

Dead Zone Compensation in Direct Current Motors: A Review

Leonardo Pires de Souza* Rodrigo Zelir Azzolin**

* *Computer Science Center, Federal University of Rio Grande, RS,
(e-mail: leo_pires300@furg.br).*

** *Computer Science Center, Federal University of Rio Grande, RS
(e-mail: rodrigoazzolin@furg.br)*

Abstract: As one of the types of electric motors, DC motors are presented, a class of motors that is commonly used in torque and speed control systems. The control of these motors in real applications is affected by system nonlinearities, such as the dead zone, which limits the motor to fulfill its task with precision since it disables the motor movement for certain applied inputs. Thus, control methods need to be implemented to compensate it. Three modern control methods generate good compensation results: artificial neural networks, fuzzy logic and sliding mode control. Thus, this study aims to perform a review of the available literature on the use of these methods in the compensation of the dead zone in direct current motors.

Keywords: dead zone; compensation; artificial neural network; fuzzy logic; sliding mode control.

1. INTRODUCTION

Electric motors were responsible for great industrial advances, mainly for combining the advantages of electric energy, such as its low cost, ease of transport and being a clean source, with a simple constructive form, with great versatility and applicability. The class of electric motors, in response to an electrical input command, efficiently control the speed and/or position of a mechanical load Mohan (2012).

Historically, direct current motors (DC motors) have been the most popular in position and speed control applications. Following the definition of electric motors as a basis, a DC motor, or simply a continuous motor, is an electrical machine that transforms electrical energy in the form of direct current into mechanical energy for handling loads.

In their physical aspect, these motors are usually small and do not pollute the environment. The Figure 1 illustrates a direct current motor, as well as its component parts.

According to Mohan (2012), the biggest advantage of DC motors is the ease with which torque and speed can be controlled. Due to the ease of controlling these variables, direct current machines can often be used in applications that require a wide range of motor speeds or precise control of the motor output, both for dynamic operations and for steady state Fitzgerald et al. (2003).

They are the most used today, and their applications range from steel rolling mills, railway traction, to a wide variety of industrial drives, robotics, printers and precision servos Hughes and Drury (2019).

However, in real implementations, direct current motors do not only present advantages, mainly due to the non-linearity of the systems. Unlike linear systems, the response characteristics of nonlinear systems depend on the

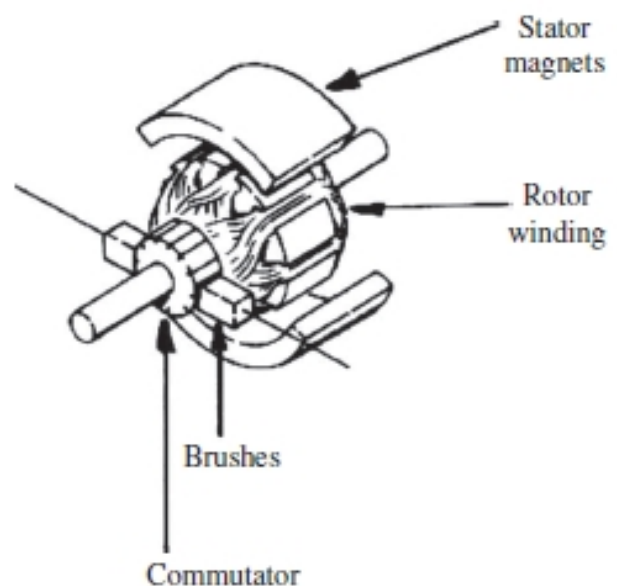


Figure 1. Exploded view of a DC motor, by Mohan (2012).

input. This makes nonlinear systems much more complex in terms of behavior. Usually these nonlinearities cause undesirable effects to the systems, and they must be compensated appropriately.

In the case of systems composed of direct current motors, the dead zone (DZ) is a recurrent nonlinearity. According to Jang et al. (2005), dead zone is a static nonlinearity that describes a lack of sensitivity in a system to work with small signals. It is configured as an operational range of input values that does not respond to the output dynamics of the system Salcedo et al. (2010). For He et al. (2015), the presence of a dead zone will cause the system to lose performance or become unstable. Perfect dead zone

compensation is difficult, but its performance degradation effects can be minimized Valdiero et al. (2005). According to Borowski (2013), control methods need to be implemented to compensate the dead zone.

According to He et al. (2015), sliding mode control (SMC), fuzzy control, and others intelligent control methods, such as artificial neural networks (ANN), are used to compensate the negative effects of the dead zone.

With the property of universal approach and learning capacity, artificial neural networks have proven to be powerful tools for controlling the complex dynamics of nonlinear systems with uncertain parameters Jang et al. (2005).

The approximation properties of fuzzy logic functions and the ability of fuzzy systems to discriminate information based on the regions of the input variables, makes them an ideal candidate in compensating for nonlinearities of non-analytical actuators.

The sliding mode control approach, according to Utkin et al. (1999), is recognized as one of the most efficient tools for developing robust controls for highly complex dynamic nonlinear plants, operating under uncertain conditions.

The aim of this study is to carry out a review of the literature found on dead zone compensation in direct current motors, based on the techniques of artificial neural networks, fuzzy logic and sliding mode control, as well as to present the characteristics and possible results of the studies found.

This paper is organized as follows: Section 2 presents the definitions of the nonlinearity known as the dead zone, as well as some of its characteristics. In Section 3, the main studies found in the literature on the three most prominent control strategies for dead zone compensation in DC motors will be addressed: artificial neural networks, fuzzy logic and sliding mode control. The final discussion of this paper will be presented in Section 4.

2. DEAD ZONE IN DC MOTORS

The dead zone is a recurrent nonlinearity in systems with direct current motors. It is caused primarily by the Coulomb frictional force of the motor rotor Kara and Eker (2004). According to Slotine et al. (1991), a motor's dead zone limits the motor ability to respond to small inputs since the torque generated by small inputs will typically be less than the torque required to overcome Coulomb frictional force. The dead zone prevents a system from fulfilling its task accurately, since it disables the motor rotation over some applied torques, representing a loss of information when the signal is within the dead band, which can cause limit cycles, tracking error, among others problems.

The characteristic of the dead zone is shown in Figure 2. The dead zone can be of two types. As cited above, the dead band is comprehended as the values between $-Z_M$ and Z_M and for input values (u), like voltage, within the dead band, the output value ($y(u)$), like torque, will be zero.

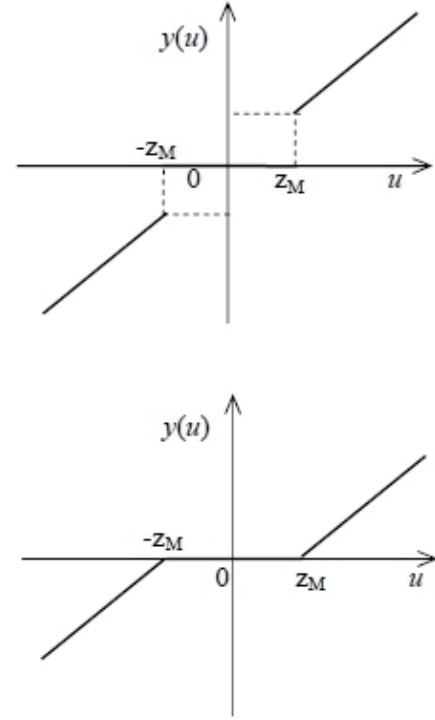


Figure 2. Dead zone characteristics in DC motors, by da Silva (2006).

As stated by Jang et al. (2005), although there are some open loop applications of which the dead zone characteristic is highly desired and therefore intentionally applied, in most closed loop applications, the dead zone causes unwanted effects on the dynamics of feedback and system control performance. Affirmed by Borowski (2013), the dead zone of the motor introduces position errors that can severely affect the performance of an application with DC motors. Figure 3 shows the difference in position of a motor with and without dead zone nonlinearity.

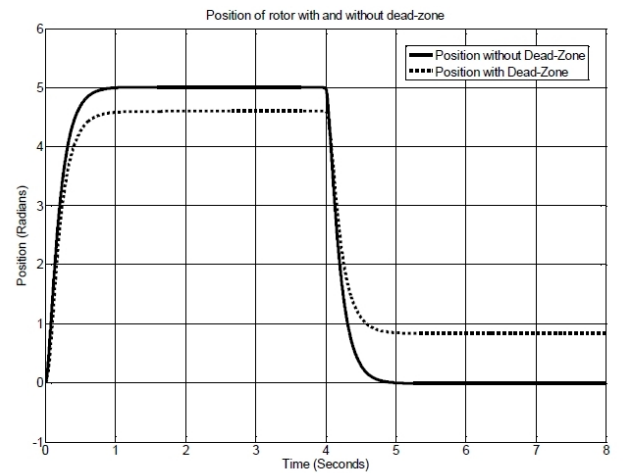


Figure 3. Position error, by Borowski (2013).

As noted by Borowski (2013), errors generated by the dead zone can be quite significant and can become a major

problem in physical systems that require high precision in position control, for example.

3. CONTROL STRATEGIES FOR COMPENSATION

Due to the difficulty of controlling systems with nonlinearities, inaccuracies and uncertainties, conventional methods of control are not as effective as necessary. In this way, some modern control methods are being more used in these applications. When performing the literature search, the main point that can be observed is the wide application of artificial neural network controls, fuzzy logic and sliding mode control to solve dead zone compensation problems. This finding can be seen as evidence of the efficiency of these modern control methods.

3.1 Artificial Neural Network

Much has been researched in intelligent controls using artificial neural networks. Artificial neural networks were developed by observing the functioning of the human brain. For Haykin (2007), a ANN is a massively distributed processor, consisting of simple processing units, which has the natural propensity to store experimental knowledge and make it available for use.

According to da Silva (2006), an artificial neural network is a mathematical structure consisting of a finite number of individualized units, also called neurons, organized in layers. Figure 4 is an example of an artificial neural network, that can be observed the neurons, represented by the 6 circles organized in 2 layers, the first one with 4 neurons, known as intermediated layer, and the second one with 2 neurons, called output layer. Its also represents the input values (X_1, X_2, \dots, X_{10}) used by the neurons to calculate the outputs (Y_1, Y_2) of the ANN.

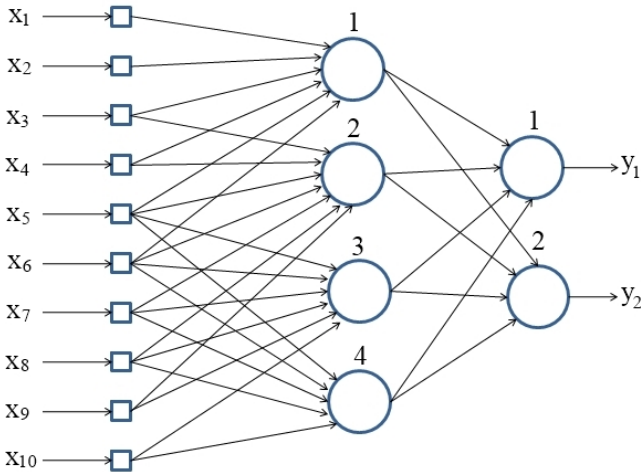


Figure 4. Example of an ANN, adapted from Haykin (2007).

Among the literature found on the use of compensation methods with artificial neural networks, the studies Jang and Jeon (2000), Gervini and Gomes (2001), Gervini et al. (2003) and Selmic and Lewis (2000) stand out. These researches presented different ways of using neural networks to compensate the dead zone and are the studies most cited by publications on the same topic.

In the article Jang and Jeon (2000) a neural network control method is proposed to compensate for nonlinearity, which the proposed neuro-controller consists of a linear controller in parallel with a neural network controller (NNC). The final version of the controller is illustrated in Figure 5. The neural network (NNC) will adapt its own weights based on the identification of the plant error. For estimates the dynamics of the plant and calculate the error, was applied a neural network identifier (NNI).

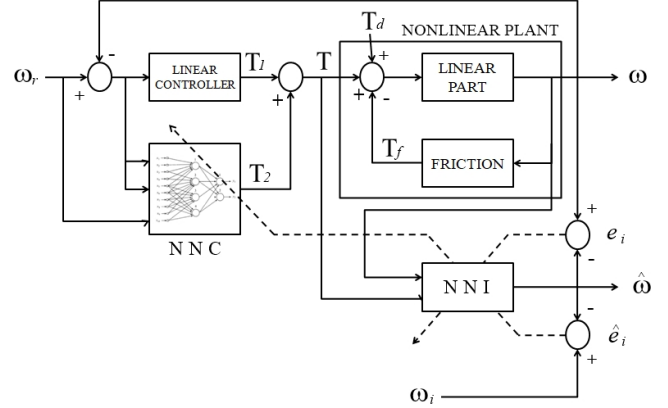


Figure 5. Block diagram of the neuro-controller in parallel, adapted from Jang and Jeon (2000).

After experimentation, the results of this article, represented in Table 1, demonstrated that the neuro-controller reduced the sum of the square error by approximately 50% compared to a conventional PI controller.

Table 1. Sum of the square error with sinusoidal and step reference signal in a experiment

Controller	With DZ	With Additional DZ
PI Controller	143.38	160.69
Neuro-Controller	73.54	80.635

Source: Adapted from Jang and Jeon (2000)

A sequence of papers published by S. C. P. Gomes and V. I. Gervini draws attention. Initially, in the article Gervini and Gomes (2001) a training strategy is presented and a structure of a neural network is proposed to learn the torque friction of a robotic actuator. The authors created and trained a backpropagation neural network with two input neurons to receive the motor torque and rotor speed variables and estimate an output referring to the estimated friction torque variable, this being the value responsible for compensating the losses from the dead zone. Simulations were carried out and excellent results were achieved.

Subsequently, a second article Gervini et al. (2003), with the contribution of V. S. da Rosa, used this same neural network created earlier, this time to perform experimental tests with an isolated real motor on a bench. According to Gervini et al. (2003), the proposed compensation mechanism, which uses the estimated friction torque at the output of the neural network, proved to be very efficient and significantly reduced the torque dead zone in the motor used in the experiments.

Finally, the study Selmic and Lewis (2000) presents a strategy for using neural networks different from the others described here. This article creates a compensator, which

the configuration is illustrated in Figure 6, that uses two neural networks, the first one (NN I) to estimate the unknown dead zone, called deadzone estimator, and the second one (NN II) to provide adaptive compensation in a direct path, called deadzone precompensator. Through an tuning algorithm, the weights of both neural networks are adjusted considering that the changes in the weights of NN II depends on the ajustes made in NN I. An analysis of the stability of the closed-loop system is also provided.

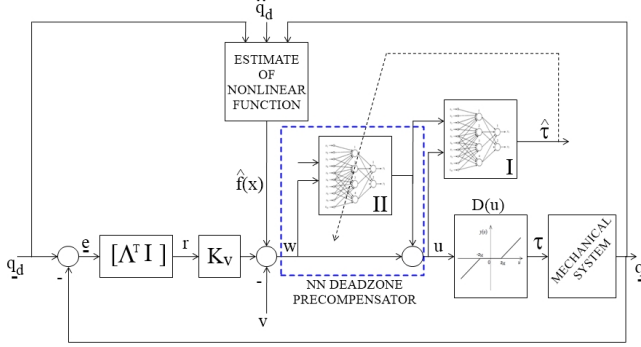


Figure 6. Position control with neural network compensator, adapted from Selmic and Lewis (2000).

3.2 Fuzzy Logic

According to Campos and Lewis (1999), fuzzy logic systems offer significant advantages over adaptive control, including the lack of linearity in the assumption of parameters and the need to compute the regression matrix for each specific system. Figure 7 shows an example of a fuzzy system used to analyze energy consumption for data transeiver. It is possible to see the 7 fuzzy sets designed, ranging from "Very Small" to "Very Large".

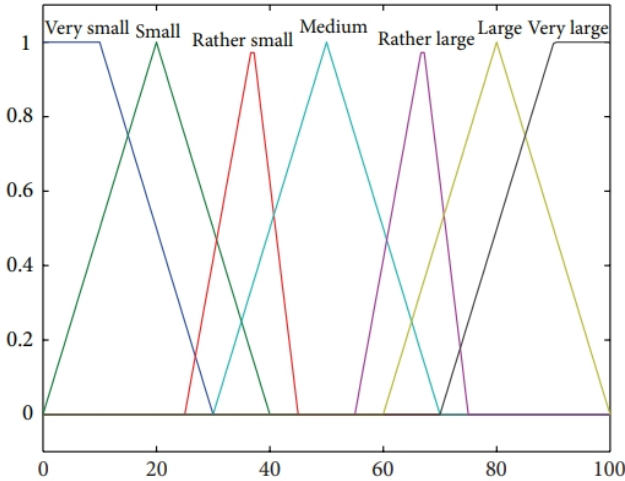


Figure 7. Example of fuzzy system, by Jiang et al. (2013).

Among the most cited studies in relation to the use of fuzzy logic in dead zone compensation, are the articles Campos and Lewis (1999) and Lewis et al. (1999). Both articles propose the creation of a fuzzy controller for industrial position control systems, also described in the articles as Lagrangian mechanical systems with multiple inputs. The parameters of the fuzzy controller are adjusted by an algorithm in order to make this controller able to estimate

online the sizes of the unknown dead zones. Figure 8 below illustrates the block diagram developed for position control using an adaptive fuzzy compensator.

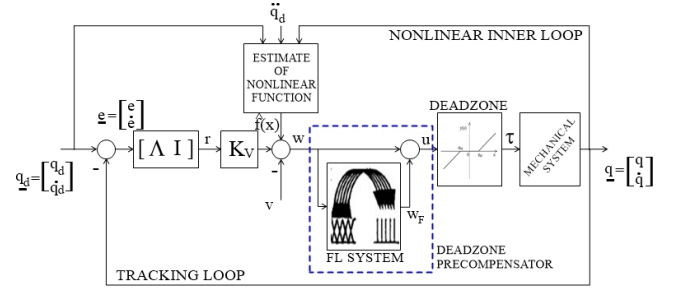


Figure 8. Block diagram of position control with fuzzy compensator, adapted from Lewis et al. (1999).

The differences between the papers are in relation to how the results were found. While in Campos and Lewis (1999) the results was generated in computer simulations, in Lewis et al. (1999) the controller was implemented in a CNC (Computer Numerically Controlled) machine. In both articles, the results were positive.

In Ramadan et al. (2014), a speed controller for a DC motor was created from fuzzy logic. In this research, the implementation took place in FPGA (Field Programmable Gate Array). Affirmed in Ramadan et al. (2014), the controller's performance is successfully validated, with good tracking results in different operating conditions.

3.3 Sliding Mode Control

The emergence of the sliding mode control theory is mainly due to the pioneering research on differential equations with discontinuities by the Russian mathematician Alexei Fedorovich Filippov. As reported in Utkin (1978), its application has been extensively investigated in the specialized literature of the former Soviet Union. For Utkin (2013), the sliding mode technique allows robust control of a nonlinear system by "sliding" the states over a predefined surface. As mentioned in Utkin (1978), in cases where there are uncertainties in the system, such as the presence of inaccuracies in the modeling or external disturbances, there can be strong adverse effects on the performance of this system. For these cases, control by sliding mode has been widely studied in the last 50 years.

Due to its properties, sliding mode control has proven to be applicable to a wide range of problems in robotics, electrical systems and process control Utkin et al. (1999). As cited by Sivaramakrishnan et al. (2017), the methodology behind the sliding mode control is to force the system to reach toward a selected surface. The idea behind SMC is to choose a sliding surface along which the system can slide to its desired final value. The Figure 9 illustrates this basic process of sliding mode control. The selected surface is the sliding surface and the desired final value was the origin point.

As prominent researches found in the literature can be quoted Bessa (2005) and Jing and Bo (2008). In Bessa (2005), the paper describes the development of a robust and adaptive control strategy for uncertain nonlinear systems with unknown dead zones. The author developed a

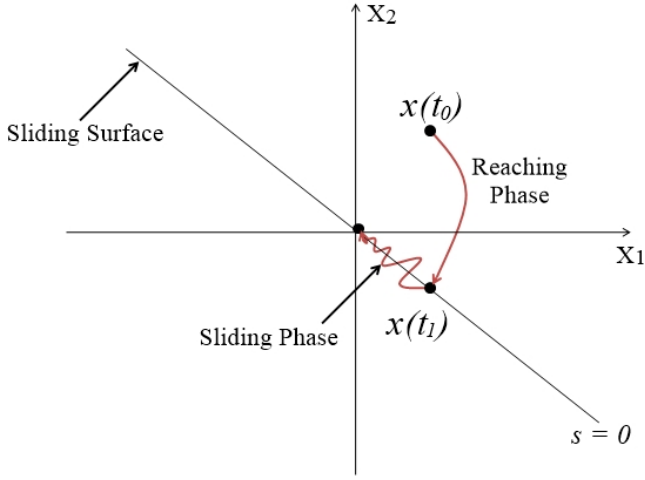


Figure 9. Basic process of SMC, adapted from Sivaramakrishnan et al. (2017).

controller for sliding mode, which incorporated an adaptive compensation strategy based on fuzzy logic, to minimize the loss of performance caused by the dead zone. Finally, the convergence properties and the stability of the system were demonstrated from Lyapunov's theory of stability, with the help of Barbalat's motto.

Another relevant study was Jing and Bo (2008). The authors classified the dead zone as an uncertain item in the system that varies over time. Based on this definition, they developed an SMC controller with an uncertain item and a compensating item, where the uncertain item was expressed by a finite Fourier series. Then, the Lyapunov method was used to guarantee the asymptotic stability of the sliding surface. Simulation results validated the effectiveness of the proposed controller applied to position controls.

3.4 Artificial Neural Networks, Fuzzy Logic and Sliding Mode Control

Among the papers that were found, some use the control strategies discussed in this article, but with one of the controls with a different function from compensating for the dead zone. This is the case in the article Machado et al. (2007), that an artificial neural network is used to compensate, in torque, the dead zone and a fuzzy logic to make adjustments to the neural network. The output of the ANN, which obtains an estimated torque that compensates for the torque lost by the dead zone, is multiplied by a gain from the fuzzy logic, in order to compensate for changes in the dead zone due to the time and operating conditions.

A similar case is seen in Hsu (2014). According to the author, the proposal is to develop an intelligent control by sliding mode control to compensate for the dead zone. This intelligent controller is composed of a main controller and a robust compensator. To create an approximator for the main controller, the author used a neural network model. It can be seen the block diagram used in this article in Figure 10.

Another model of approach found in the searches was the overviews on nonlinearity compensation. In this type of article, it is possible to find descriptions of the three control

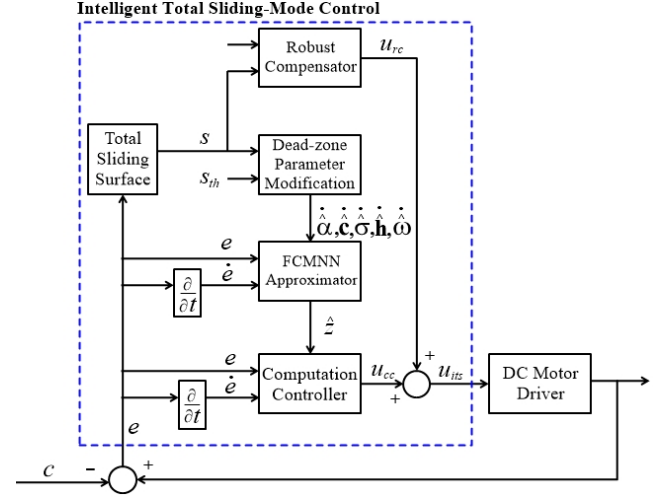


Figure 10. Block diagram of sliding mode control with neural network, adapted from Hsu (2014).

methods covered. As examples can be cited Armstrong-Hélouvry et al. (1994) and Bona and Indri (2005). Both articles are focused on definitions, theoretical foundations and the advantages of using different methods in different systems. However, they do not develop the methods, practical applications and results.

The paper Rossato et al. (2017) describes the application and analysis of two nonlinear control techniques: fuzzy logic and sliding mode for the control of biochemical reactions. A PID controller was applied to obtain a reference regarding the behavior of the other nonlinear controllers. At the end of the paper, comparative analyzes are carried out, concluding that both the control by fuzzy logic, and the control by sliding modes were more robust and had better performance than the conventional PID controller.

4. DISCUSSION

The aim of this article is to conduct a review of the technical literature considering the development and application of three modern control methods (artificial neural networks, fuzzy logic and sliding mode control), which are valuable tools in dead zone compensation, a recurrent nonlinearity in DC motors. As a final conclusion, it was possible to observe, through studies that had experimental results, that modern control methods generated good results, especially when compared to conventional control methods such as the PID controller. This indicates the efficiency of the use of artificial neural networks, fuzzy logic and sliding mode control for dead zone compensation.

As future works, the development of these three control methods and the implementation in a virtual and/or real DC motors to simulate and generate expected results to confirm efficiency of the described methods. In addition, they can be compared to find out the best method to this kind of application. Finally the development of a pros and cons chart to better conclusions.

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