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The cross-coupling of lateral-longitudinal vehicle dynamics: Towards decentralized Fault-Tolerant Control Schemes

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ABSTRACT

In recent years there has been an increasing interest in improving vehicle characteristics through the use of *Vehicle Control Systems* (*VCS*). In particular, *VCS* for the lateral (steering) and longitudinal (velocity) dynamics are used to improve the handling properties of a vehicle. Nonetheless, the introduction of the additional elements required for implementing these control systems also increases the possibility of faults. This problem can be mitigated by using *Fault Tolerant Control* (*FTC*) systems. The most common approach for steering *FTC* design is based on the use of a linear *Bicycle Model* (*BM*). Using this model decentralized steering controllers can be designed. However, the *BM* lacks significant lateral and longitudinal cross-coupling dynamics. In fact, the steering and velocity control problem could be viewed as a multivariable cross-coupled problem. In this article *VCS* for the steering and velocity are designed. The resulting controllers are decentralized and capable of practically eliminating the cross-coupling. A further problem, which has not been widely reported, is the propagation of the failure of one subsystem to other subsystems. It is shown that when the *Velocity Control System* (*VelCS*) fails, then the steering subsystem has a degraded performance due to cross-coupling. The main contribution of this article consists in showing that it is possible to detect and accommodate a failure of the *VelCS* within the steering control system, *i.e.* without requiring communication among subsystems. This enables a fully independent operation even if faults occur, that is a *Decentralized Fault-Tolerant Control Scheme*.

1. Introduction

Passenger vehicles are complex systems made of several interconnected subsystems such as braking, suspension, steering, powertrain, *etc*. The recent technological development in (micro)-electronics, actuators and sensors has enabled the use of a wide diversity of *Vehicle Control Systems* (*VCS*) such as the *Anti-lock Braking System* (*ABS*) and the *Electronic Stability Control* (*ESC*). These systems allow the vehicle to comply with increasingly stringent requirements for efficiency, safety and handling qualities.

The handling properties of the vehicle can be described fundamentally by the lateral and longitudinal dynamics. The lateral dynamics mainly deal with the steering behavior whereas the longitudinal dynamics mainly deal with the vehicle velocity. Due to the recent interest in controlling the vehicle movement, the design of improved *VCS* for these vehicle subsystems has gained attention.

Fault Tolerant Control (*FTC*) is also of particular interest as failures of any *VCS* may degrade the overall handling capabilities and safety. Many model-based approaches for *FTC* design have been proposed in literature, [1]. Their success depends on model accuracy; however, the most accurate vehicle models can be complex due to the nonlinearities and cross-coupling among subsystems.

Since each *VCS* focuses in a particular vehicle subsystem, it is common to use simplified models which facilitate the design. That is, a decentralized control design approach is often used, in which each subsystem is treated independently. This approach also has the advantage of being easy to implement and introduces the possibility of implementing control systems that are physically independent.

The simplest model for lateral *FTC* design is the well-known linear *Bicycle Model* (*BM*), [2,3]. In [4] the authors developed a fault tolerant monitoring system based on a state observer to detect and

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isolate sensor faults. Using the same model, in [5] a sensor *FTC* strategy based on a switching *Kalman Filter* was proposed. In this case the *FTC* used the estimated state instead of the sensor measurements when faults occur. The drawback of these approaches is that they rely on the validity of the *BM*, which is a simplification of the lateral dynamics that neglects the suspension, load transfer and velocity dynamics.

This shortcoming can be partially alleviated by using more comprehensive vehicle models. In [6] the authors used a *Takagi–Sugeno* (*T–S*) fuzzy *BM* to take into account the nonlinear tire behavior and proposed a *proportional integral observer* to estimate actuator faults. By using the *T–S* model, in [7] a sensor *FTC* was proposed. In this case the state and faults were estimated using a descriptor observer. In [8,9] an observer-based *FTC* system considering sensor faults was designed. Two observers were used, each one driven by a single sensor to generate residual signals. After isolating the faulty sensor, a switching element was used to select the observer with the healthy sensor. On the other hand, in [10] an actuator *FTC* for 4W-steering vehicles was proposed considering a *BM* with unknown and time-varying cornering stiffness.

In order to improve the vehicle model accuracy some studies consider an extended *BM* which includes the longitudinal dynamics. For instance, in [11] a *Fault Detection and Isolation* (*FDI*) method based on structured residuals was developed for sensor and actuator faults in an over-actuated *X-by-Wire* vehicle. In [12] a lateral stabilization controller was proposed for a four wheel independent drive vehicle and in [13] a yaw moment control strategy was proposed for a vehicle with electric drive-trains and friction brakes. On the other hand, some studies consider tire dynamic equations. In [14] the longitudinal slip dynamics is considered for the design of a *model predictive control* for the yaw rate; while in [15,16] the tire rotational dynamics were considered for the design of a *GCC* and a slip controller for in-wheel motors, respectively.

These studies show the benefits of using more accurate models, although there are still few results considering the full body dynamics. On the other hand, more complex models are more difficult to manage; therefore, increasing model complexity brings returns only up to a certain point. Nonetheless, there may be operating conditions in which more complex models are indeed required for accurately representing the vehicle behavior. This must be elucidated before the controller design phase. In this regard, the traditional *BM* has been shown to be adequate for many applications; however, it lacks significant cross-coupling information among the lateral and longitudinal dynamics. In this article, a comprehensive non-linear model is presented and then a linear approximation is derived. The resulting model is shown to be better than the *BM* for analyzing the lateral and longitudinal cross-coupling while at the same time being relatively simple.

When several *VCS* operate simultaneously, the performance could also be degraded because of the cross-coupling dynamics. One possibility to deal with these interactions is to take into account the changes in the operating condition of the other subsystems. In [17] a fault-tolerant *Linear Time Varying* (*LTV*) controller was designed by considering changes in the longitudinal velocity. In particular, a degraded-mode lateral control for an automated highway system was designed using feedback linearization and a mismatched observer synthesized with $\mathcal{H}_\infty$. Alternatively, in [18,19] a *Linear Parameter Varying* (*LPV*) *BM* which considers the velocity as a varying parameter was used for the design of a fault detection scheme. In [20] a robust yaw rate control was designed using an uncertain *LPV-BM*. However, in these cases the velocity is treated as an external signal; *i.e*. not explicitly dependent on the vehicle states. This characteristic precludes the use of these models for studying lateral-longitudinal cross-coupling. That is, for cross-coupling analysis it is no sufficient for the velocity to be time-varying, it must be explicitly dependent on the other vehicle variables.

Another, more direct, alternative to deal with interactions among vehicle subsystems is the synthesis of a centralized controller for several subsystems, an approach called *Global Chasis Control* [21–23]. Nevertheless, this is not a trivial task since it involves the use of more complex models and theoretical tools. In [24] a model vehicle model that considers the lateral and yaw motions and the roll moment of the sprung and unsprung masses was used to design a *LPV* fault-tolerant *GCC*. In [25] a $\mathcal{H}_\infty$/*LPV GCC* was designed considering a 3 *DoF* model for the lateral dynamics and a 7 *DoF* model for the vertical dynamics. In [26] a nonlinear *GCC* was designed using a 14 *DoF* model.

In addition, centralized controllers usually also require more complex hardware and software for their implementation, and the increased complexity renders them more susceptible to faults. Moreover, typical centralized control schemes do not allow the implementation of physically independent control systems and failure of one subsystem may easily propagate to other subsystems. Due to these difficulties, it is not surprising that the decentralized approach is still predominant in many practical applications [24,27]. In this context it would be attractive to retain the advantages of decentralized schemes while at the same time being able to reduce or eliminate the cross-coupling effects.

The literature review reveals that most of the reported *VCS* deal with decentralized schemes and more recently with schemes that adapt to other subsystem operating conditions. At the same time, reports dealing with centralized control of more than one vehicle subsystem are less widespread at this time, but are increasingly gaining attention. Notwithstanding the current knowledge in the subject, an issue which (up to the best knowledge of the authors) has been practically neglected is the fact that *a failure can propagate to other subsystems through cross-coupling*.

For instance, when the steering and velocity control systems operate simultaneously and the *VelCS* fails, several questions may be of interest: Will this failure degrade the performance of the steering subsystem? Can something be done *within* the steering subsystem to accommodate this failure? Can a *FTC* steering system be operated independently from the velocity subsystem? It will be shown in this article that a failure of the *VelCS* indeed propagates to the steering subsystem. However, it is possible to improve the steering response when the *VelCS* fails. Moreover, this can be achieved without communication between subsystems; *i.e.* the steering subsystem can accommodate the fault without requiring any additional signal from the velocity subsystem.

Dealing with multiple *VCS*, and decoupling their failures can be very involved because of the required model complexity and vastness of conceivable interactions and operating conditions. Although the results presented in this article do not solve all these issues, they do represent an initial approach to the issue through a relevant case study.

In this article a theoretical framework that allows designing decentralized controllers using classical robustness and performance considerations, known as *Individual Channel Analysis and Design (ICAD)* [28], is used as a basis to study the cross-coupling between the velocity and the steering subsystems. Through the use of the *ICAD* framework the resulting control scheme was able to comply with classical robustness margins, which have shown to be useful in practical applications to assess the robustness of a control system to generalized perturbations. Nonetheless, a more thorough study of the robustness to particular kinds of perturbations is out of the scope of the article. On the other hand, for the detection of failure in the velocity control loop a parametric identification algorithm based on *recursive least squares* is used. The main contributions of this article are: (1) the design of decentralized controllers for the steering and velocity subsystems which are not affected by