant. By resorting to field tests, the compensation of these inertial forces has been proven important for automotive vehicle manufacturers, in order to limit sliding and crashing. Therefore, in the X-by-Wire technology the most appropriate strategy will be to utilize a control program using Ackermann conditions at low speeds and alternative conditions at high speeds. Using an electronic system to implement such a behaviour is a pertinent strategy, since this behaviour is programmable. Indeed, even if Ackermann steering could be produced by purely mechanical means, it would be difficult, if not impossible, to produce different conditions, depending on the operation regime.

On the contrary, the behaviour algorithms of many electronic systems can be changed or reconfigured on software. By the same token, beyond the steering system, this electronic paradigm is of interest in the design of all the other subsystems of an automotive vehicle. In particular, by implementing electronic equivalents of the differential mechanism and by attaching stand-alone motors to each wheel, any smart algorithm can be used to produce angular traction velocities.

## 4. DESIGN OF A PROOF-OF-CONCEPT X-BY-WIRE PROTOTYPE

The objective of the research work reported here is to build a proof-of-concept complete X-by-Wire prototype, test it and estimate potential benefits of such an architecture for automotive vehicles. Indeed, by-wire technologies are now well known, in particular Steer-by-Wire. There has been a handful of automotive vehicles, including Mercedes-Benz and Nissan models, with Steer-by-Wire and Brake-by-Wire systems. Moreover, many prototypes using one or a combination of these by-wire technologies have been created and researched, as discussed in [8, 9]. Although they are well known, full X-by-Wire architectures (using all or most of the by-wire technologies) have seldom been implemented. One of the main obstacles for general acceptance of X-by-Wire systems is the difficulty to prove that all the necessary safety measures are followed. One of the main obstacles for general acceptance of X-by-Wire systems is the difficulty to prove that all the necessary safety measures are followed [10]. Furthermore, such prototypes are omni-directional (i.e., each wheel is steering and propelling the vehicle). Of these omni-directional complete X-by-Wire prototypes, one of the first to combine all the by-wire technologies in a four-wheel steering, as reported by Eder and Knoll [11], was built a couple of years before the beginning of the project described here. More recently, Xu [12] published a book on a new omni-directional X-by-Wire prototype. The aforementioned test prototypes have not been tested in the field; only in simulation. The main purpose of work reported in this paper is, therefore, to develop and build a complete X-by-Wire prototype, rear-drive and front-wheel steering (so that our model closely resembles the more common architecture), and to prove that the new architecture can be implemented in automotive vehicles by testing it in the field.

## 5. MECHATRONICS DESIGN

### 5.1. Mechanical Design

The goal was to create a prototype mimicking as much as possible a chosen automotive vehicle, in order to prove that by building a small prototype to be tested in the field, this complete X-by-Wire architecture could be implemented in automotive vehicles.

The first and most important part of the design process, in order to mimic an existing automotive vehicle, is to create a layout with the same proportions as a particular model, so that after choosing it, the final proof-of-concept prototype behaves as this particular model. After conducted a feasibility study and a short market survey, the Toyota Tacoma was selected.

The proportions of the track, wheelbase and diameter of the wheels have been selected as the relevant criteria. These parameters appear in the Ackermann equations; their values were readily found, as opposed to the value of the scrub radius, which was impossible to scale, and was therefore excluded from the scaling criteria.

An important objective was to imitate the dynamics of the chosen model. Hence, the maximum speed (for the sake of brevity, in terms of maximum heading velocity), acceleration time and maximum slope have been mimicked. The speed has been scaled down by means of simple division, which gives a maximum of 15 $km/h$ or 4.17 $m/s$. These values, which have been found after a few design iterations, produce a scale of 3:20. The acceleration time is the same as that of the automotive vehicle, i.e., 7 $s$, which, in turn, leads to a maximum acceleration of 0.59 $m/s^2$, when we take into account the chosen maximum speed. Maximum gradeability is 20%, influencing the choice of traction motors. To accelerate at maximum acceleration and on a slope corresponding to the maximum inclination, the condition

$$\tau_t \geq \frac{mr_\omega(a_v + g\sin\theta)}{2} \tag{2}$$

must be satisfied. The choice of the motors was verified after the completion of the detailed design. Their maximum continuous torque is 0.56 Nm, maximum efficiency 0.91, and supplied with GP52C gear heads with the ratio 4.3. The expression for the resulting torque applied to a rear wheel takes the form:

$$\tau_t = \tau_{1rm} r_{gh} \eta_{gh} \tag{3}$$

After detailed design and prototype-building its mass was found to be 19.5 $kg$. Introducing this value into eqs. (2) and (3) , the relation

$$\tau_t = 2.19Nm \geq 1.32Nm = \frac{mr_\omega(a_v + g\sin\theta)}{2} \tag{4}$$

was found, which means that the traction motors provide sufficient torque to satisfy the requirements.

Tests were conducted on horizontal terrain. Since the tests were conducted indoors, the size of the prototype was limited. It was decided that the prototype should occupy an area of 0.008 $m^2$, while having a length and width bigger than 0.3 $m$.

In the current prototype the suspension is limited to accommodate vertical motion. The suspension was designed simply as a spring in a one-tip-closed tube pushed by a rod. The natural frequency of the vehicle should be around 1 $Hz$, to lie within the range of frequencies of terrestrial vehicles.

#### 5.1.1. Embodiment and Detailed Design

The overall dimensions of the prototype were defined so that the dimensions specified were satisfied.

First, the proportions and the 3:20 scale were determined, to lead to wheel radius, wheel base and track targets, with the physical quantities defined by Sauze [13]. The proportions of the Toyota TACOMA access cab were chosen as the benchmark for the proof-of-concept prototype.

#### 5.1.2. Vibration Modelling

For the analysis of the suspension and selection of the appropriate components, a simplified model of the prototype was formulated, so that the heaving frequency could be obtained, in correlation with the mass. The model is a standard mass-spring system [14]. No dashpot is included, because there was no need for one in this study, as the prototype tests were planned on horizontal ground. For additional tests on bumps, we suggest to add proper damping.

Furthermore, once the detailed design of the suspension was completed, the load-carrying capacity of the whole suspension is known. This capacity is equal to 12.7 $kg$, for the overall suspension.

#### 5.1.3. Front Steering Mechanism

The front steering mechanism is placed under the two front suspensions, as depicted in Fig. 2. The front wheels are steered by means of two servomotors located on top of two half-axles. The motor shafts are vertically oriented and attached to the two plates that are, in turn, attached to four needle bearings. These bearings are connected to the two half-axles, which are mechanically independent. The front structure comprises reinforcing cages, in which the servomotors are placed.

#### 5.1.4. Rear Driving Structure

The prototype is a rear-drive vehicle. Although they propel the vehicle, the rear wheels must not turn about a vertical axis with respect to the chassis. Hence, the driving axle carries the traction motors coaxially

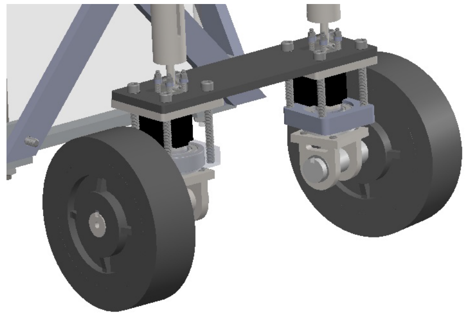

Fig. 2. 3D CAD model of the front steering

collocated with the traction wheels, which are controlled independently, so as implement the differential-by-wire concept. This subsystem is also placed below the two rear suspensions, as illustrated in Fig. 3.

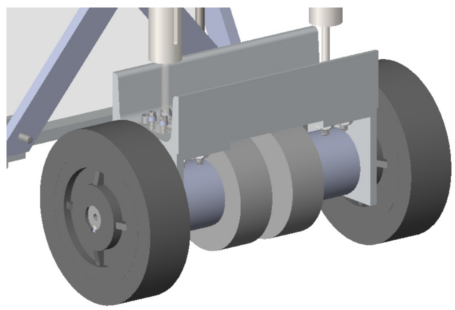

Fig. 3. 3D CAD model of the rear propelling system

#### 5.1.5. Power Source

The important part of any electric vehicle is an electric power source, and for an X-by-wire prototype the electric battery becomes an essential component.

The box, or cradle, holding and protecting the battery was attached to the main beam of the chassis so that the weight of the battery would be considered on top of the springs in the vibration model and at the same time as low as possible to increase the stability of the prototype as can be appreciated in Fig. 4. The box is composed of aluminum narrow bars on top to attach the box to the longest beam of the chassis, several aluminum trusses to increase torsion and flexion stiffness as well as to provide protection, and a plate below the battery. The white box shown inside the trusses is the main battery.

The designed and built prototype is shown in Fig. 5.

### 5.2. Electronic Design and Control System

The prototype shown in Fig. 5 is composed of a chassis, power supplies (batteries), an Arduino Mega Board (controller), wireless Xbee series-1 modules, two smart servo motors as independent steering motors with 0.325° resolution and two rear traction motors with maximum speed of 5000 $RPM$ and continuous torque of 0.554 $Nm$.

The Arduino Mega board receives commands from LabVIEW via a serial port and distributes the command to the steering and traction motors. The latter are tuned for a closed-loop speed control, which maps voltage commands from 0 to 5 $V$ to angular velocity from 0 to 1000 $RPM$. Smart steering servo motors are

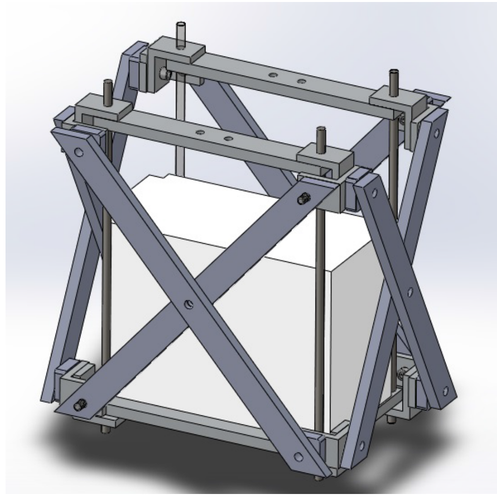

Fig. 4. 3D CAD model of the prototype battery box

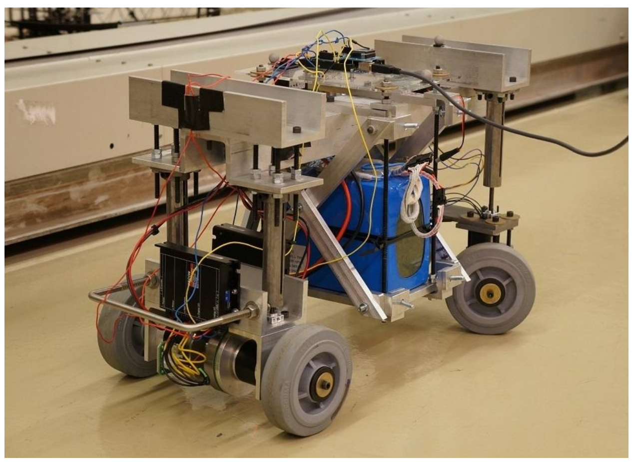

Fig. 5. Side View of the Proof-of-concept Prototype

controlled via serial command for the desired position, with PD feedback control.

The Vicon motion-capture system is used to measure the actual pose of the prototype. This system uses small balls as trackers; balls are attached to any physical object, and cameras are placed around the object, to obtain its pose in real time. Furthermore, during the experiments, one or several operators see in real-time a set of points in the shape of a polygon, each point being the location of a tracker, and a frame created with respect to these points appearing on screens.

The feedback signal from the steering and traction motors is compared with the data gathered from the Vicon system to measure the accuracy of the test and slip of the tires.

## 6. EXPERIMENTAL RESULTS

In this section, the experimental results are presented. First, the prototype was tested while moving in a straight line. This test was used to validate that the control system is capable of following the simplest path. Afterward, the prototype was driven under turning, in order to study the influence of the heading velocity and steering angle on the pose error. Each measured turn is compared with the corresponding prescribed path, thus verifying the non-slippage assumption. A description of the five tests that the robot underwent is

Table 1. Brief description of the tests

| Test number | Heading velocity $(m/s)$ | Steering angle (degrees) | Manoeuvre |
|---|---|---|---|
| 1 | 0.286 | 0 | Straight line |
| 2 | 0.226 | -35 | Turn |
| 3 | 0.386 | -35 | Turn |
| 4 | 0.462 | -50 | Turn |

shown in Table 1. It should be noted that the position measurement unit of Vicon system is in *mm* and all the provided results are in *mm* which demonstrates the accuracy of the test as well.

In Fig. 6 the actual path of the robot along with the prescribed path, a straight segment, are shown. The length of the segment corresponds to the prescribed length of the largest arc in the following tests, namely 1200 *mm*.

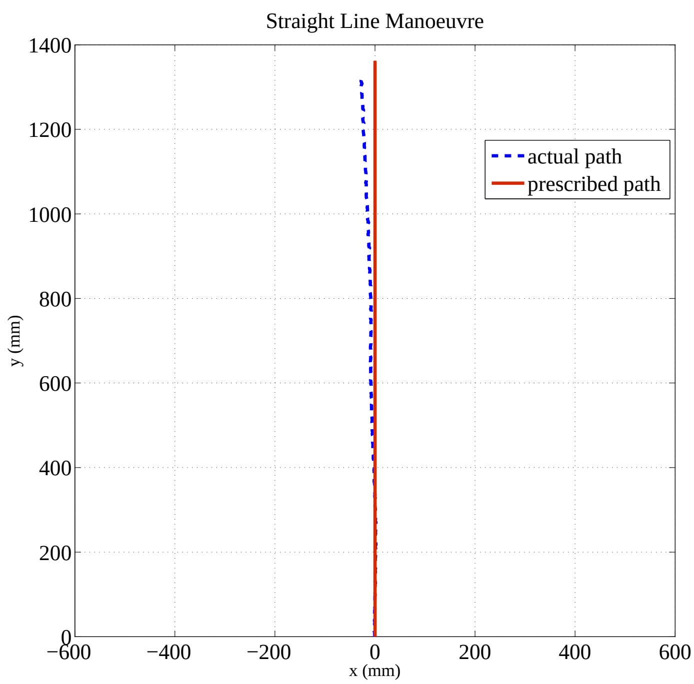


Fig. 6. Test 1

A turning maneuver was conducted for a 90° arc, whose radius depends only on the steering angle. The radius of the prescribed path is expressed as

$$r = a \tan \phi \tag{5}$$

The wheel base $a$ and the steering angle $\phi$ are shown in Fig. 1. Tests 2 and 3, shown in Fig. 7, correspond to two turns at the same steering angle, -35° . The difference is that Test 3 was conducted at a higher heading velocity.

Test 4, shown in Fig. 8, corresponds to a turn at a higher heading velocity and a larger steering angle, as compared to Tests 2 and 3. A larger error was expected in this test.

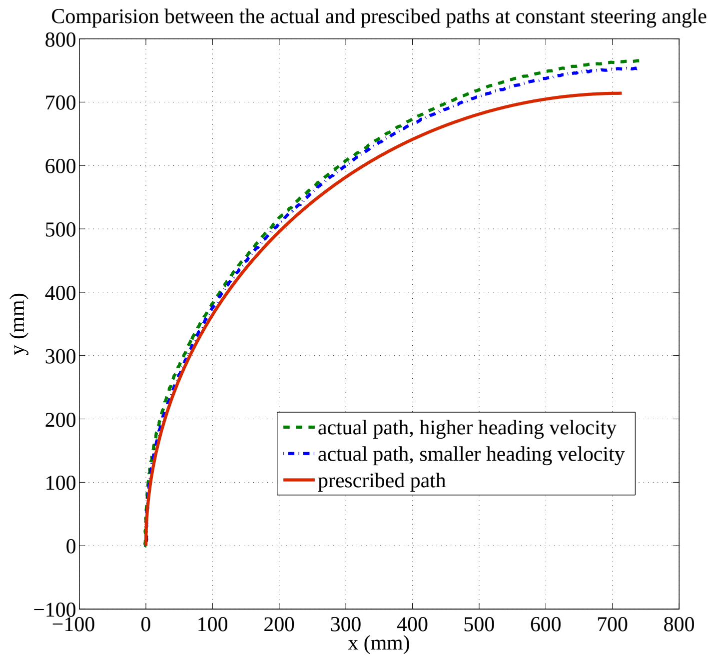


Fig. 7. Test 2 and Test 3

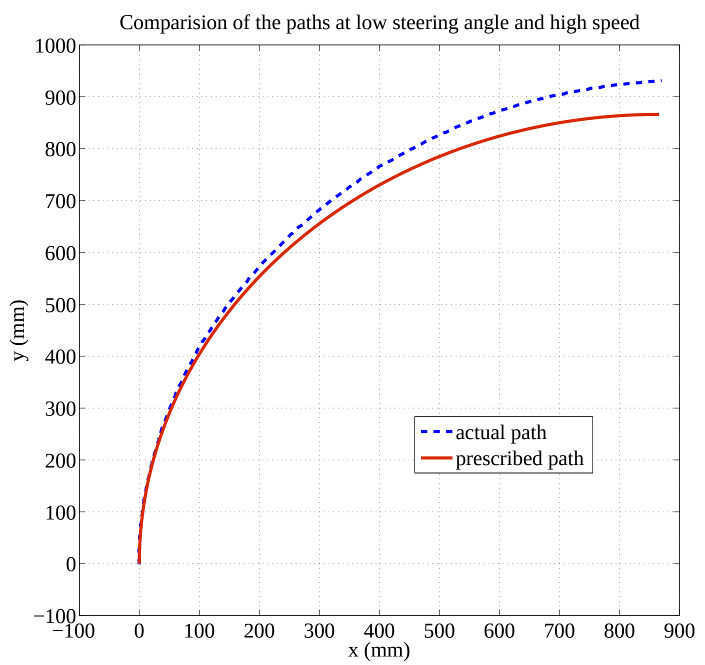


Fig. 8. Test 4

In order to compare the test results, we considered the "path error", defined as

$$e = \frac{\|\overline{AB}\|}{l_c} \tag{6}$$

where $A$ is the end point of the prescribed trajectory, $B$ is the end point of the actual trajectory, and $l_c$ is the arc length of the real trajectory. The length of the actual trajectory, that is, the trajectory obtained as a set of points, was computed as the sum of the distances between two successive points. For this, splines between measurement points were applied, and the lengths of the segments between successive points were added. The results of the computation are shown in Table 2.

Table 2. Path errors of the tests

| Test number | Error (%) |
|---|---|
| 1 | 3.39 |
| 2 | 3.87 |
| 3 | 5.18 |
| 4 | 10.9 |

During the first test, shown in Fig. 6, there was some drift, even when the robot was moving on a straight course. The robot tended to veer slightly to the left, but the distance between the last position of the robot and the place where it should stop was about 0.02 $m$. As a result, part of the error seen in the ensuing tests was due to this drift, which remained small and was not caused by slipping, since it was observed even when the robot was not turning.

Moreover, the second and the third tests, shown in Fig. 7, correspond to two turns, at the same steering angle but different heading velocities. A deviation was observed, with the errors being larger than the one observed during Test 1. This additional drift was mostly caused by slipping, which increases with speed, as one can see in this figure. The results obtained are consistent with our expectations: there is some drift at low speed and heading velocity, partly caused by the control system and partly by slipping. The prescribed paths were never met, of course, mainly because of two factors, centrifugal and friction forces. Moreover, as the error remains small, the non-slippage assumption is confirmed as relevant at a low speed and a low heading velocity. For these reasons, the Ackermann condition is better approximated at low speed and low steering angle, as in Tests 2 and 3. The next test allowed us to determine whether the Ackermann condition at a high steering angle and high heading velocity can be satisfied, and what is the influence of the control inputs on the slippage. Fig. 8 shows the results of the fourth test, where both the heading velocity and the steering angle drastically increase. As expected, in this case the slippage is not negligible anymore. In fact, the error becomes high, mainly because of slippage. Thus, satisfying the Ackermann condition at high heading velocity and high steering angle is not possible because our model does not take into account the centrifugal forces. An alternative model should be used, implementing control for the steering angles and angular velocities that would counteract and balance the slippage. However, research on possible solutions is still to be conducted.

## 7. CONCLUSIONS AND FUTURE WORK

In this paper, the design and preliminary tests of a full X-by-wire automotive prototype were reported. Kinematic and geometric Ackermann conditions were cast in a form suitable to X-by-wire technologies. These conditions correspond to the kinematically correct way to turn; they cannot be satisfied with purely means. These tests show that the prototype works reasonably well at low velocities and low steering angles. The effects of the two inputs on the path error, compared with the prescribed path, were analyzed. The errors are not that significant, considering that the system is generally open-loop and that it uses only a single-behaviour algorithm that does not adapt to the various operation conditions. Furthermore, the model implemented in this algorithm should be used only at low speed and steering angle. Given that the static and kinetic friction coefficients have a significant impact on skidding, these coefficients should be made as high as possible, through the proper choice of the wheels. Current research demonstrates that X-by-Wire architectures can be implemented in automotive vehicles. Although this technology requires further development, the proof-of-concept prototype clearly shows that the X-by-Wire architecture is feasible, that X-by-Wire vehicles should be feasible in the foreseeable future.

Further research on this topic is underway at the Centre for Intelligent Machines (CIM) of McGill University on auto-parking and emergency algorithms, including algorithms for preventing automobile crashes. Furthermore, by means of additional sensors including cameras, path-tracking algorithms, or even automatic control algorithms, can be implemented that would make the vehicle highly reliable. For the existing prototype a provision must be made, with feedback control, to ensure that the Ackermann conditions are observed under high inertia forces. Afterward, a dynamic model will be created and analyzed, to investigate possible methods to prevent or limit skidding by means of using non-Ackermann steering algorithms.

## 8. ACKNOWLEDGEMENTS

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