Design of an Electronics Swapping System for Electric Guitars

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Abstract

The electronic components of electric guitars have a notorious influence on the sounds that can be produced with them. On the other hand, floating bridges allow the user to change the pitch by moving one end of the strings/varying the applied tension; floating bridges that work with springs located at the guitar rear are the most common. To improve the sonic capabilities of the guitar, it was designed an electronic swapping system that compatible with a rear springs bridge configuration. The design method used combined the Pahl & Beitz requirements approach with the Excitement Feature concept of the Kano model. This article presents the design of a guitar body with a side-removable module that contains the entire electronic system and can be swapped without removing the guitar strings.

Keywords
Design methodology, electric guitar, assembly design.

1. Introduction
The electric guitar is one of the most popular musical instruments nowadays. Several options in the electric guitar market offer aesthetic variety not only on the visual side of things, but in their sonic capabilities. Components such as the bridge and the electronics delimitate the sounds that can be generated with the instrument.

The bridge is located at the guitar body, and it is the element that sets the vibrating lengths of the strings and -in most cases- secures the ends of the strings. It is possible to classify the bridges in two categories: fixed and floating (also referred as tremolo or vibrato). Whereas a fixed bridge has just the functions previously mentioned, a floating bridge allow the player to change the tension on the strings by using a lever, this changes the pitch (French, 2012). Floating bridges that work with springs located at the guitar rear are the most common.

Speaking of sonic capabilities of the electric guitar, its electronics play a huge role in the electric signal that the instrument sends to the amplifier, and it is noticeable in the produced sound. There are commercial guitars that incorporate pickup swapping systems and others that swap the complete electronic system. On one hand, the Ampeg Dan Armstrong Lucite guitar allows the user to swap pickups and connect them to the rest of the electronic system; this guitar has an extended cavity for the pickups to allow a sideways swap. As can be observed in Figure 1, Relish Guitars allow to swap the pickups from the rear of the guitar body.

Figure 1. Pickup swapping system located at the rear of a guitar
(image courtesy of Relish Guitars, https://relish.swiss).

On the other hand, Fern Guitars uses side-removable modules that contain the whole the electronic system of the guitar (Figure 2 – left). Reddick Guitars let the user to interchange the whole electronics system by dividing it into modules (Figure 2 – right); a rear-removable module for the pickups and a side-removable for the controls and the output jack.

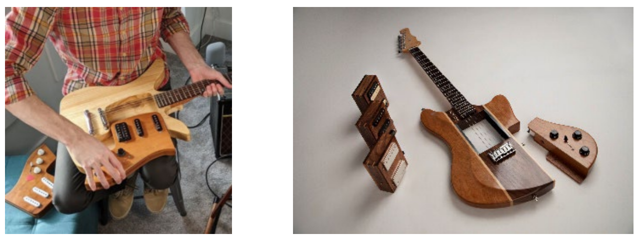

Figure 2 (left). Sideways removal of an electronics system module
(image courtesy of Fern Guitars, https://www.fernguitars.com).

Figure 2 (right). Modular guitar with interchangeable pickup sets and controls module
(image courtesy of Reddick Guitars, https://reddickguitars.com).

Additionally, Gyrock system -available on Wild Custom Guitars- can mount up to six pickups in a guitar. In this case, the user can select what transducers by operating a gyratory mechanism through levers.

All the mentioned electronics-swapping guitars have fixed bridges and there are no commercial alternatives with floating bridges. A guitar that incorporates an electronics-swapping system in combination with a floating bridge could fulfill the needs that usually require multiple instruments and become an intensely usable product. Any product used more intensely than other similar leads to a reduction in the actual number of those products at a given moment and place (Vezzoli and Manzini 2008).

The aim of this project is to design a system that allows guitar players to swap electronic components easily, even if the guitar has a floating bridge with rear springs.

2. Literature Review

2.1 The floating bridge

The Fender tremolo bridge pivots against a set of screws set into the guitar body. The tension of the strings at the top of the bridge assembly is countered by springs located at the rear of the guitar body. This way, the strings can stay at the correct pitch until the player moves the whammy bar and provides an additional torque (French 2012).

This configuration has been used in many bridge designs and allows the user to modify the number of springs, as well as the placement of the neutral position of the assembly. There are even devices to lock this type of bridges and release them whenever the user wants (Geier 2008).

2.2 Magnetic pickups

Electric guitars use transducers to convert the movement of the strings to electric signals, these devices are called pickups. There are many types of pickups that use different working principles (Kubilay, 2018) (Kodama et al. 2020), but the most popular is the electromagnetic pickup. It uses electromagnetic induction to convert the motion of a ferromagnetic string into an electrical signal. A simple electromagnetic pickup is comprised of a magnet wrapped inside a coil of wire with typically thousands of turns. The pickup is placed so the ferromagnetic material (string) is parallel to the face of the magnet. Then, the movement of the string changes the magnetic flux through the coil, producing a time-varying current. This is an application of the Faraday's Law (Horton and Moore, 2009).

The number of coils of a magnetic pickup influences its frequency response and its sensitivity to electromagnetic and electrostatic noise. Electromagnetic pickups are generally available in either single coil or double coil (also called humbucker) configurations (French 2009).

A humbucker is made with two coils of opposing polarities; this arrangement reduces or cancels unwanted electromagnetic interference. Whereas a single coil is usually defined as "bright" sounding, a humbucker produces a "warmer" tone (Houghtaling, 2021). It is interesting to note that the two coils on a humbucker are connected in series and produce a certain tone, but the typical combination of two single coil pickups (as the positions 2 and 4 in a Fender Stratocaster), is achieved by connecting them in parallel, which generates a very different sound. Because of this, there are guitars that allow to select the type of pickup connection (Paiva et al., 2012).

Whereas passive pickups don not need external power and have just the mentioned components, an active pickup typically has a small solid-state amplifier built in and might even have additional elements that modify the output signal (French, 2012). Active pickup systems may provide buffering, EQ, feedback control, filtering, and level boosting (Sweetwater, 2009). There are even active systems that use controlled electromagnetic fields to continuously sustain the strings movement, these devices are called sustainers and allow to sustain all six strings simultaneously while the player perform with both hands (Frengel, 2017).

As Paiva pointed out, the pickup position has an effect on the energy levels it can transduce of each harmonic, due to this; most electric guitars use multiple pickups (Paiva et al., 2012).

Pickup configurations are usually referred as a sequence of letters – one for each pickup - that indicates their layout; these letters may be S (single coil pickup) or H (humbucking pickup). Some of the standard pickup configurations used by Fender are (from bridge to neck position): S-S, S-S-S, H-H, and H-S-S (Houghtaling, 2021).

2.3 Controls

Electric guitars usually incorporate elements such as knobs and switches to control the volume, tone, and operating pickups, as well as other things. Due to the popularity of certain guitar models, there are pickup combinations that are related to specific controls configurations. For example, the standard Fender Stratocaster S-S-S pickup set operates with two tone knobs, one volume knob, and a 5-way toggle switch and many other guitars use the exact same combination of configurations. On the opposite, the standard Gibson Les Paul uses an H-H pickup set connected to two tone knobs, two volume knobs, and a three-way toggle switch. Unlike the S-S-S configuration, there are plenty guitars in the market that use an H-H pickup configuration with a different controls set.

3. Methods

The design method used consisted of four phases showed in Figure 3, although this structure was followed, the design process was iterative and cyclic, and many activities were revisited when acquiring new useful information. The approach and planning phase centered on the exploration of the electronics system items and variants. A list of customer requirements was made, and a Quality Function Development (QFD) matrix was used to relate them with the functional requirements (the design specifications).

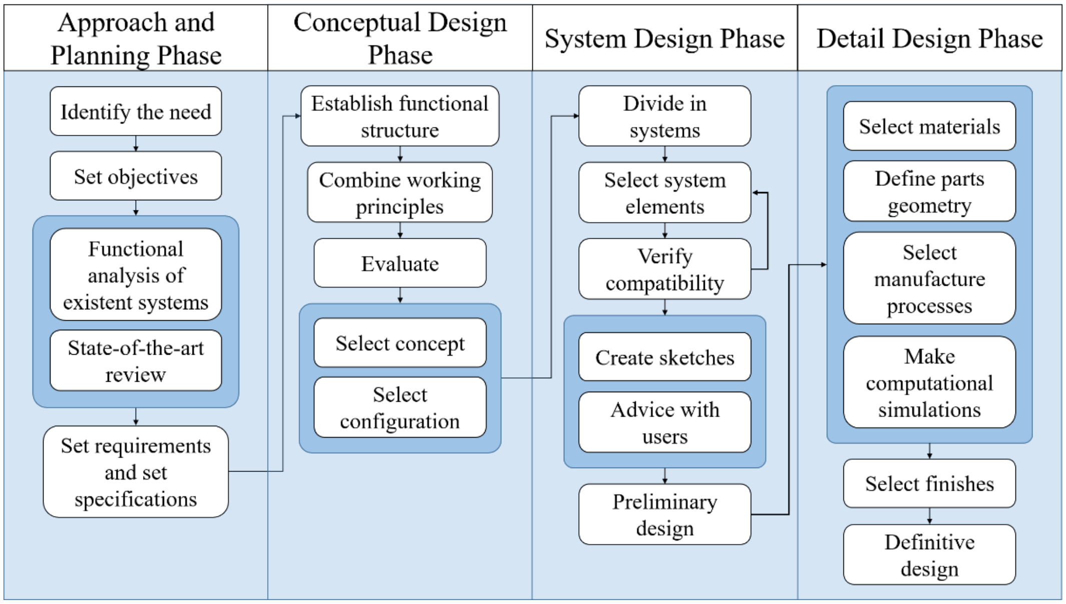

Figure 3. Design Method.

The conceptual design phase was focused on the generation and selection of concepts and configurations, i.e., different combinations of working principles and elements disposal. Both functional analysis and users' opinions were considered to make this selection process.

On the system design phase, four systems were considered: bridge, body, electronics swapping and electronics. The interactions between the systems were analyzed. The selection of elements for each system guided to a verification of compatibility between them. Sketches generation and advice taking with users, in combination with the selected elements, led to the preliminary designs.

The detail design phase encompasses the materials, geometry, and manufacture processes selection as a whole module, which outcome was evaluated with computational simulations. The finishes were selected. Finally, the definitive design is presented.

4. Data Collection

A list of 16 customer requirements was made and is presented in Table 1: Customer requirements. These requirements were classified according to the Pahl and Beitz method (Basic and Technical Performance) and the Kano model (Excitement) (Pahl et al., 2007) (Tontini, 2007). The excitement features were the electronics swapping system and its compatibility with active systems. A QFD matrix was made to relate all the customer requirements with functional requirements (specifications) such as the wood volume needed, material utilization, number of wood pieces at the body, number of raw materials, number of manufacture processes and components, weight, safety factor, manufacture time and cost.

Table 1. Customer requirements

#	Type	Requirement
1	Basic	The guitar must be able to bear the strings tension.
2	Basic	The guitar must be compatible with a strap.
3	Basic	The guitar body must be comfortable.
4	Basic	The guitar must be light
5	Basic	Input jack must be located so the cable does not touch the user when playing.
6	Basic	Controls disposal must be comfortable.
7	Basic	The guitar must be compatible with standard size pickups

8	Basic	Each pickup must be placed at a specific string length.
9	Basic	The electronics system must have a ground connection.
10	Basic	The electronics system must be protected to avoid unwilling manipulation.
11	Technical Performance	The electronic system must be isolated to avoid hum in the signal.
12	Technical Performance	The pickups - strings distance must be adjustable.
13	Technical Performance	Guitar maintenance must be easy.
14	Technical Performance	The guitar must be easy to transport.
15	Excitement	The guitar must be compatible with active pickups
16	Excitement	The guitar must be able to swap electronic components and pickups without removing the strings.

5. Results and Discussion

5.1 Functional structure

As can be seen in Figure 4, the guitar body was divided in three theoretical portions while performing the functional analysis. It was identified that portion A of the body is the one with the highest level of direct interaction with the user because -in both standing and sitting scenarios- it is lightly pressed against the user body and provides a surface to rest the arm. Additionally, this portion incorporates strap buttons, this means that when a performer plays the guitar standing with a strap, the weight and the loads applied by the user while playing is supported by this element.

The electronics system is located in portions B and C of the body and portion C acts as the interface between the user knees and the instrument when playing seated.

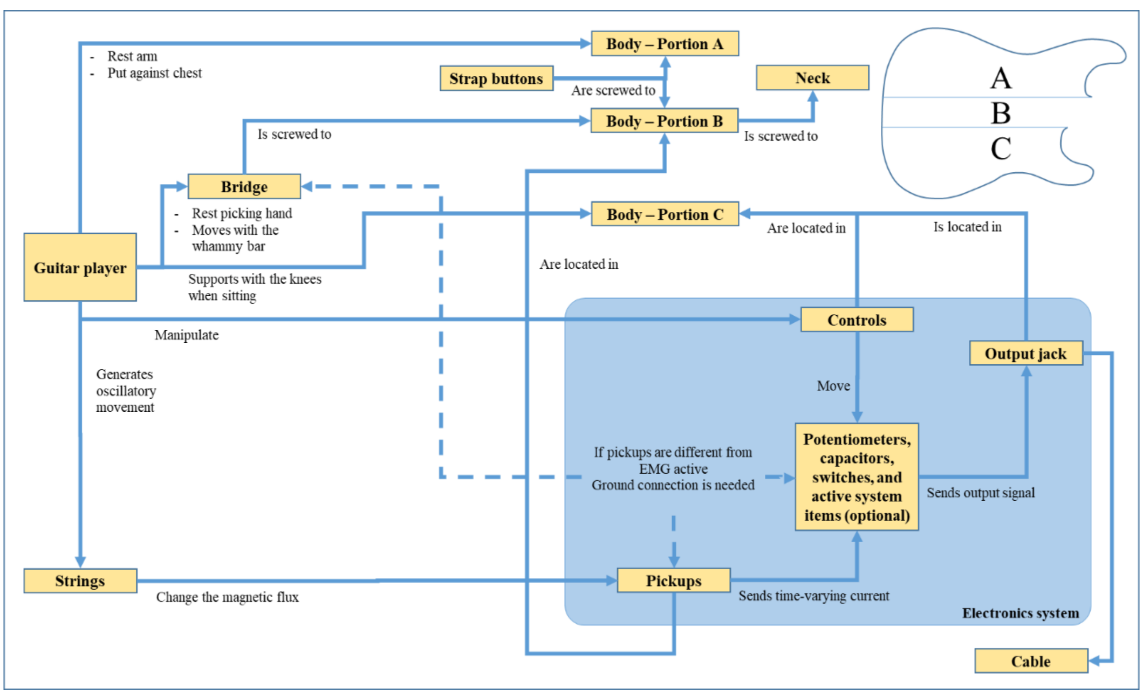

Figure 4. Functional structure of the electric guitar body.

5.2 Concept and configuration

Three electronic swapping concepts were proposed:

- Individual pickup swap with steady controls.
- Pickups set swap with steady controls.
- Full circuit swap.

Considering that there are control configurations that players associate immediately to specific pickups configurations, as well as elements that only work with specific types of pickups, it was decided to use a full circuit swap concept. As the electronics system does not interfere with portion A, and the springs obstruct the free pass at the guitar back, the selected configuration was a sideways removable electronics storage unit.

5.3 System design

As the functional analysis pointed out, each one of the guitar body portions has its specific functions and ways to interact with the user and the other elements. Because of this, each portion was treated as an individual element for configuration decision making.

Traditionally, the manufacture of solid body electric guitars implies the generation of cavities on sections B and C to storage the electronic items. This configuration was compared with two proposals that leave a large empty space to storage electronics without needing of routing but add an additional element to storage the electronics. Table 2: Guitar body proposals evaluation show how these options were compared. The number of checkmarks indicates the performance of the proposals in each specification; the total score was calculated by multiplying the performance evaluation by the normalized importance of the respective specifications. It was decided to use different materials for portions A and B and a separated item for C.

Table 2. Guitar body proposals evaluation.

Specification	Direction of improvement	Full body with a route for the electronics swapping system	Portion A and B routed from the same block. Portion C as a separated item.	Portion A and B routed from independent blocks (different materials). Portion C as a separated item.
Wood volume needed [cm^3]	▼	✓	✓✓	✓✓✓
Material utilization [%]	▲	✓	✓✓	✓✓✓
Number of wood pieces	▼	✓✓✓	✓✓	✓✓
Number of raw materials	▼	✓✓✓	✓✓	✓
Number of processes	▼	✓✓✓	✓✓	✓✓
Weight [kg]	▼	✓✓✓	✓✓	✓✓
Safety factor	▲	✓	✓✓	✓✓✓
Manufacture time [hours]	▼	✓✓	✓✓✓	✓
Cost [$]	▼	✓✓	✓✓✓	✓✓
Total score		13.86	14.7	14.87

The storage of the electronics system was proposed as a metallic box so it can act as a Faraday cage and reduce the guitar sensitivity to stray fields (Sweetwater, 1999). Different storage options were evaluated as shown in Table 3:

Electronics storage proposals evaluation. It was decided to use a folded sheet metal box with the electronics mounted on a flat element (commonly referred as pickguard).

Table 3. Electronics storage proposals evaluation.

Specification	Direction of improvement	Milled block and pickguard	Sheet metal - Two C's encountered	Sheet metal open box and pickguard
Material utilization [%]	▲	✓	✓✓✓	✓✓✓
Number of processes	▼	✓✓✓	✓✓	✓✓✓
Number of components	▼	✓✓✓	✓✓✓	✓✓
Weight [kg]	▼	✓	✓✓✓	✓✓✓
Manufacture time [hours]	▼	✓	✓✓✓	✓✓
Cost [$]	▼	✓	✓✓	✓✓✓
Total score		7.96	12.34	12.57

The holding and releasing mechanism for the electronics storage needed to allow the user to operate it directly by hand. For this purpose, four different options to join the elements were proposed. As can be seen in Table 4: Holding and releasing methods evaluation, the use of magnets for joining the elements was the one with the highest score. This option has proved to work as is the one used in Relish guitars but may require the generation of models or prototypes to determine the optimal position, type and size of magnets.

Table 4. Holding and releasing methods evaluation.

Specification	Direction of improvement	Slide with slots	Screw	Expansive bolt	Magnet
Number of raw materials	▼	✓✓✓	✓✓	✓✓	✓
Number of processes	▼	✓	✓✓	✓✓	✓✓✓
Number of components	▼	✓✓	✓✓	✓✓	✓✓✓
Manufacture time [hours]	▼	✓✓	✓✓✓	✓✓✓	✓✓✓
Total score		6.26	6.52	6.52	7.23

5.4 Materials selection and simulations

A list of recommended non-endangered tonewoods was evaluated, considering their price and availability in Mexico (Ahvenainen, 2018). This led to the selection of Poplar wood for the body wooden elements. Portion B of the body was decided to be an aluminum frame because of its stability, density and the excitement that generates in the guitar user's community. Aluminum was also selected for the electronics storage because it is an electrical conductor and can create a Faraday cage.

As can be seen in Figure 5, a simplified electric guitar body was modeled. Finite Element Analysis (FEA) were performed to ensure that the portion B does not present permanent deformations when loads are applied, i. e. plastic deformation. Fixed constraints were assigned to the screw holes that join the guitar body with the neck and a 671.68 N load was applied –this is the higher tension for six string sets of the brand Elixir (Elixir Strings 2021)- at the bridge position. Four iterations were made, using different commercial thicknesses; the thickness of the element that connects the frame with the bridge was settled as 3/8 inches for assembly purposes. As Table 5: Simulations results show, the stress on the frame increases as its thickness decreases.

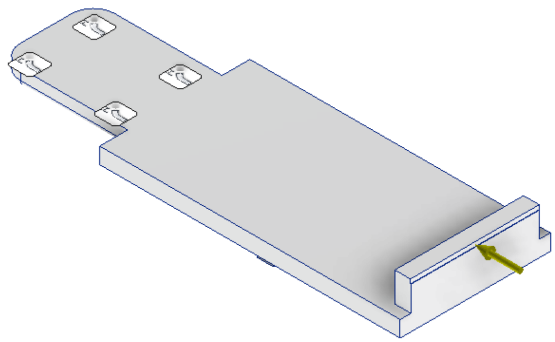

Figure 5. Simplified electric guitar body model with loads and constraints.

Table 5. Simulation results.

Frame thickness [in]	1/2	3/8	0.3	0.134
Max. Stress [MPa]	23.05	38.87	75.88	444.1
Mass [kg]	0.735	0.57	0.472	0.253

It was decided to use a 3/8 inches thickness because it presented stresses that most aluminum alloys can bear. As can be seen in Table 6: Materials evaluation, the usage of two different aluminum alloys was evaluated: 3003 (Al –Mn alloy) and 6061 (Al-Mg-Si alloy). Aluminum 6061 is 8% more expensive than 3003, but it can be machined easily, so it diminishes the manufacture time. Aluminum 3003 was the selected material for the guitar frame.

Table 6. Materials evaluation.

Specification	Direction of improvement	6061 Frame 6061 Bridge support	3003 Frame 3003 Bridge support	3003 Frame 6061 Bridge support
Number of raw materials	▼	✓✓✓	✓✓✓	✓✓
Safety factor	▲	✓✓✓	✓✓	✓✓✓
Manufacture time [hours]	▼	✓✓✓	✓✓	✓✓
Cost [$]	▼	✓	✓✓✓	✓✓
Total score		7.43	7.58	6.76

5.5 Proposed design

According with the previously presented studies, the proposed design is presented in Figure 6.

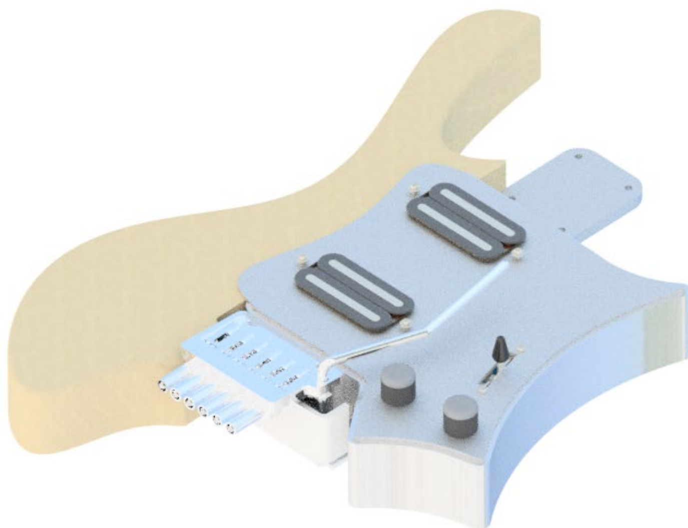

Figure 6. Proposed design render.

6. Conclusion

This design allows to easily swap the whole electronics system in a guitar equipped with the most versatile floating bridge configuration in the market, therefore, it combines in a single instrument feature that otherwise would require multiple guitars. The functional analysis of the body showed that each guitar body portion has its functions and ways to interact with the user. There is a specific portion that storage the electronics and supports the guitar when the player performs seated. The usage of just a metal box for portion C allowed to get a big empty space for the electronics system and provides electromagnetic isolation; this configuration is advised even for instruments that do not include an electronic swapping system.

The electronics storage proposal has enough space behind the strings for up to four standard size humbucker pickups; additionally, the empty space in section C allows to place knobs and switches without interfering with the user plucking hand, as well as a 9 V battery and some active circuits.

It is hard to say if the proposed design is compatible with sustainer systems. Although there have been guitars with so much aluminum that the circulating electrical currents were dissipated before they reached the bridge pickup (i.e. the sustainer driver), the usage of non-magnetic metals near the pickups is not recommended in guitars that include a Sustainiac (Sustainiac, 2018). Testing and simulations are requiered to determine this compatibility.

For this particular design, it was considered to place the tuning elements at the guitar body (commonly referred as headless configuration), this configuration has been used in ergonomic instrument design (Genani, 2013). This disposal allows to reduce the guitar body weight easily than the traditional configuration. Future design iterations may consider the optimization of the aluminum frame, as well as the usage of other high strength materials.

Finally, it is important to mention that there are floating bridges that do not obstruct the rear face of the guitar, but most of them are not as versatile as the rear springs' configuration. For future designs, it could be considered to combine a rear electronic swapping system with one of these bridges. Some examples are the Floyd Rose FRX, the Kahler, the Bigsby, and the Fender Jaguar bridge.

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Biographies

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Rafael González-Parra was born in Mexico City on October 5, 1989. He graduated from Mechanical Engineering and Master in Materials Science and Engineering at the National Autonomous University of Mexico, UNAM (Mexico City, Mexico). At the same university, he got his PhD in Materials Science and Engineering. He is a collaborator of the Surface Engineering Center (CENISA). Dr. González-Parra has research interests in corrosion, electrochemical techniques, coatings. He is a member of the Mexican Society of Electrochemistry (SMEQ) and has been part of a work group of the Surface Engineering and Tribology Network (REDISYT).

Alba Covelo was born in Vigo, Spain in July 1977. She studied Chemistry Sciences at the University of Vigo, Spain. She got her PhD at the same university in Technology Materials with the development and characterization of nanocoatings Sol-gel on aluminum alloys. Her expertise area comprises conversion coatings to protect metal/alloys against corrosion phenomena. She carried out postdoctoral research at the CENISA group of the National University of Mexico from 2012-2014 developing hybrid sol-gel coatings doped with nanocontainers and corrosion inhibitors loaded in nanofibers produced by the electrospinning technique. Her current position since 2015 is at the CENISA group of the Engineering School of the National University of Mexico. In this group, she is the leader to generate and to characterize superficial treatments of materials to modify their mechanical and electrochemical properties, mainly focused to corrosion protection.

Miguel A. Hernandez was born in Mexico City in November 1975. He got his PhD in materials engineering at the Chemistry School of the National University of Mexico in 2004 (Mexico City, Mexico) studying the electrochemical and the anti-corrosion properties of waterborne organic coatings applied on steel substrates. His expertise area relies on the electrochemical-corrosion properties of materials mainly metals/alloys.
He accomplished several fellowship jobs during his career. In 2003 he was at the Ecole Polytechnique Federal de Lausanne (EPFL), Switzerland with Prof. D. Landolt. From 2008-2010 and in 2019 he was at the University of Vigo, Spain with Prof. R. Nóvoa developing sol-gel coatings on aluminum alloys and hydrophobic anodized layers. In 2010 he also stayed with Prof. M. Zheludkevich at the University of Aveiro, Portugal studying localized corrosion measurements on AA2024 alloys. His current job since 2010 is located at the Engineering School of the National University of Mexico, Mexico at the CENISA group.

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