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Fuzzy Shared Semi-Autonomous Control System For Military Vehicles

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Abstract

Semi-autonomous control systems applied to automobiles are Advanced Driver Assistance Systems (ADAS) that have gained importance from similar devices with applications in robotics. The control sharing between humans and automatic controllers is the main characteristic of these systems, and can be accomplished through various different manners. However, the use of Artificial Intelligence (AI) techniques for this purpose remains unexplored. In this paper we propose the design of a semi-autonomous control system applied to military vehicles through the use of Fuzzy Inference Systems for the definition of the controller intervention level. Simulations of a vehicle being operated in highly dangerous situations, represented by the existence of hostile military threats or by unexpected maneuvers that could put the stability of the car at risk were performed. The control system's level of intervention during the simulations was observed, and we could realize the increase of this variable according to the level of threat that the car was exposed to. The application of the proposed system results in safer operation of the vehicle, which shall be controlled with greater influence of the automatic controller when in greater danger. We present a critical analysis of these results and new directions for the future of this work.

Introduction

The considerable risk to life inherent to automobile's traffic is a serious problem that has driven discussions and analysis by various agencies (governmental or otherwise) in the world. Many studies like [1] and [2] evidence this concern, as they covered aspects about safety on roads and highways, and served as tools for assessing progress in the area and for the development of public policies aiming to reduce traffic risks.

Although many factors could increase the probability of a car accident, it is a common sense that the drivers of the vehicles are in general responsible for the accident occurrence, whether by imprudence, incompetence or incapacity for direction.

When it comes to military vehicles being employed in operations, accident risks can become even greater. This is justified by the fact that, in addition to the risks involved in the control and the behavior of drivers, during a military operation the vehicles are exposed to hostile enemy threats (e.g. Improvised Explosive Devices - IED, LASER sight anti-tank weapons, etc.). For that reason, in order to mitigate these risks and to maximize the safety in military vehicles, innovative technological solutions with the use of inertial and external threats sensors are welcome. These solutions can be based on the strategy of providing assistance to the driver, correcting or canceling any unsatisfactory performance by implementing systems that can enable the capability of shared control (or semi-autonomous control) of the vehicle in question.

By analyzing the latest trends in the development of autonomous military vehicles, Xin and Bin stated that Unmanned Ground Vehicles (UGV) will be protagonists in future combat operations [3]. However, in that same work various areas of knowledge that need to be further developed were identified, leading to the conclusion that a transition to this paradigm should occur gradually. In this context, military vehicles should incorporate technological innovations slowly, as has happened with commercial and passenger vehicles. Recent studies have shown a tendency to solutions of this type [4, 5, 6, 7, 8], and will be analyzed in more detail on the next sections.

This paper aims to present the continuity of the work proposed by the authors in [9], where a complex Fuzzy system was used as a tool for the development of a semi-autonomous control system for use in military vehicles. The main difference between the works is in the implementation of the Sub-Controller device, where in the present case a control strategy based on MPCs was implemented (rather than a neural networks based approach, which hadn't shown to be efficient). However, both works keep the main objective, to consist of an analytical study on the implementation of a semi-autonomous control system taking into account the following input parameters: (i) the driver's behavior; (ii) the presence of external threats; and (iii) the tendency of the vehicle to evolve to instability.

In order to make this paper a self-contained text, some concepts about semi-autonomous control are presented once again, but including important information for the MPCs-based approach now proposed.

This work has its text organized as follows: the second section contains some details about Advanced Driver Assistance Systems, in special the Semi-autonomous Control Systems with a little description of the related work on this area and our Fuzzy-based approach for the problem. The mathematical models used on the development of this work are presented on the following section. We also present some simulation results on the fourth section, which is followed by a little section for comments and conclusions. It is important to observe that the descriptions of the Fuzzy Inference Systems used in this work are presented on [9].

Advanced Driver Assistance Systems

Advanced Driver Assistance Systems (ADAS) are complex devices which are expected to enhance driver capabilities and safey in vehicles. Many of them have been developed and studied by researchers, encouraged by industry and the scientific community.

As stated by Nilsson in [11] and reinforced by Chen et al. in [12], this kind of systems can be divided into three categories, as organized on the Table 1.

Table 1. ADAS Categories and main characteristics.

Information/Warning Systems	Systems that provide information through different modalities and by different emergency levels, warning the driver of potential hazards.
Active assistance/semi-automation Systems	Systems designed to assist drivers in their driving tasks (acceleration, braking, steering, etc.).
Full/high automation Systems	Systems designed to take over the control of the vehicles and act automatically during driving.

The system proposed in this work can be classified as an **Active assistance/semi-automation system**. In general, these systems can also be subdivided into two types: (i) **Reactive Systems**, when the states of the dynamic system (in this case, the vehicle) are approximating to some critical stability boundary, which may lead to dangerous operation or accidents; and (ii) **Predictive Systems**, which also consider the forecast evolution of the states of the dynamic system, and estimates undesired disturbances from the environment.

Shared (Or Semi-Autonomous) Control Systems

Much work has been developed in order to investigate the capabilities of a synergistic integration of the control abilities of a human being and automated devices [13,14,15]. The concept of a shared control system has been addressed by many researchers, particularly in the development of theories as supervisory control and telerobotics [10]. Increasing the level of automation of certain processes that used to be strictly controlled by humans manually had not always shown to be effective, because of the intrusiveness or the difficulty to deal with automation failures [16]. However, recent developments indicate the growth of importance of shared control systems, in which the main characteristic is the blending and application of control inputs from a human and a controller on a specific process or plant.

A seminal work proposed by Yu et al. in [17] presented the employment of a shared control system for helping the elderly on their mobility tasks. In their approach, the level of control authority between the human user and a controller was adjusted according to the user's performance. It was essentially reactive, which makes it inappropriate for high speed applications such as automotive or robotics.

Since then, some research was developed in order to adequate that concept to the automobiles' reality. Anderson et al. presented a method for the control of vehicles that included the evaluation of collision threats and planning trajectories [13]. This approach resulted in the planning of an optimal path (from the vehicle's stability point of view) on the safer region of the terrain. This method was based on the development of a framework for active safety (presented in [4]), which allowed the identification of obstacles (so they could be avoided) and vehicle stability control. For both studies, they used optimal control techniques for the system design, and an intervention law was generated from the minimization of threats identified by a Model Predictive Controller (MPC). This work also generated subsidies to [14] and [15].

Storms and Tilbury recently demonstrated the effectiveness of using similar techniques for teleoperated mobile robots control at high speed [5]. Their work show the importance of the assistive semi-autonomous applications, due to the fact that human operators are often essential in the control loop ("human in the loop"), because of their knowledge as specialists.

The most difficult task on these systems is to define how to allocate the control authority between the human operator and the automatic controller. It is generally related to finding ways to minimize an "undesired" objective function, such as: collision threat level; deviation between the inputs provided by the driver and those provided by the controller; or some abstract function that considers both.

From the assessment of some of these metrics and an optimization method, a parameter $K \in [0,1]$, representing the optimal level of the controller's intervention is generated. This parameter is then used for the weighting of the inputs to be applied to the dynamic system, resulting on a total input given by

$$u = K\, u_c + (1 - K)u_h, \tag{1}$$

where u_c is the input from the controller and u_h is the input from the human operator.

In this work, we propose that the inputs from the controller are also generated by a MPC, while the real-time choice of the value K is made by a fuzzy logic based system, drawn up in order to take into account some relevant inputs for the safe and confortable driving, but also other important inputs for the military operations context.

Fuzzy-Based Approach

In this work, the approach for achieving the mixture of the control inputs from the controller and the human driver shall be made by the deployment of a complex Fuzzy Inference System for processing some important attributes, such as: the external threats which the vehicles are exposed to; the drivers' behavior; and the stability of the vehicle. To quantify these attributes, we must consider:

1. The calculation of stability parameters known as Stability Moments (SM), and then the generation of a representative measurement of the tendency to rollover of the vehicle as well (The Stability Moment was defined in [18], and will be briefly discussed on next sections and subsections), also considering the employment of ideal inertial sensors on the vehicle, as accelerometers and gyroscopes; and,
2. The presence of ideal military sensors in the vehicle. These sensors must be able to identify whether the vehicle is being illuminated by a LASER sighting device and also the existence of IED on the ground in which it is used.
3. The difference between the inputs provided by the driver and the controller;

A general, high-level architecture is proposed and described in the next topic.

Proposed Architecture

Figure 1 shows a closed control loop where the controller can be considered its main element. The design of this controller represents the essential goal within the development of this work. To achieve this, we propose the controller architecture illustrated on Figure 2, formed by two main sub-elements (named Fuzzy Panderer and MPC Sub-controller).

It can be observed that the inputs for this controller are strictly related to the attributes enumerated above, in a sense that they must be quantified with measurements of the driver's inputs, of the stability parameter and of an external threats parameter.

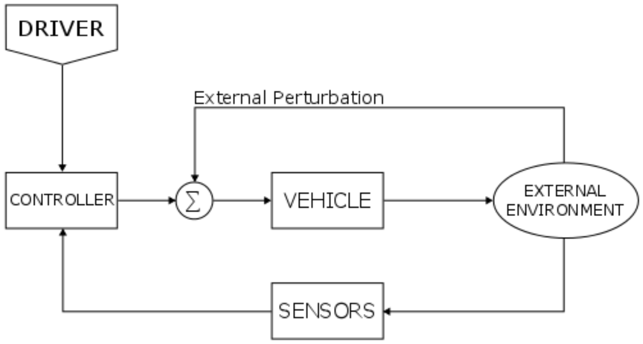


Figure 1. Semi-autonomous (or shared) control loop proposed, where the controller (on the left) is the main element.

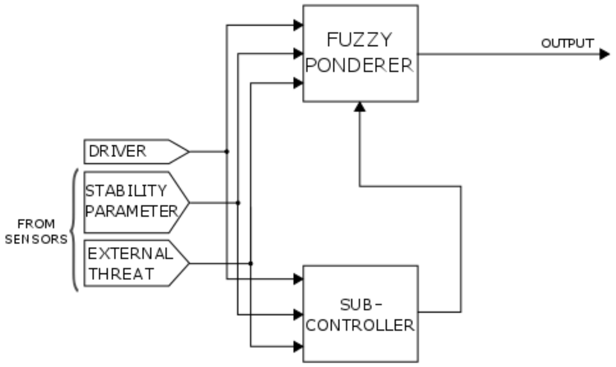


Figure 2. Architecture of the controller, with the two sub-elements (Fuzzy Ponderer and Sub-Controller).

Mathematical Modeling

The development of the proposed semi-autonomous controller can be subdivided in minor parts, as the calculation of the necessary input parameters for the Fuzzy Ponderer (mainly the stability parameter); the implementation of the Fuzzy Ponderer itself; and the development of the mathematical models of the vehicle (in this case, the dynamic system to be studied) necessary for the simulations and for the MPC Sub-Controller design.

Stability Metric

As mentioned, the "Stability Moment" proposed by Peters and Iagnemma in [18] was used in order to quantify the tendency of the vehicle to evolve into a rollover condition and generate a metric for stability. However, we used the metric (similar to the "load transfer" metric) defined by

$$R_{SM} = \frac{SM_l - SM_r}{SM_l + SM_r}, \quad R_{SM} \in [-1,1], \tag{2}$$

for measuring the total destabilizing factor for the vehicle. With this parameter, if $R_{SM} \to -1$ the vehicle is tending to a rollover about the left tipover axis, while if $R_{SM} \to 1$ the same occurs for the right tipover axis. Clearly if $R_{SM} \to 0$, the vehicle tends to keep itself stable, with roll angle near zero.

In the simulation environment, a subsystem has been implemented to perform the calculation of these parameters, allowing the metric defined in (2) to be used as an input variable for the Fuzzy Ponderer proposed.

Fuzzy Ponderer

It can be observed in Figure 2 that the Fuzzy Ponderer should be proposed taking into account the following antecedents:

1. Driver (or driver's behavior);
2. Stability Parameter; and
3. External threats.

The architecture of the Fuzzy Ponderer is illustrated with more details in Figure 3. To describe the attributes mentioned above, the following input variables were used:

- Δu - Difference between the input provided by the driver and the automatic controller;
- $|R_{SM}|$ - Absolute value of the stability metric defined in (2);
- $D_{a,i}$ - Relative distance between the vehicle and the i^{th} shooter's line of sight;
- $V_{a,i}$ - Relative velocity between the vehicle and the i^{th} shooter's line of sight;
- $D_{e,i}$ - Relative distance between the vehicle and the i^{th} IED; and,
- $V_{e,i}$ - Relative velocity between the vehicle and the i^{th} IED.

Besides these, we also used the following intermediate variables:

- $A_{e,i}$ - External threat posed by the i^{th} IED;
- $A_{e,i}$ - External threat posed by the i^{th} shooter;
- A_t - Total external threat; and,
- B_{Motr} - Driver's behavior.

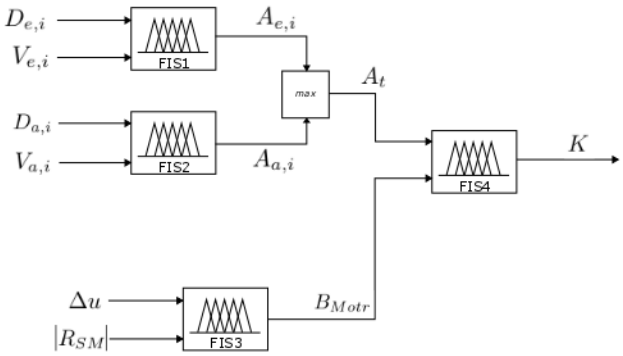


Figure 3. Architecture of the Fuzzy Ponderer, with the listed input and intermediate variables and the generation of K.

With those input variables, a system capable of generating the intervention variable K (system output) is developed. However, as the number of variables is considerably large, the system is designed in order to take four Fuzzy Inference Systems (FIS), generating the intermediate variables shown.

The FIS used to develop this architecture was described with more details on [9].

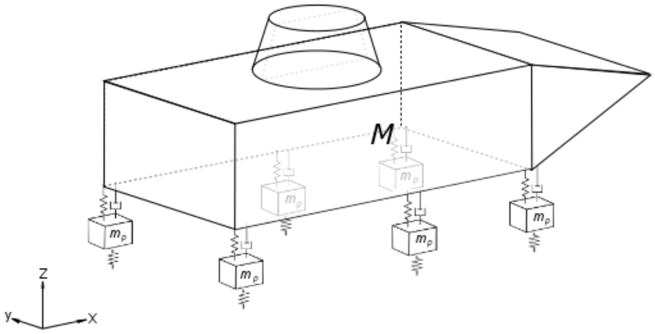
Model For Simulation Environment

The first mathematical model developed for this work was generated to represent the dynamic behavior of the vehicle considered. It is a complex nonlinear model used exclusively to simulate the dynamics of the system, while the MPC Sub-Controller's design is achieved with a simpler kinematic model.

6x6 Vehicle Models From The Equations Of Motion

The equations of motion of a simplified multibody system can lead to an useful mathematical model for simulation. From some basic information of an Armored Personal Carrier (APC) vehicle of the GUARANI family obtained in technical documentation [18], a mathematical model was conceived.

This model has a total of twelve degrees of freedom (DOF), represented by its Euler angles (three DOF), the position of a reference point (three DOF) considered the roll center of the sprung mass (rigid body of the vehicle) and the position of the mass points representing each of the six tire-suspension assemblies (six DOF). In Addition, we considered that the longitudinal acceleration of the vehicle is zero, and that the slip angle cannot be neglected. Figures 4 and 5 illustrate the considered simplifications.



4. Simplified schematic for the 6x6 vehicle (perspective view).

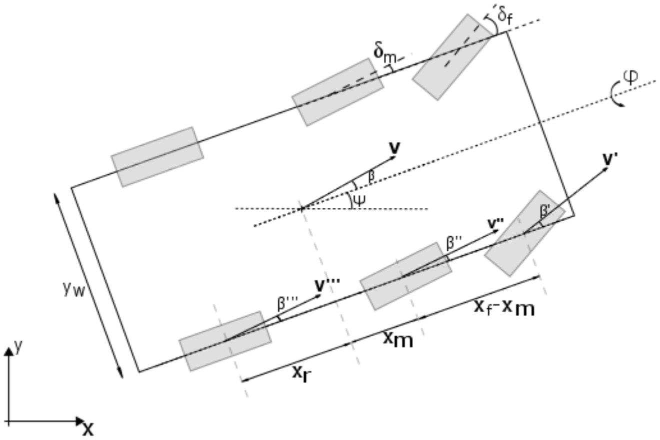


Figure 5. Simplified schematic for the 6x6 vehicle (top view).

Looking at Figure 4, we can reach the equations of motion on the vertical axis for both the sprung mass M and the mass blocks m_p (relative to their centers of gravity). The equations will be given by

$$\sum_{m_{p,i}} \boldsymbol{F} = m_{p,i}\,\ddot{z}_i \implies$$

$$m_{p,i}\,\ddot{z}_i =$$

$$k_p[h_0 - (z_i - r_i)] - k_i\left[l - \left(z \pm \frac{y_w}{2}\,\varphi \pm x_r\theta - z_i\right)\right]$$

$$- b_i\left[-\left(\dot{z} \pm \frac{y_w}{2}\,\dot{\varphi} \pm x_r\,\dot{\theta}\right) + \dot{z}_i\right] - m_{p,i}\,g\,,$$

$$(i = 1,2,\dots,6), \qquad (3)$$

where the parameters represent the following: $m_{p,i}$ is the mass block representing the i^{th} tire-suspension assembly; z_i is the (time-varying) height of the mass block $m_{p,i}$; k_p is the stiffness of the spring representing each of the vehicle's tires; h_0 is the height where the mass blocks $m_{p,i}$ would be if there were no gravity; r_i is the height at the point of contact of the i^{th} tire with the ground; k_i the spring stiffness of the i^{th} suspension; l is the distance between the sprung mass center of gravity and the height of the mass blocks $m_{p,i}$ if there were no gravity; z is the (time-varying) height of the center of gravity of the sprung mass M; b_i the damping constant of the ith suspension; y_w and x_r are the distances indicated in Figure 5; φ the (time-varying) roll angle the sprung mass; θ the (time-varying) pitch angle the sprung mass; and g the gravitational acceleration.

In equation (3), all terms that are proportional to φ and θ were labeled with $\pm$ because their signals vary according to each of the six tire-suspension assemblies.

For the sprung mass M we can also write

$$\sum_{M} \boldsymbol{F} = M\ddot{z} \implies$$

$$M\ddot{z} = \sum_{i=1}^{6} F_i - Mg\,, \tag{4}$$

where

$$F_i = k_i\left[l - \left(z \pm \frac{y_w}{2}\,\varphi \pm x_r\theta - z_i\right)\right] + b_i\left[-\left(\dot{z} \pm \frac{y_w}{2}\,\dot{\varphi} \pm x_r\dot{\theta} - \dot{z}_i\right)\right]. \tag{5}$$

Considering the top view illustrated on Figure 5 one can obtain a bicycle type model for the vehicle, which can be represented by the equation

$$\sum \boldsymbol{F}_y = M_t\ddot{y} - Mh[\ddot{\varphi}\,\cos\varphi - \dot{\varphi}^2\sin\varphi]\cos\psi, \tag{6}$$

where $M_t = M + 6\,m_p$ e h is the distance between the center of gravity of the sprung mass and its roll center.

Taking into account that in this work we will consider only situations where no longitudinal acceleration is applied to the vehicle, we can observe that

$$\begin{cases} \dot{x} = V\cos(\psi + \beta) \\ \dot{y} = V\sin(\psi + \beta) \end{cases},$$

therefore

$$\begin{cases} \ddot{x} = -V\sin(\psi + \beta)(\dot{\psi} + \dot{\beta}) \\ \ddot{y} = V\cos(\psi + \beta)\,(\dot{\psi} + \dot{\beta}) \end{cases},$$

from where one could conclude that

$$M_t\,V\cos(\psi + \beta)\,(\dot{\psi} + \dot{\beta}) = Mh[\ddot{\varphi} - \dot{\varphi}^2\,\sin\varphi]\cos\psi + 2\,F_f\cos(\delta_f + \psi) + 2\,F_m\cos(\delta_m + \psi) - 2\,F_r\cos\psi, \tag{7}$$

The forces F_f, F_m and F_r are calculated in a similar way from that presented in [4], with the cornering stiffness C_f, C_m and C_r of the tires, by the expression

$$\begin{bmatrix} F_f \\ F_m \\ F_r \end{bmatrix} = \begin{bmatrix} C_f & 0 & 0 \\ 0 & C_m & 0 \\ 0 & 0 & C_r \end{bmatrix}\begin{bmatrix} \alpha_f \\ \alpha_m \\ \alpha_r \end{bmatrix}, \tag{8}$$

where α_f, α_m and α_r are the angles between the longitudinal axis of the tires on the front, intermediary and rear axis and their velocity vectors. Therefore it can be said that

$$\begin{cases} F_f = C_f(\delta_f - \beta') \\ F_m = C_m(\delta_m - \beta'') \\ F_r = C_r(\beta''') \end{cases}, \tag{9}$$

where

$$\delta_f = k_\delta\,\delta_m, \tag{10}$$

and the angles β', β'' and β''' are approximated by

$$\begin{cases} \beta' = \beta + \frac{x_f}{V}\dot{\psi} \\ \beta'' = \beta + \frac{x_m}{V}\dot{\psi} \\ \beta''' = \beta - \frac{x_r}{V}\dot{\psi} \end{cases}. \tag{11}$$

The moments of the forces can be addressed as

$$\begin{bmatrix} \sum M_x \\ \sum M_y \\ \sum M_z \end{bmatrix} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix}\begin{bmatrix} \ddot{\varphi} \\ \ddot{\theta} \\ \ddot{\psi} \end{bmatrix}, \tag{12}$$

where we shall have

$$\sum M_x = 2\,F_f h\,\cos\delta_f + 2\,F_m h\,\cos\delta_m - 2\,F_r h + Mgh\,\sin\varphi - \frac{y_w^2}{4}\varphi\sum_{i=1}^{6} k_i - \frac{y_w^2}{4}\dot{\varphi}\sum_{i=1}^{6} b_i, \tag{13}$$

$$\sum M_y = (F_3 + F_4)x_r - (F_2 + F_5)x_m - (F_1 + F_6)x_f, \tag{14}$$

and

$$\sum M_z = 2\,F_f\,x_f\,\cos\delta_f + 2\,F_m x_m\cos\delta_m + 2F_r x_f. \tag{15}$$

The model resulting from these equations was implemented on a numerical simulation environment and it generated good results, similar to those illustrated in [22], which makes this a valuable model to be used for the development of sub-controller proposed.

Model Predictive Controller Design

Model Predictive Control is a sophisticated methodology for process control that was originally applied to chemical industry plants with hundreds of inputs and outputs and subject to constraints [19]. Its main characteristics are: the application of an explicit process model to predict the responses of the plant; and the periodic optimization of an objective function to find the best-case control inputs to be applied to the plant. Recent applications of MPC's show that the evolution of microprocessors and the increase of their computational capacity allowed the use of the method in a wide variety of application areas. Figure 6 represent the structure of an MPC.

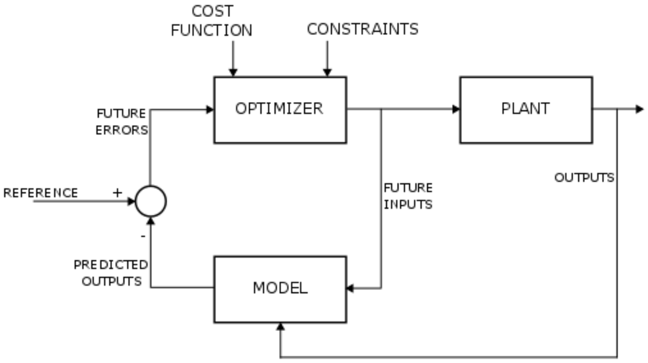


Figure 6. Structure of an MPC.

The MPC strategy can be summarized by the following actions:

1. Prediction of the outputs of the dynamical system for a pre-defined time horizon, using the process model;
2. Optimization of a determined criterion that lead to the calculation of the control signals to be applied to the plant or process. As mentioned before, this criterion is often represented by an objective function that should be minimized;
3. The calculated control signals are applied to the plant or process through a more restrictive horizon, and action 1 is repeated with the new values.

This control strategy can be represented by Figure 7.

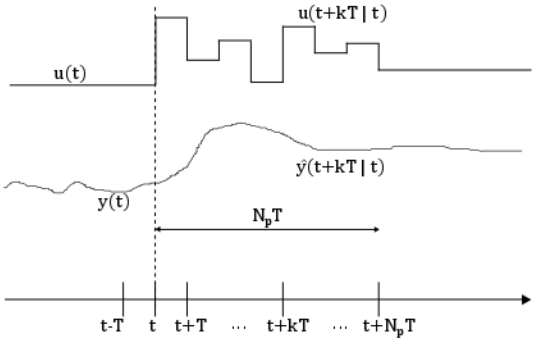


Figure 7. MPC strategy.

The MPC strategy can be compared to the control strategy for driving cars [20]. This is an interesting analogy that clarifies the predictive characteristics of this methodology. When driving a car, the driver must identify the reference trajectory for a finite time horizon and apply the appropriate control signals (steering, acceleration and braking) to track it, considering his mental model for the vehicle.

The Model Predictive Controller designed for this work was implemented taking into account a kinematic model for the GUARANI vehicle, a threat-oriented objective function and a restrictive constraint setup, presented below.

6x6 Vehicle Kinematic Model

In order to implement the MPC, a kinematic model of the vehicle was used. We assume that this should be a first approach to the problem, making it simpler, although it is appropriate to use other models that represent the system dynamics. As the use of a kinematic model is more suitable for situations where the vehicle's longitudinal velocity is lower than that assumed here, there is no way to ensure an accurate representation of the dynamic behavior of the vehicle. However, it is considered that in this model it should be possible to calculate with good approximation the inputs to be applied to the system, by the use of the optimization algorithms.

The development of the model was similar to that found in [21], where a kinematic model of lateral vehicle motion is presented. Considering Figure 8, it can be seen that there are two different possibilities for the development of the model: based on the front axle steering (and the instantaneous rolling center O_f), or based on the intermediate axle steering (and the instantaneous rolling center O_m). Actually, the true instantaneous rolling center is a point inside the triangle $O_iO_mO_f$. Considering the worst case as the one in which the curve performed by the center of gravity is the most open, we chose the far rolling center (in this case O_m), and thus we took the intermediate axle steering as basis.

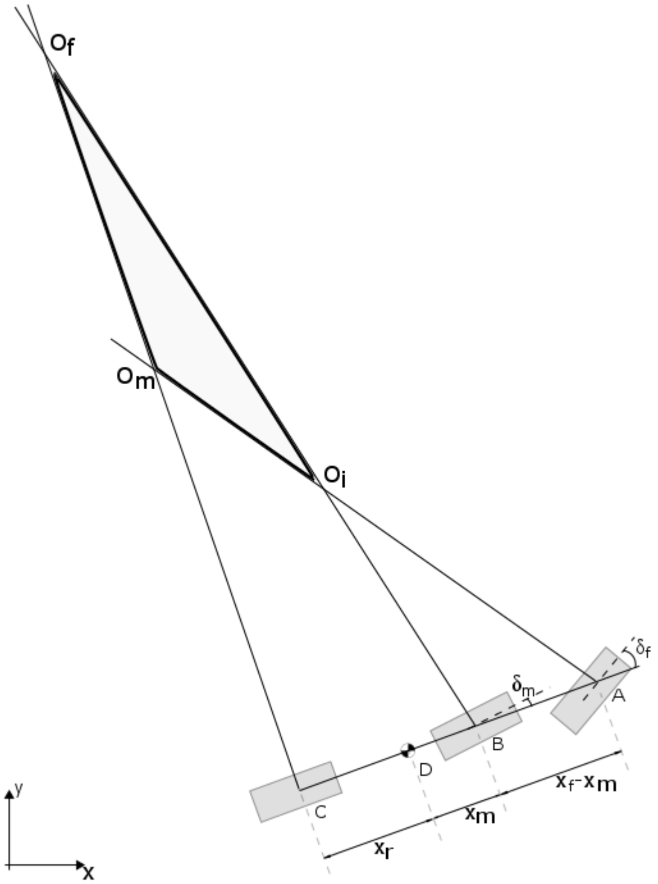


Figure 8. Three-axle vehicle's bicycle model.

Therefore, the continuous time model can be represented by

$$\begin{cases} \dot{x} = V\ \cos(\psi + \beta) \\ \dot{y} = V\ \sin(\psi + \beta) \\ \dot{\psi} = \frac{V\ \cos\beta}{x_m + x_r}\ \tan\delta_m \end{cases}, \tag{16}$$

where,

$$\beta = \arctan\left(\frac{x_r \tan\delta_m}{x_m + x_r}\right). \tag{17}$$

The inputs of this nonlinear model are V and $\delta_m = \delta_f / k_\delta$. However, for simplicity and to not consider the effects of longitudinal dynamics, in this work V is set constant. The steering angle δ_f (or δ_m), in turn, is discretized with a period T, assuming the input form shown in Figure 7.

In order to discretize the model, it can be observed that $\dot{\psi}$ is constant over time intervals of length T, and if its not zero,

$$\psi(kT + T) - \psi(kT) = \dot{\psi}_k\ T. \tag{18}$$

For the longitudinal position we have,

$$x(kT + T) - x(kT) = \int_{kT}^{kT+T} V\cos(\psi + \beta)dt$$

$$= \frac{V}{\dot{\psi}_k}\left[\sin\left(\dot{\psi}_k T + \psi_k + \beta_k\right) - \sin(\psi_k + \beta_k)\right], \tag{19}$$

and additionally, for the lateral position,

$$y(kT + T) - y(kT) = \int_{kT}^{kT+T} V\sin(\psi + \beta)dt$$

$$= -\frac{V}{\dot{\psi}_k}\left[\cos\left(\dot{\psi}_k T + \psi_k + \beta_k\right) - \cos(\psi_k + \beta_k)\right]. \tag{20}$$

If $\dot{\psi} = 0$, the model is simpler, becoming

$$\begin{cases} x(kT + T) = V\ \cos(\psi + \beta)\,T + x(kT) \\ y(kT + T) = V\ \sin(\psi + \beta)\,T + y(kT)\ . \\ \psi(kT + T) = \psi(kT) \end{cases} \tag{21}$$

Using this discrete-time nonlinear model for the vehicle, it is possible to predict with calculations and to optimize the objective function considering the constraints that the problem is subjected to.

Objective Function

The objective function is an essential element for the MPC project, because through it we can predict and identify undesired behaviors of the dynamic system, and then try to correct them generating the adequate control signals. In general, this function incorporates a reference to the output signal as well as penalties for the input efforts and their variation between two consecutive control periods, or even for any inconvenient measurement or state.

As mentioned, one of our assumptions is the existence of ideal military sensors equipping the vehicle with the ability to identify the position of threats within their combat zone. From these data, the distance between the vehicle and those threats can be easily calculated, making it possible to define an instantaneous potential threat ϕ such that

$$\phi = \sum_{i=1}^{N_T} \frac{\tau_i}{d_i^2}, \tag{22}$$

where N_T is the number of identified threats, τ_i is the constant that quantify the level of danger associated to the i^{th} threat and d_i is its distance to the vehicle. This potential threat serves as the output to the system, and the reference signal to be followed is simply $\phi_R = 0$.

In addition to the potential threat, penalties were considered for input efforts and also for the lateral position of the vehicle, as we tried to define lateral boundaries to the movement. Therefore, the objective function at the instant time t was defined as

$$J(t) = R_\phi \sum_{k=1}^{N_p} \hat{\phi}^2(t + kT \mid t) + R_\delta \sum_{k=1}^{N_c} \delta_f^2(t + kT) + R_y \sum_{k=1}^{N_p} \left[\hat{y}^2(t + kT \mid t) - \Lambda^2\right]. \tag{23}$$

The above parameters are defined:

- N_p - the prediction horizon of the MPC;
- N_c - the control horizon;
- R_ϕ - the potential threat penalty weight on the objective function;
- R_δ - the input efforts penalty weight; and,
- R_y - the lateral distance (to the boundary) penalty weight.

Here, the general standard notation

$$\hat{w}(t + kT \mid t)$$

means "the predicted value of $w(t + kT)$ on the time instant t".

On Figure 9, a general situation for a given time instant t is shown.

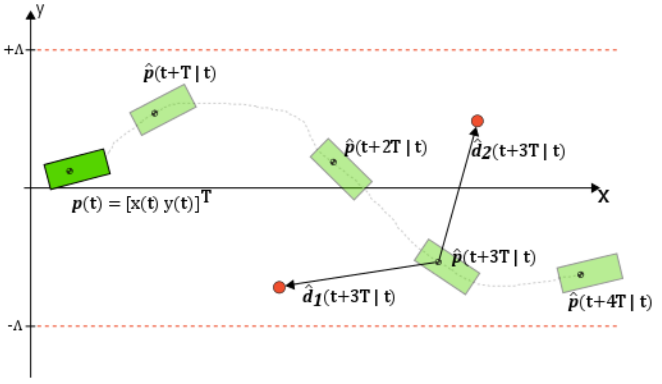


Figure 9. Predicted position obtained by the MPC.

Constraint Setup

The stated optimization problem may be subjected to several constraints. In this case we considered only constraints (equality and inequality) on the input signals of the kinematic model in order to restrict them according to the physical feasibility of the vehicle. The constraints are represented by

$$V(t+kT) = V_0\,, \tag{24}$$

and

$$\delta_f^2(t+kT) \leq \delta_{f,max}^2\,, \tag{25}$$

for $k = 1, 2, \ldots, N_p$ and the values: $V_0 = 25\,m/s$; $\delta_{f,max} = \pi/18\,rad = 20^o$. The time instant t represents when the optimizations begin.

Simulations and Results

The next step after the development of the mathematical models, of the Fuzzy Ponderer and the implementation of the MPC was to perform some simulations of the vehicle with the application of the proposed semi-autonomous control system.

Parameters Configurations

These simulations were carried out for some different penalty weight parameters values, which allowed us to obtain different results. Four of them, which were considered the most promising parameter configurations, will be presented. These results demonstrate the semi-autonomously controlled vehicle's behavior in an area threatened by the employment of IEDs. On Table 2 the different parameters values for the simulations are presented.

Table 2. Values for the objective function parameters.

Test #	R_ϕ	R_δ	R_y
1	1	10	0,00001
2	10	100	0,00001
3	1	1000	0,00001
4	1	1000	0,00002

All tests were performed with two IEDs installed at the same position, that is,

$$\boldsymbol{p}_{IED1} = \begin{bmatrix}50\\0\end{bmatrix} m \text{ and } \boldsymbol{p}_{IED2} = \begin{bmatrix}100\\0\end{bmatrix} m\,,$$

and the lateral limits were selected as $\pm\Lambda = \pm 30m$.

Test Results

The performed simulations allowed us to obtain the trajectories described by the vehicle movements, and also the evolution curves of the time-varying intervention variable K.

Figures 10, 11, 12 and 13 show the results for the tests #1, #2, #3 and #4, respectively.

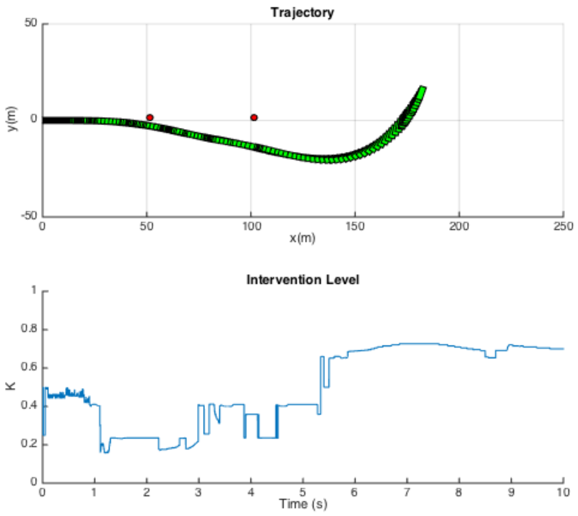


Figure 10. Vehicle's Trajectory and Intervention Level's behavior for Test #1.

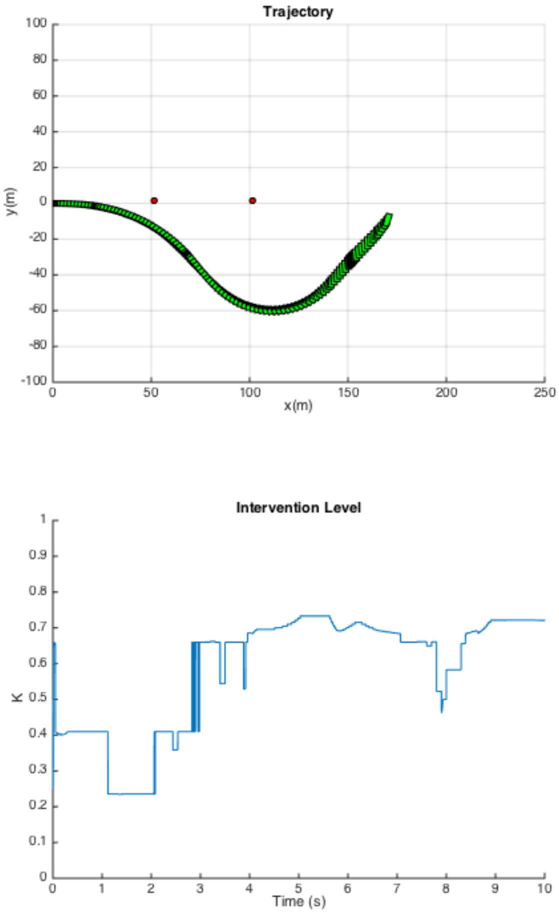


Figure 11. Vehicle's Trajectory and Intervention Level's behavior for Test #2.

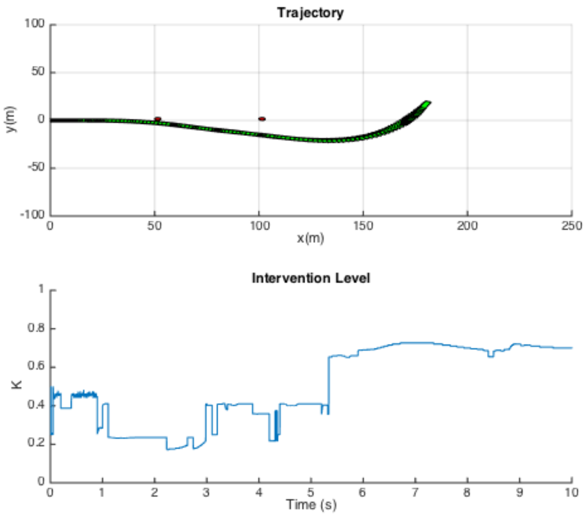


Figure 12. Vehicle's Trajectory and Intervention Level's behavior for Test #3.

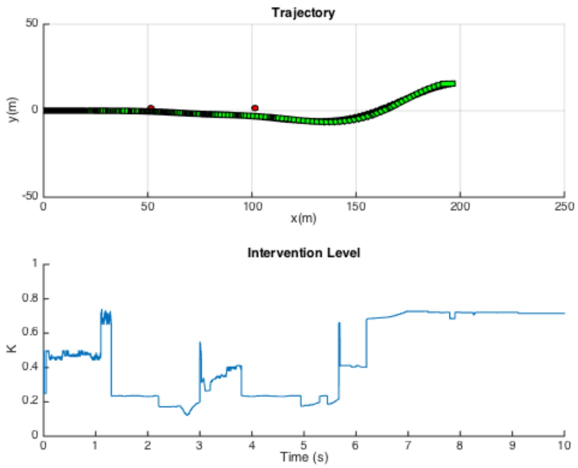


Figure 13. Vehicle's Trajectory and Intervention Level's behavior for Test #4.

As one can observe from the results, the behavior of the proposed system is extremely sensitive to the configuration of the objective function parameters. This becomes evident by the difference between the trajectories presented in Figures 10, 11, 12 and 13 and thus opens the way for the rise of a new demand: the definition of a consistent methodology for the tuning of these parameters according to the characteristics of the vehicle being controlled, and with the user's operational needs.

In accordance with the expectations, the action of the proposed control system on the car was enough to make the maneuvers required to keep the system within a safe area of the terrain, slipping away from the hostile threats. Still a point to be observed, the behavior of the level of intervention K occurred as expected, becoming greater in the final period of each of the tests, at the same time that the lateral stability of the vehicle was harmed due to previous maneuvers.

Summary/Conclusions

In this paper we proposed a semi-autonomous control system based on Fuzzy techniques and Model Predictive Controllers to be deployed in military vehicles. This proposed system is composed of two main subsystems, which are the "Fuzzy Ponderer" and the "MPC Sub-controller", which are developed from mathematical models that were also presented. Some concepts about the semi-autonomous control of vehicles were presented, as well as the architecture of the proposed system. For this work, in particular, we can mention the development and the use of a kinematic model of the vehicle to the design of the MPC Sub-Controller MPC, which in turn complemented the system proposed in [9]. All the presented mathematical tools allowed us to perform simulations of the proposed semi-autonomous control system in a military vehicle being employed on a high-risk situation of risk, within an area threatened by the presence of hostile explosives. The results obtained from four different simulated test situations were presented. It was seen that the system behaved as expected, preventing the vehicle to take high risk positions within the terrain upon which it was employed and assuming higher levels of control authority as the lateral stability of the vehicle was being harmed.

For the future, we intend to continue the development of the system, trying to conduct tests for comparing the proposed system with other systems available in the literature. An important goal would be the reduction of the levels of intervention variable K, as an attempt to make the system less intrusive to the driver, which can be considered a problem in the proposed system for now.

References

1. World Health Organization, "Global status report on road safety 2013: supporting a decade of action." 2013, ISBN 978-92-4-156456-4.
2. National Highway Traffic Safety Administration (NHTSA), "Traffic Safety Facts 2012". NHTSA National Center for Statistics and Analysis, 2014.
3. Liu, X. and Dai, B., "The Latest Status and Development Trends of Military Unmanned Ground Vehicles", in Chinese Automation Congress (CAC), IEEE 2013, pp. 533 - 537.
4. Anderson, S. J. "A Unified Framework for Trajectory Planning, Threat Assessment, and Semi-Autonomous Control of Passenger Vehicles". Master Thesis, Dept. of Mechanical Engineering, MIT, 2009.
5. Storms, J. and Tilbury, D., "Blending of Human and Obstacle Avoidance Control for a High Speed Mobile Robot", in *American Control Conference (ACC)*, IEEE 2014.
6. Jansson, J., Johansson, J. and Gustafsson, F. "Decision making for collision avoidance systems," Society of Automotive Engineering (SAE), p. 403, 2002.
7. Huang, W. H., Fajen, B. R., Fink, J. R. and Warren, W. H. "Visual navigation and obstacle avoidance using a steering potential function," *Robotics and Autonomous Systems, vol. 54, no. 4*, pp. 288 - 299, 2006.
8. Richier, M., Lenain, R., Thuilot, B. and Berducat, M. "ATV rollover prevention system including varying grip conditions and bank angle", in *3rd International Conference on Machine Control and Guidance*, pp. 701-720, 2009.
9. Azevedo Sá, H., Neto, M. S. and Meggiolaro, M. A., "Artificial Intelligence based semi-autonomous control system for military vehicle", in *5º Colloquium SAE BRASIL de Eletro Eletrônica e Mostra de Engenharia*, 2015.

10. Sheridan, T. “Telerobotics, Automation, and Human Supervisory Control”. Cambridge: MIT Press, 1992.
11. Nilsson, J. “On the Interaction Between Driver Assistance Systems and Drivers in Situations of System Failure,” Chalmers University of Technology, 2011.
12. Chen, F., Wang, M. and Duan, L. “Letting Drivers Know What is Going on in Traffic,” in *Advances in Intelligent Vehicles*, Elsevier, 2014. ISBN 978-0-12-397199-9.
13. Anderson, S. J., Peters, S.C., Iagnemma, K. and Overholt, J. “Semi-Autonomous Stability Control and Hazard Avoidance for Manned and Unmanned Ground Vehicles”. Dept. of Mechanical Engineering, MIT, 2010.
14. Anderson, S.J., Karumanchi, S.B. and Iagnemma, K., “Constraint-based planning and control for safe, semi-autonomous operation of vehicles”, in *Intelligent Vehicles Symp*. IEEE, 2012, pp. 383 - 388.
15. Anderson, S.J., “Constraint-based navigation for safe, shared control of ground vehicles.” Ph.D. Thesis - Dept. of Mechanical Engineering, MIT, 2013.
16. Strand, N., Nilsson J., Karlson, M. and Nilsson, L., “Semi-automated versus highly automated driving in critical situations caused by automation failures”, in *Transportation Research Part F: Traffic Psychology and Behaviour*, *27, Part B*, pp. 218-228, 2014
17. Yu, H., Spenko, M. and Dubowsky, S., “An Adaptive Shared Control System for an Intelligent Mobility Aid for the Elderly”, in *Autonomous Robots 15*, pp. 53-66, 2003.
18. Peters, S. C. and Iagnemma, K., “Stability measurement of high-speed vehicles”, in *Vehicle System Dynamics, vol. 47, no 6*, pp. 701-720, 2009.
19. Qin, S. J. and Badgwell, T. A., “A survey of industrial model predictive control technology”, in *Control Engineering Practice 11*, pp. 733-764, 2003.
20. Camacho, E. F. and Bordons, C., “Model Predictive Control – 2nd Ed.”, Springer, 2007.
21. Rajamani, R., “Vehicle Dynamics and Control – 2nd Ed.”, Springer, 2012.
22. MULTICORPOS ENGENHARIA, “Modelagem e análises da Viatura Blindada para Transporte de Pessoal (VBTP)”. Technical Report, 2009.

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Definitions/Abbreviations

ADAS	Advanced Drive Assistant Systems
AI	Artificial Intelligence
APC	Armored Personel Carrier
DOF	Degree Of Freedom
FIS	Fuzzy Inference Systems
IED	Improvised Explosive Device
LASER	Light Amplification by Stimulated Emission of Radiation

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