UNIVERSITAT POLITÈCNICA DE CATALUNYA

Doctoral Program:

AUTOMÀTICA, ROBÒTICA I VISIÓ

Research plan:

Advanced fuel cell control and motion planning for durability and efficiency improvement of a mobile robot PEMFC power plant

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September, 2019

CONTENT

1. Introduction and motivation

Renewable energy and robotics are technological areas that receive strong worldwide research effort, largely because of the great impact they may have in the improvement of society as a whole.

Developing efficient, clean, renewable, energy generation and storage systems is a fundamental requirement for transitioning into a post-fossil fuel economy; this transition, according to increasing evidence is inevitable and urgent in order to reduce climate change and mitigate its consequences. In this line, it has been widely studied that transportation industry causes a large amount of the emissions of greenhouse effect gases, thus, it makes sense to address important effort in developing clean and renewable energy based powertrains for transportation.

On the other hand, robotics in general has had an immense impact in upgrading manufacturing productivity, reducing production costs and freeing human labor from hard or dangerous tasks. Most of the robotic equipment installed and operated worldwide are industrial manipulators (i.e. robotic arms), however now there is a major push into the advancement of mobile service robots, for tasks such as surveillance, material handling, dangerous terrain recognition, earth sciences research, space exploration, human assistance. Mobile robotic platforms, ranging from small service robots to large vehicles (self-driving cars can be included here) powered by renewable energy plants are at the intersection of those two technological branches. Autonomous mobile robots and vehicles must be endowed with capabilities to optimize operation, paths, motion and driving modes in order to achieve a more efficient use of energy resources.

Fuel cells are electrochemical based energy sources that produce power by directly extracting the chemical energy of a fuel and an oxidant without the need of combustion. They combine what can be thought as the best of two worlds: storage and production of clean electrical energy (such as batteries), and the capacity of fast and continued refueling (such as internal combustion machines). There exist several types of fuel cells classified mainly by taking into account two factors: the type of electrolyte and the kind of fuel they use.

This thesis project will focus its research over Proton-Exchange Membrane Fuel Cells (PEMFC). These cells use an acid membrane as electrolyte and possess many advantageous characteristics [1]: larger specific energy (kW-h / kg) than batteries, an acceptable energy density (kW-h / m3) as compared to internal combustion engines, they produce energy from a clean process (water is the main sub-product), operate in low temperature ranges (below 100°C), and use a renewable fuel (hydrogen); all these properties make them excellent candidates as power plants in transportation equipment such as automobiles, trains, aircrafts and ships, substituting or complementing hydrocarbon power-drives and battery based electrical supply systems, fig. 1.

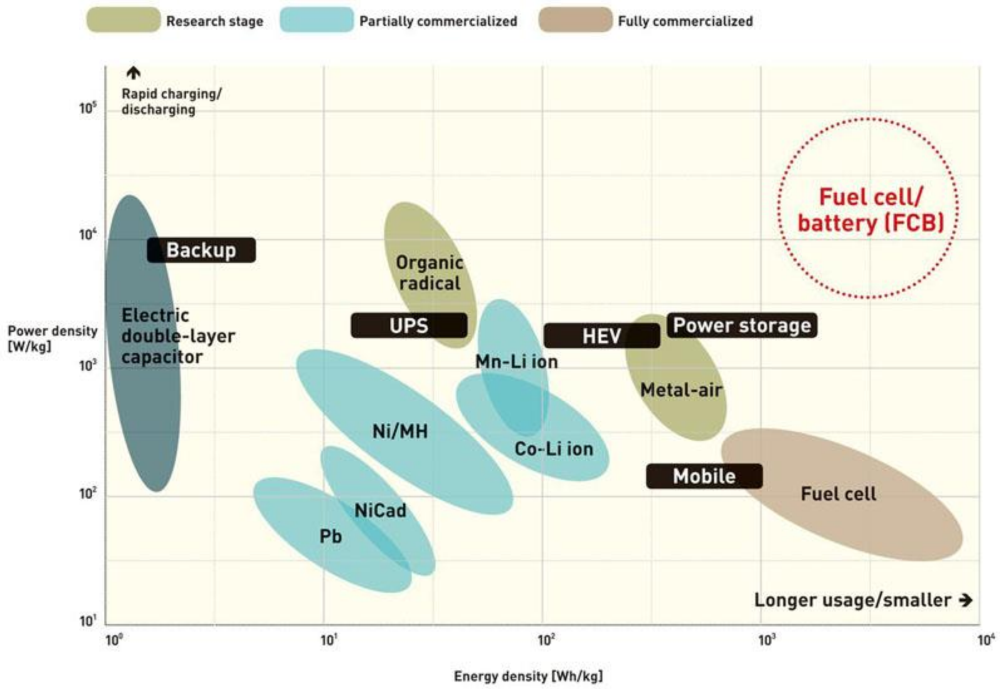


Figure 1. Ragone plot of several energy storage and generation devices (power density/energy density relation). [Atsushi Tsutsumi, University of Tokyo]

However, PEMFC also have several drawbacks that must be addressed, among which the most stringent are: they have low specific power (W/kg), a still high relative cost and their main components (membrane and catalyst) suffer fast degradation depending on the operating conditions. Specially, below-required durability is an important factor that hinders its widespread use, thus, novel operating and control approaches are required to surpass this shortcoming.

The motivation of project is to improve those control strategies to advance in a broader use of fuel cell as energy plants of autonomous mobile robots and vehicles in general.

A secondary motivation of the project is in contributing to a greater interaction between advanced control strategies and high level robotics tools, which are the two main research areas within IRI; this interaction is relevant since it can produce interesting results from a basic research point of view and also outcomes that can be readily implemented in a practical scenario. Machines that take advantage of those interactions, that is, being capable, on one hand, to control and optimize their internal operating conditions based on external required tasks, not only working on pre-programmed set points, and on the other hand, select or redirect their external tasks taking into account its internal conditions, are among the groups called intelligent cyber-physical systems, and are of great interest in industrial and service environments.

2. Objectives

The main objective of the PhD thesis is to develop and implement an integrated control system for a PEMFC powered mobile robot where the middle level control of the power plant and the higher level motion planner and, the overall control architecture takes into account catalyst degradation reduction as the main design objective in order to increase durability and efficiency of the power plant.

Figure 2 shows a schematic graph of the interconnected proposed architecture, it consists mainly of two energy storage/generation elements: a PEMFC and a battery (or super-capacitor); and three main control elements: fuel cell controller, robot motion planner and energy management system. The shown architecture represents a general point of view and is expected to be simplified to accommodate for the capability of elements that can be physically implemented in the mobile platform.

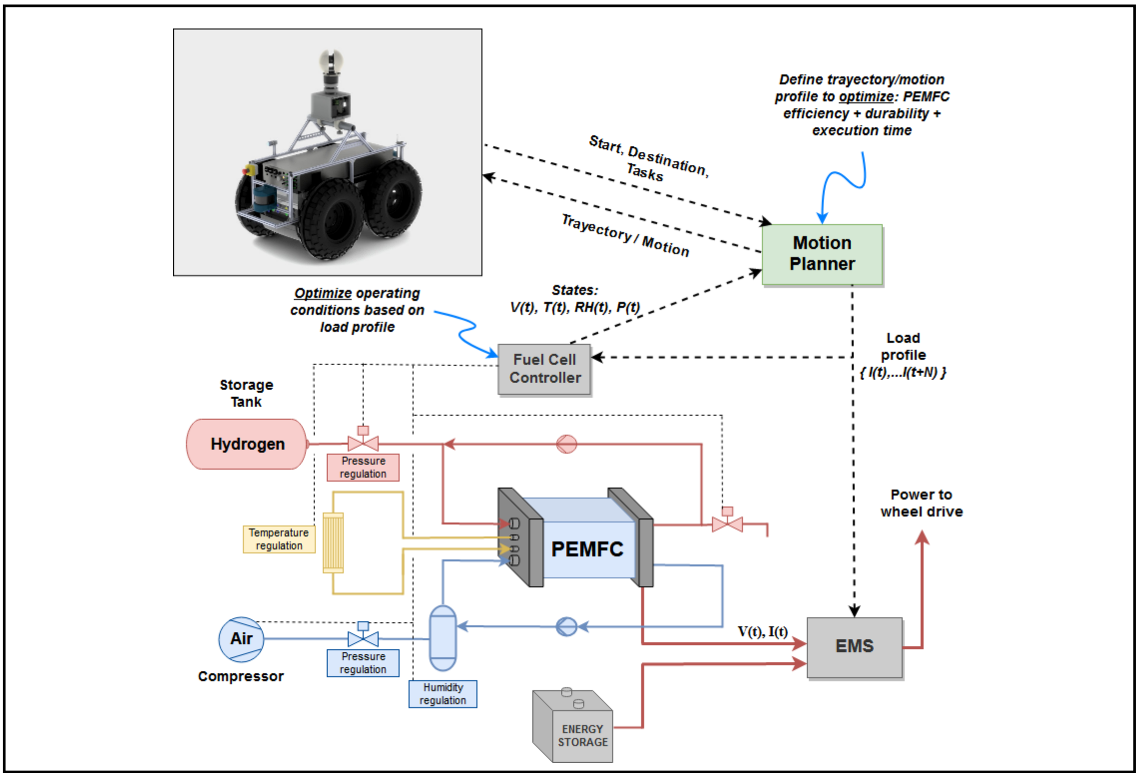


Figure 2. Schematic graph of the base goal architecture with modules interaction.

Starting from the main objective and with the proposed architecture as a goal, there are four key specific objectives that the project aims to attain:

- Design a model-based upper level control that finds optimum PEMFC operating conditions with the explicit objective of minimizing fuel cell catalyst degradation.
- Design a robot motion planner that incorporates fuel cell internal condition dynamics as a variable in the path/navigation decision process.
- Define an energy management strategy that regulates power flows of the hybrid structure in order to improve the system efficiency.
- Integrate physical hybrid (PEMFC/battery) power plant, fuel cell controller and motion planner in an autonomous mobile robot and perform a field validation of the interconnected architecture and control strategies.

These objectives are expected to be built by advancing through several milestones:

1) *Define an appropriate fuel cell model.*
2) *Propose a control algorithm that, focusing on specific objectives, finds optimum values of the most relevant fuel cell operating conditions, i.e.: temperature, gases humidity, water content, voltage.*
3) *Define an appropriate motion planning algorithm*
4) *Find motion profile (and therefore load profile) features that better describe energy plant degradation through a specific translation*
5) *Include fuel cell condition and predicted degradation evolution in the motion planning algorithm.*
6) *Define an appropriate energy management system.*
7) *Build a simulation of the integrated system.*
8) *Define the appropriate size, type, configuration and capacities of the different modules that will integrate the mobile platform: fuel cell, hydrogen tank, balance of plant elements.*
9) *Installation of the fuel cell based power plant and energy storage system on the existing robotic platform.*

3. State-of-the-art

3.1 Fuel cell structure

Production of electrical power in a fuel cell is based on an electrochemical reaction. Specifically, for PEM fuel cells, it involves the oxidation of hydrogen as fuel: every hydrogen atom splits into electrons and ions and, the subsequent reduction of oxygen: oxidant atoms bond with hydrogen ions and electrons [2]. The final product of the overall reaction is water:

$$2H_2 \rightarrow 4H^+ + 4e^- \quad (1)$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \qquad (2)$$

Overall:

$$2H_2 + O_2 \rightarrow 2H_2O \qquad (3)$$

PEM fuel cells are constructed by several components that can be grouped based on the function they perform in the internal process of sustaining and accelerating the electrochemical reaction.

- Bipolar plates/gas channel: made out of metallic material, serve as ducts to distribute the gases (fuel and oxidant) through the whole area of the fuel cell.
- Gas diffusion layer: it function is to distribute fuel and oxidant gases along the broader area possible of the cell in order to reach all the sites where the reaction can occur, commonly made out of an intricate porous structure of carbon (C) paper or fabric.
- Catalyst layer: this is the layer where the electrochemical reaction occurs. Once the gases have been diffused by the diffusion layer, ideally, every fuel and oxidant atom will reach a site where a catalyst material will accelerate the corresponding half reaction: oxidation of the fuel (hydrogen) and reduction of the oxidant (oxygen). The most common configuration of the catalyst layer currently is platinum (Pt) as the catalytic material where platinum nanoparticles (particles composed a few atoms) are supported on an agglomeration of carbon particles. Carbon serves as support of the catalyst, preventing its dissolution and also as conductor of the electrons that are either produced by the reaction in the anode side or that will joint oxygen atoms and ions in the cathode side.
- Electrolyte layer: in PEM fuel cells the electrolyte is thin solid membrane with special characteristics, ideally, it is impermeable to gases, non-conductive of electrons and can conduct protons (hydrogen ions), also, it can withstand (to a certain level) thermal and mechanical stress. In order to fulfil its function in an efficient way, the membrane must be appropriately humidified, a dry membrane will significantly reduce the cell performance.
- As shown in figure 3, the membrane conduct only ions and works as insulator for electrons, the electrons produced by the oxidation reaction in the anode are forced to travel through and external circuit in order to reach the cathode, this potential difference is exploited as electrical power by an external load.

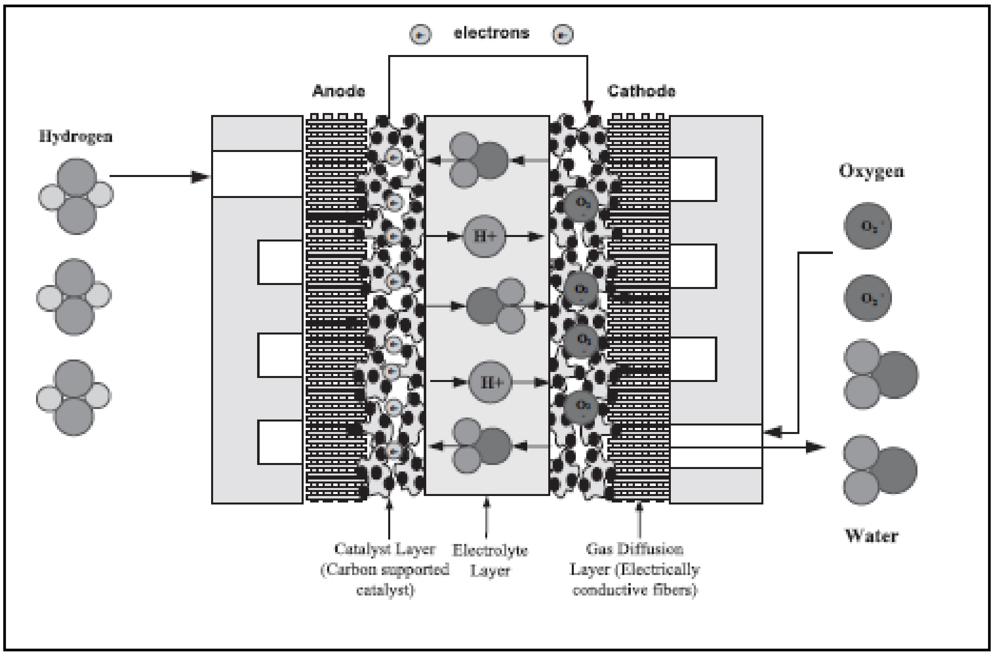


Figure 3. Schematic of the internal structure of a PEMFC.

3.2 Fuel cell systems

A complete fuel cell power system is composed of the fuel cell itself and a number of elements required to sustain its operation, those components are referred as Balance of Plant (BoP), figure 3 shows the most common BoP elements: an oxidant feeding system with a compressor (or fan) and required valves for flow and pressure regulation, the fuel storage system with the corresponding valves, temperature regulation system, which can have many configuration, from a simple fan to a complex coolant recirculating system and a humidifying system whose work is to maintain an adequate hydration in the cell (specially for the membrane). Depending on the application, the fuel cell system will integrate all of those elements or will leave some of them out.

3.3 Fuel cell modelling

Fuel cells are a very complex system to model due to the multilevel characteristic of the dynamics taking place inside, from mechanisms occurring at an atomic level like the process of ions and electrons bonding to single atoms, through microscale dynamics such as dissolution and translation of nanoparticles to large scale phenomena such as diffusion, mass transports, voltage drops and current flows and the inherent distributed evolution of the variables involved mass, temperature, pressure; thus, it is clear that several knowledge areas are involved in its analysis such as: chemistry, electrochemistry, material science, thermodynamics, and electromagnetism.

There are extensive modelling options and approaches, for example [3] focuses on specific middle scale and large scale phenomena in a lumped parameter configuration; [4] on the other hand take into account a larger amount dynamics in a distributed parameter model; in another common approach the study focus just in the mechanisms in the cell that affect a specific variable to be controlled, such as temperature [6] or ; [7] presents another type of modelling, where the fuel cell is treated as an electrical system and every component correspond to a circuit element; resistance, capacitance and inductance; modelling and analysis are performed using circuit theory.

3.4 Catalyst degradation modelling

While we are interested in the full cell model and in trying to represent the internal dynamics of the cell as accurate as possible for the pursued objectives, the present thesis will focus specially on the degradation mechanisms in the catalyst layer. Strahl et al. [8] propose to model and analyze the catalyst layer as a porous structure. They present it as a three phase interaction pore, where fuel and oxidant gases interact with solid catalyst nanoparticles supported on solid carbon and with the liquid phase composed of water molecules and liquid ionomer.

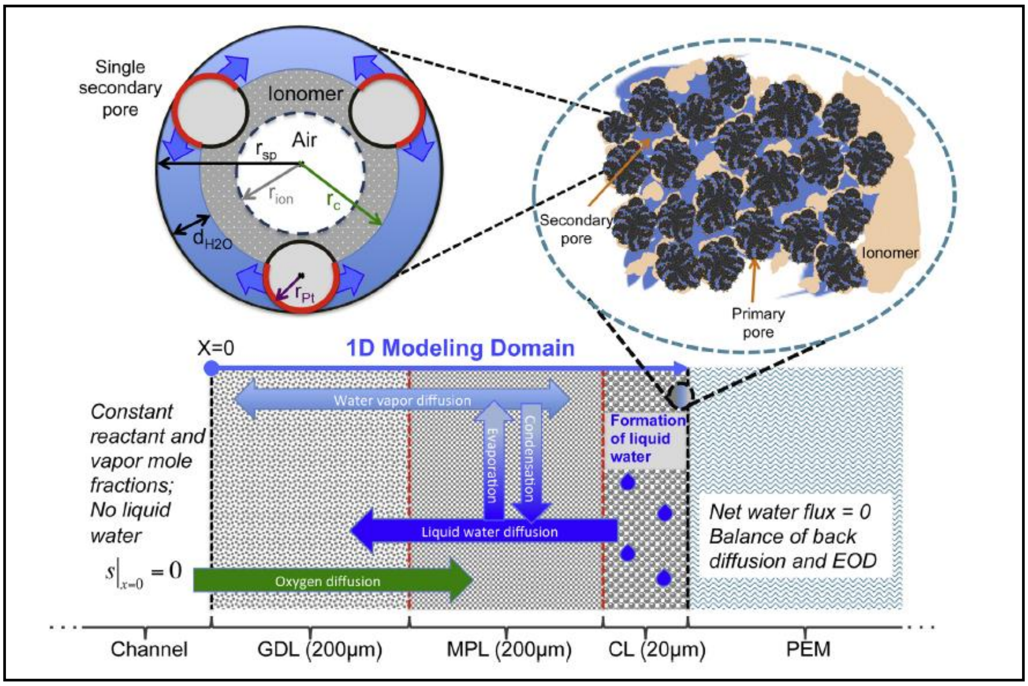


Figure 4. Catalyst porous structure. (From Strahl et al. [8])

The evolution of those pores, that is the space occupied by the interacting species is directly related to the ECSA evolution, and defines the performance of the cell, figure 4.

Therefore, in order to model the degradation of the catalyst layer it necessary to model the geometrical of platinum, carbon and water in that zone.
Two base and highly cited research works to model the dynamics of the platinum and carbon support in the catalyst layer are the papers by Darling and Meyers [9, 10], they proposed a mechanism driven by three basic reactions for the dissolution of platinum and one reaction for the carbon corrosion:

$$Pt \leftrightarrow Pt^{2+} + 2e^{-} \tag{4}$$

$$Pt + H_2\text{O} \leftrightarrow PtO + 2H^{+} + 2e^{-} \tag{5}$$

$$PtO + 2H^{+} \rightarrow Pt^{2+} + 2H^{+} + H_2\text{O} \tag{6}$$

$$C + 2H_2\text{O} \rightarrow CO_2 + 4H^{+} + 2e^{-} \tag{7}$$

Reaction (4) corresponds to the electrochemical dissolution of platinum, in this mechanism, platinum nanoparticles are directly dissolved when an energy threshold is trespassed and the reaction is triggered. Reaction (5) is another pathway for the degradation of platinum where the particle, via an electrochemical reaction, first oxides becoming a new specie, platinum oxide (PtO), and then this specie is dissolved through a chemical reaction (6). Electrochemical reaction (7) models the corrosion of pure carbon and conversion into carbon dioxide (CO_2).
Departing from this electrochemical equations, several more detailed models have been proposed to represent catalyst degradation, Reginaldo et al. [11] relate platinum dissolution rate with the radius of platinum nanoparticles and thus evolution of ECSA, Dam and Bruijn [12] take an experimental approach to find the curves relating the dissolution rates of electrochemical reactions defined in [9] and operating conditions such as cell potential and temperature. Other studies focus on the degradation of the carbon support, making use of the same electrochemistry analysis point of view, Macauley at al. [13] define a process where carbon corrosion is the result of six reactions and includes more than 8 interacting species, Pandy et al. [14] propose to model the carbon corrosion with up to 14 reaction equations and they differentiate 3 different interaction zones in the catalyst layer areas where carbon, platinum and ionomer meet. Schneider et al. [15] present a detailed model that describes several types of platinum dissolution dynamics taking place both in anode and cathode and includes the carbon corrosion. The present thesis will build upon these researches to define an appropriate catalyst degradation model and then and objective function suitable for real time optimization.

Figure 5 shows a schematic representation of the dissolution mechanisms taken into account in [15], the catalyst structure consists of platinum nanoparticles (ideally a near spherical agglomeration of Pt atoms) laying on the surface of large carbon particles, the mechanisms shown in the diagram are:

a) Atoms of an oxide specie deposit in the surface of the platinum nanoparticle.
b) This oxide specie penetrates the Pt lattice weakening the bonds between the platinum atoms, this process is called place exchange.
c) A number of atoms detach from the structure; this mechanism represents a type of dissolution.
d) There is also the possibility that, by corrosion of the carbon corrosion and the subsequent loss of carbon, the whole particle detaches from the support.
e) In a final pathway, the nanoparticle directly dissolves and the Pt ions either diffuse (probably towards the electrolyte membrane) or deposit back onto another particle growing its diameter.

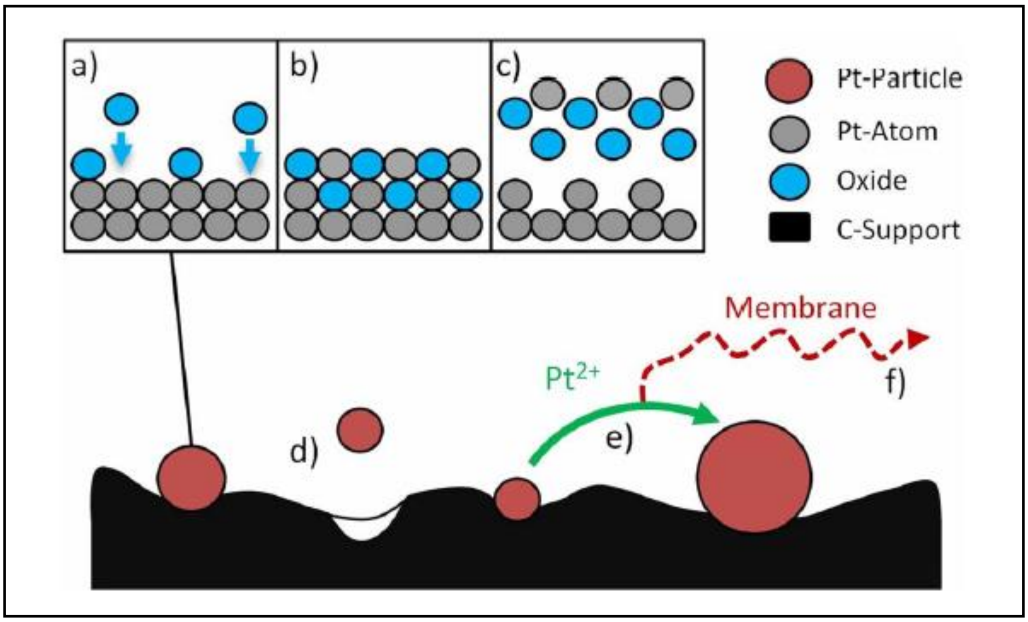


Figure 5. Catalyst degradation mechanisms. (From Schenider et al. [15])

It represents a total of six mechanisms of platinum degradation and one mechanism to model carbon corrosion with corresponding chemical or electrochemical reaction equations:

Platinum Anodic Dissolution: $Pt \leftrightarrow Pt^{2+} + 2e^-$ (8)

Platinum Oxidation: $Pt + H_2O \leftrightarrow PtO + 2H^+ + 2e^-$ (9)

PlatinumOxide Chemical Dissolution: $PtO + 2H^+ \rightarrow Pt^{2+} + 2H^+ + H_2O$ (10)

Place Exchange: $PtO \leftrightarrow \mathrm{O - Pt}$ (11)

Platinum Cathodic Dissolution: $O - Pt + 2H^{+} \leftrightarrow H_2O + Pt^{2+}$ (12)

Carbon Corrosion: $C + 2H_2O \rightarrow CO_2 + 4H^{+} + 2e^{-}$ (13)

Each reaction has an associated equation to describe the rates of reaction, which a variation of the Butler-Volmer, for example, for the platinum anodic dissolution reaction:

$$R_{a.diss} = k_{a.diss}\theta_{vac}\left[e^{(\frac{\alpha nF}{RT})(\emptyset-\emptyset_{eq})} - \left(\frac{c_{Pt2+}}{c_{Pt2+}^{ref}}\right)e^{-(\frac{\alpha nF}{RT})(\emptyset-\emptyset_{eq})}\right] \qquad (14)$$

Where $R_{a.diss}$ is the rate of reaction, θ_{vac} are the fraction of free platinum sites, α is the transference coefficient, n is the number of electrons of the reaction, c_{Pt2+} is the instantaneous concentration of platinum ions, c_{Pt2+}^{ref} is the reference concentration of platinum ions, R is the gas constant, F is the Faraday constant, T is the temperature of the catalyst layer, $\emptyset$ is the instantaneous cell voltage and $\emptyset_{eq}$ is the reaction equilibrium voltage. These type of equations describe the reaction rate of every mentioned degradation mechanism in the catalyst layer.

As (14) shows, Butler-Volmer derived equations are highly non-linear and even though they are an accurate mechanistic model of the dynamics in the catalyst layer, they are not completely suitable in their original form for use in real time optimization based control.

3.5 Cell degradation and load profile

The durability of a fuel cell catalyst layer is highly dependent on operating conditions, such as temperature, gases pressure, gases relative humidity, water content, and voltage. Voltage specifically, is usually managed as non-controllable variable since the cell controller is unaware of the load future power requirements, however load profile has a great influence in cell performance. Many studies have been carried out to experimentally relate voltage profile with platinum dissolution rates (and thus catalyst degradation) [16, 17, 18], other approaches focus in finding a semi-empirical analytic expression relating ECSA evolution (hence cell performance) for diagnostics or Remaining Useful Life (RUL) predictions based on specific load cycles (driving cycles in the case of cell powered transportation) [19, 20, 21, 22, 23].

Most of these studies however analyze the degradation/load profile relation through a whole driving cycle or use a non-realistic periodic voltage wave, therefore their results are not completely suitable to be used as useful information for the power plant controller; a deeper and shorter time scale analysis must be done for the goals of the present thesis.

3.6 Fuel cell control

There exists a large amount of literature on fuel cell control systems, an excellent review can be found in [24], listed control strategies include classical control (PID, classical MIMO and SISO controllers), linear and nonlinear adaptive type controllers (Sliding Mode Control, Extremum Seeking Control, Self-tuning PID), predictive controllers (Model Predictive Control, non-linear MPC) and data or learning base controllers (Fuzzy Logic Control, Neural Networks), each implementation of those strategies have its objective variable such as voltage tracking [25], temperature [26, 27] pressure regulation [28] or oxygen stoichiometry [29]. Most of the controllers focus in regulating a specific operating conditions in order to track a defined set point and, in many cases assume an improvement of durability based on previous semi-empirical result that plot the degradation of the fuel cell when operated in such values.

However, most studies lack the step of actually finding those optimum operating conditions set points. An upper level element (which can be tough of as a supervisory controller) should be implemented in order to define, based on mechanistic knowledge of the fuel cell degradation dynamics which ones are those optimum operating conditions. This upper level controller should take, as input an accurate model of the cell degradation mechanism (or at least the degradation of the most important components of the cell) and some function that defines cell performance as a variable of those mechanisms.

3.7 Robot motion planning

Motion planning refers to the capacity of a robot of choosing a series of movements in order to change from a start configuration (pose) to another traveling a feasible path, for arm like manipulators it implies changing from an initial vector of joint angles to another, in the case of a mobile robot, from a starting position and orientation in space to a final one (fig. 6). Extensive research has been done in the area of motion planning, [30] summarizes a good deal of strategies and algorithms. The present thesis will focus on algorithms that use a random sampling process to find first a feasible path, of which the Rapidly exploring Random Tree (RRT) is one of the most used. There is also recent increasing research interest broadening the motion planning paradigm to include internal variables of the robot (most common energy consumption) and not only external elements (obstacles, distance), [31, 32] and also interest in motion planning for renewable energy robotic systems [33]. To our knowledge there are not research studies that analyze motion planning strategies focused in fuel cell powered robots and moreover on directing the motion planning objective into preserving the integrity of components of the robot (the power plant in the case of the present research) and thus reduce the inherent degradation that those components may suffer from the operation and movement of the robot.

4. Expected contribution

This thesis aims to contribute in three areas: upper level control of PEM fuel cells, robot motion planning where the goal is to include specific internal conditions into the planning strategy and integration of power plant controller with motion planner for improvement of the overall system performance.

In the first place, stablishing an advanced control strategy, for a PEMFC based power plant, that is built on: a) a mechanistic model of fuel cell catalyst degradation, that is, a model that represents as deep as possible the electrochemical and thermodynamic changes taking place in the catalyst layer and b) the capability of specifying durability enhancement (mitigate degradation) and efficiency (optimum use of resources) as the control objectives.

Model Predictive Control (MPC) is the candidate control scheme, however, several adjustments and improvements must be done in order to define the optimization control problem and construct it in a way that is feasible for implementation in real time: the equations of mechanistic cell model will be modified to fit an algorithm able to calculate optimum operating values in real time; it will be defined whether a nonlinear approach (NMPC) where the model equations can be included as is, thus, allowing a more accurate representation of the dynamics but with the price of higher computational burden, or a linear one, where the model is less accurate but the optimization algorithm is more efficient, is the more appropriate for the application; an appropriate objective function will be defined, this function shall be physically related to the mechanisms of cell degradation and cell efficiency. These adjustments and improvements are where most of the contributions in this part are expected.

In the second area, the project aims to contribute in setting a motion planning algorithm that includes the degradation index of the fuel cell. Most planning strategies are just focused on travelling from start to destination pose avoiding obstacles and minimizing travelling distance (or time), the contributions in this area will be: translate motion profile into load profile, relate load profile curve characteristics with catalyst degradation, find appropriate features of the load curve that can be used in the planning algorithm to optimize robot path and motion in order to reduce degradation (fig. 6).

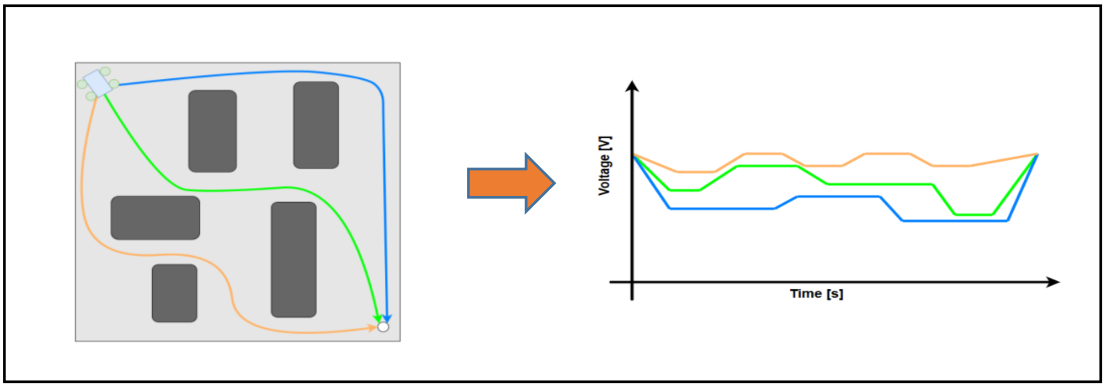


Figure 6. It is sought that every trajectory be associated with a voltage curve (load profile) and thus with a fuel cell degradation rate.

Finally, the project aims to contribute in the integration of the motion planning module and the energy plant control module. In general, fuel cell control algorithms ignore the expected power consumption of the system (the future load profile) and treat this variable mostly as a disturbance that can be measured in present time, but it is unknown in advance. The approach of the thesis will be to build an architecture where the motion planning algorithm takes into account the effect that the feasible paths and motion profiles will have on the cell in terms of its integrity and once an optimum path and motion profile is chosen, integrate the associated load profile of the movement with the fuel cell controller in order to improve the performance of the control algorithm (Fig .7). This scheme will stablish a novel interaction between the down level control of the energy plant and the up level motion control of the robot.

This thesis project is expected to produce a number of publishable papers in the areas of hydrogen energy, advanced control and robot motion planning. Titles and themes may be as follow: *"A control oriented PEMFC catalyst degradation model", "Model Predictive Control for durability improvement of a PEMFC catalyst layer based on a mechanistic degradation model", "A power plant degradation aware robot motion planning strategy", "Integration of system control and motion planning for durability improvement of a mobile robot fuel cell power plant".*

A worth to notice outcome of the project is the physical platform itself. Once the project is finalized, a mobile robot with a fuel cell as power plant is expected to be available for serving as a new testing equipment in IRI´s lab.

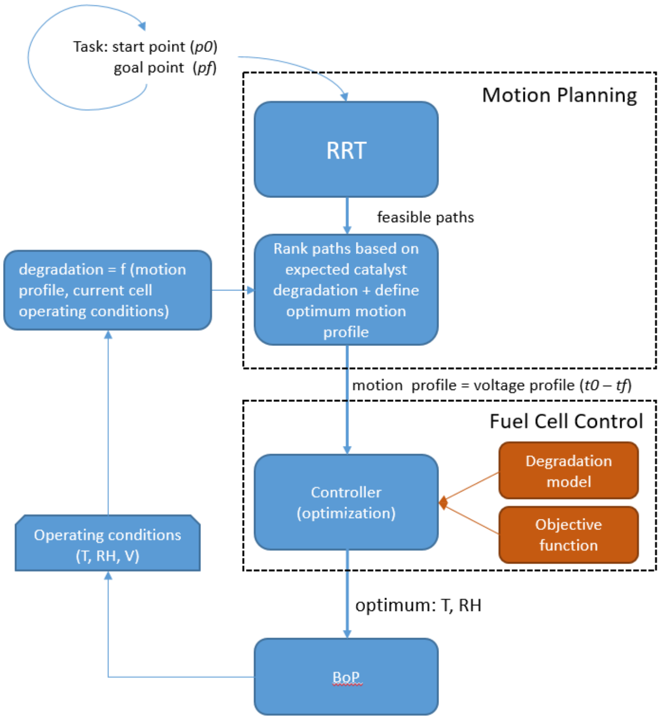


Figure 7. Simplified flow diagram of the process for the integration of motion planning and fuel cell control.

5. Preliminary work

5.1 Cell potential and catalyst evolution

The reaction kinetics of platinum (Pt) and the reactions affecting platinum stability within the cell are of mayor importance in order to study the process of cell degradation. AS stated previously several models of Pt kinetics have been proposed most of them agree on two pathways for Pt loss, based mainly on reactions (4), (5) and (6). A simulation model in MATLAB/SIMULINK has been developed based on this reaction kinetics. The results agree qualitatively with graphics of platinum oxide (PtO) evolution presented in [13,14], figure 7 shows the result of our model. A portion of the area below the PtO evolution curve defines the level of degradation suffered by the catalyst. Evolution of the electrochemical reactions (4) and (5) is strongly dependent on cell voltage, as several studies have shown, voltage cycling is one of the main conditions inducing PEMFC degradation [18,21].

5.2 Voltage profile features

In the literature, several semi-empirical relations between degradation (presented as loss of platinum area) and periodical voltage profiles have been proposed. Kneer et al. [30] proposed a first order kinetic model, (15), (16), (17) where S is the Pt surface area, N are the numer of cycles, and *k* is as factor composed of coefficients that depend on several operating conditions: k_{SC}, a baseline degradation, k_T, related to the temperature, k_{RH} related to the humidity and k_V related to the voltage profile, which is also composed of two features, upper voltage level, k_{UPL} and the time at upper level, k_{dwell}.

$$\frac{dS}{dN} = -kS(N) \tag{15}$$

$$k = k_{SC} * k_T * k_{RH} * k_V ; \tag{16}$$

$$k_V = k_{UPL} * k_{dwell} \tag{17}$$

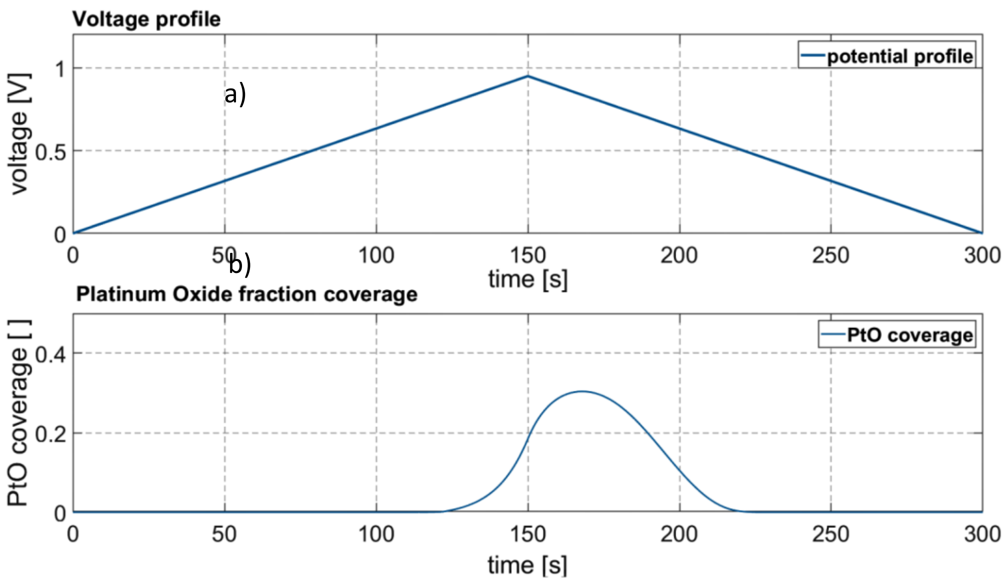


Figure 7. a) A sweep of increasing and decreasing voltage (triangular profile) is applied to our simulation model of Pt reaction kinetics. b) The result in fraction of Platinum Oxide (PtO) coverage.

Our objective is in trying to generalize the degradation-voltage profile relation and increase the number of voltage features to analyze, in order to define the most appropriate load (mission) profile to reduce the degradation of the PEMFC and improve control over its operating conditions.

Figure 4 shows the proposed features to evaluate the load profile “quality” of a single cycle in terms of cell degradation. The degradation rate (long term cell voltage decay due to ECSA reduction) is assumed to be a function of this vector of features:

$V_1 = voltage\ level\ at\ time\ t_0$ $\qquad$ $t_1 = time\ of\ transition\ from\ V_1\ to\ V_2$

$V_2 = voltage\ level\ at\ time\ t_2$ $\qquad$ $t_2 = time\ at\ V_2$

$V_3 = voltage\ level\ at\ time\ t_3$ $\qquad$ $t_3 = time\ of\ transition\ from\ V_2\ to\ V_3$

$t_0 = time\ at\ V_1$

5.3 Voltage wave with variable features

Figure 8 shows the features of 7 different testing voltage curves and the corresponding results in the evolution of PtO. The oxidation/reduction kinetics of platinum varies with the different characteristics of the voltage wave. Voltage levels, slew rates and cycling frequency analyzed at a scale of each cycle is important to determine better control and energy management strategies for improvement of PEMFC durability.

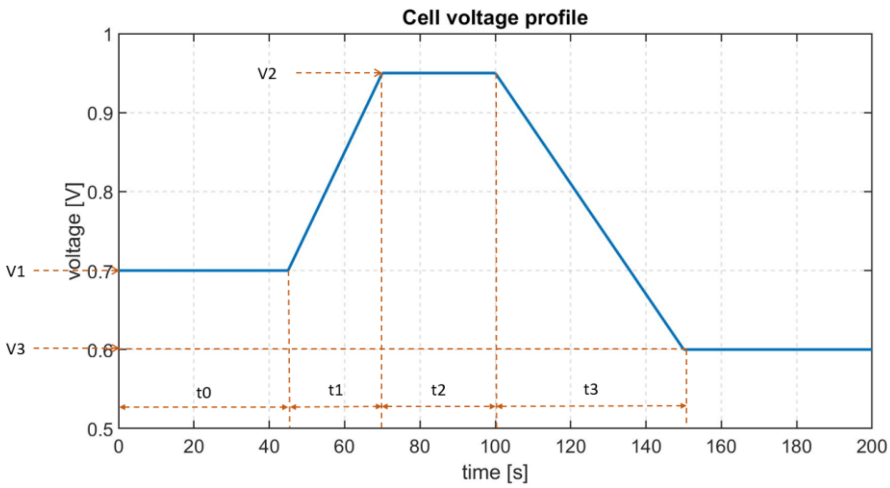


Figure 8. A generic voltage profile: one cycle is defined as a transition from three different levels of voltage, starting from a first voltage at time t0, passing through a different level at t1-t2 and reaching a final voltage at t3.

Voltage profile	Features							PtO Area
	V_1	V_2	V_3	t_0	t_1	t_2	t_3	
1	0.65	0.95	0.50	65	0	75	0	36.3
2	0.65	0.95	0.50	45	20	60	15	35.1
3	0.65	0.95	0.50	45	55	50	0	27.8
4	0.70	0.95	0.60	45	25	30	50	31.1
5	0.60	0.85	0.60	45	25	30	50	8.7
6	0.60	0.85	0.60	45	25	80	0	14.3
7	0.65	0.95	0.50	45	25	30	50	26.1

Table 1. A total of seven different voltage profiles and their corresponding characteristics.

A future task is to define an analytical expression to relate the vector of features to the degradation ratio and therefore “qualify” different mission profiles.

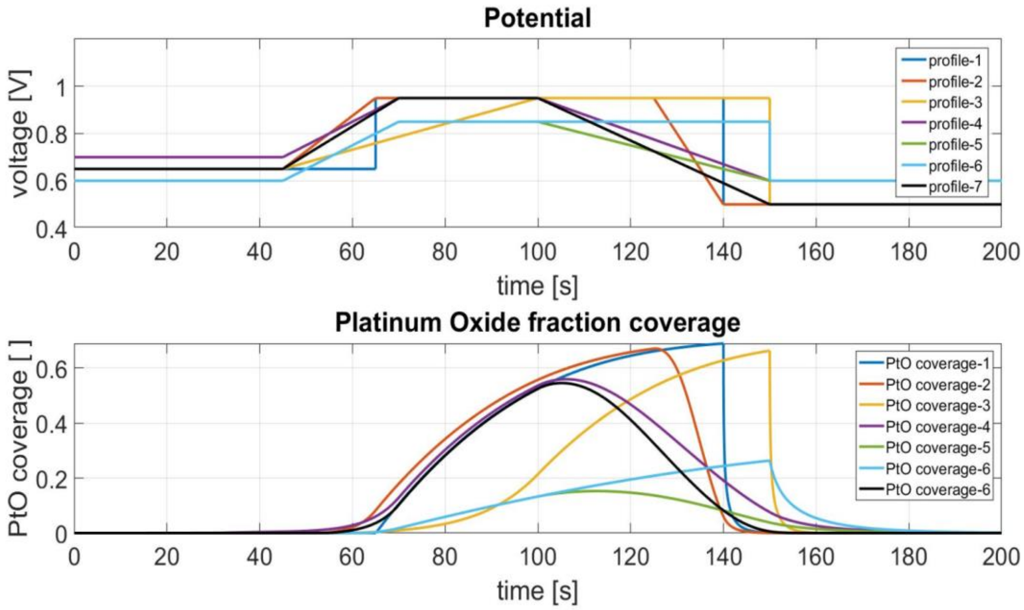


Figure 9. Seven different voltage profiles and the corresponding platinum oxide evolution, the area of the PtO coverage is related to the grade of degradation produced in the cell by the cycle of voltage.

6. Resources

This thesis is framed and receives funding from two projects currently being developed at the Institut de Robòtica i Informàtica Industrial (IRI): ***María de Maeztu Seal of Excellence to IRI***: MDM-2016-0656 and the ***INN-BALANCE EU Project*** of the Fuel Cells and Hydrogen 2 Joint Undertaking under Grant 735969. This Joint Undertaking receives support from the European Union Horizon 2020 Research and Innovation Program and from Hydrogen Europe. Research and testing will be mostly carried out in the facilities of IRI, making use of the extensive available research resources, also minimum of two international stays are planned.

6.1 Software

System models, including fuel cell, catalyst degradation mechanisms and mobile robot dynamic models will be developed in Matlab and Simulink. Control and planning algorithms will be first tested in these platforms.

It is expected that, in the second stage of the project, specific robotics, tools will be used: ROS nodes of the different system modules would be developed, integrated to build the virtual mobile platform, and then tested in physically realistic scenarios with the use of simulation tools such as Gazebo. Programming languages to be used for implementing the ROS nodes will be C++ or Python.

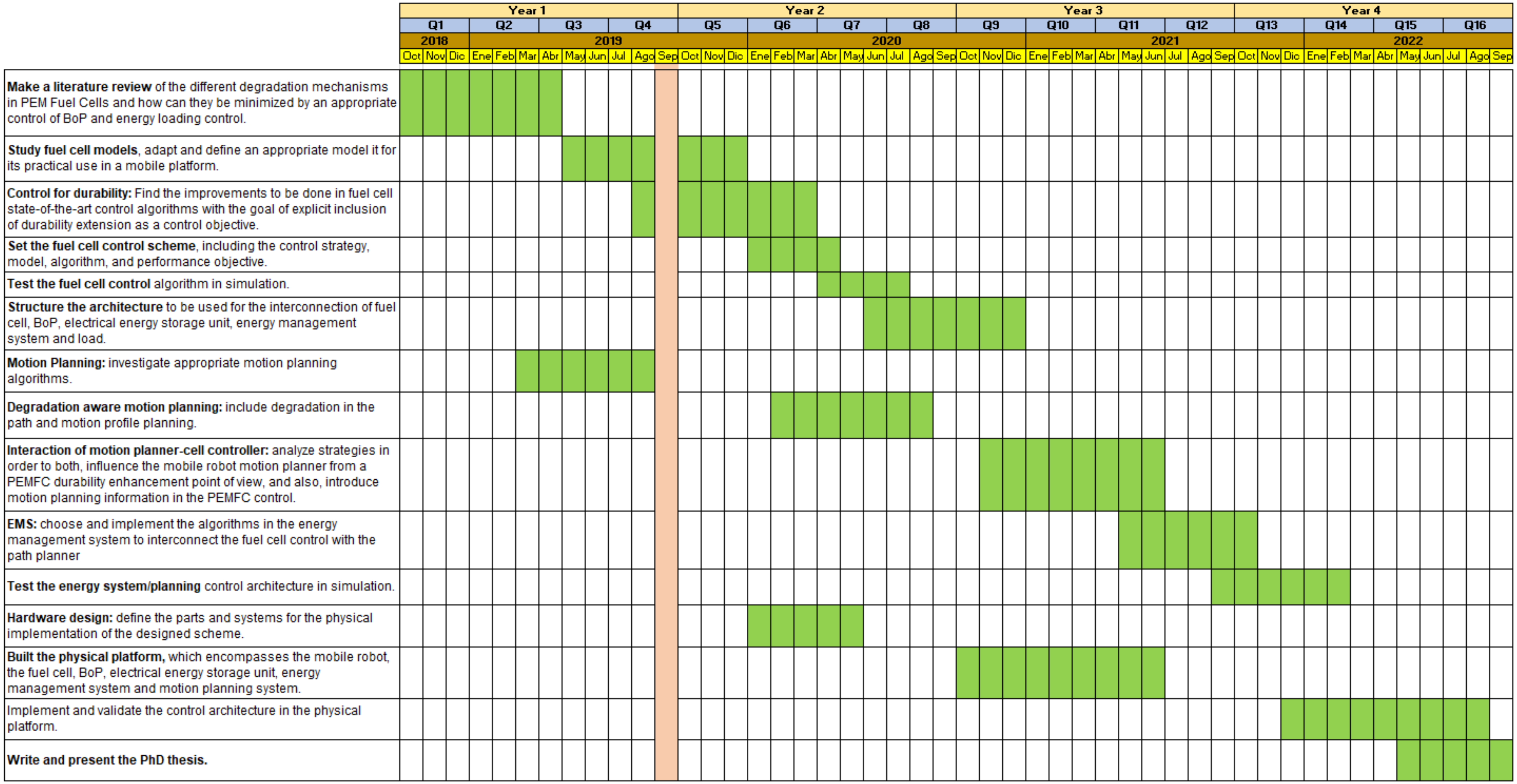
6.1 Hardware

The TEO robot (fig. 6), which is built on top of a Segway RMP 400 vehicle, will serve as the physical platform for implementing the described system and for validating the behavior of the motion planning module and its interaction with the power plant controller. Tests of control algorithms, estimation of cell parameters and degradation dynamics will be performed in IRI´s Fuel Cell Laboratory (fig. 7). Also, several equipment will be purchased specifically for the project, mainly: a PEMFC stack (with an approximate capacity of 1.5 KW) to be installed in the mobile robot, the required auxiliary elements (fan, cooling system, humidification system), electrical energy storage (batteries or super-capacitor) with appropriate capacity, control circuitry and hydrogen storage container.

Figure 10. The TEO mobile robot

Figure 11. IRI`s fuel cell lab.

7. Work plan


Year 1
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Make a literature review of the different degradation mechanisms in PEM Fuel Cells and how can they be minimized by an appropriate control of BoP and energy loading control.
Study fuel cell models, adapt and define an appropriate model it for its practical use in a mobile platform.
Control for durability: Find the improvements to be done in fuel cell state-of-the-art control algorithms with the goal of explicit inclusion of durability extension as a control objective.
Set the fuel cell control scheme, including the control strategy, model, algorithm, and performance objective.
Test the fuel cell control algorithm in simulation.
Structure the architecture to be used for the interconnection of fuel cell, BoP, electrical energy storage unit, energy management system and load.
Motion Planning: investigate appropriate motion planning algorithms.
Degradation aware motion planning: include degradation in the path and motion profile planning.
Interaction of motion planner-cell controller: analyze strategies in order to both, influence the mobile robot motion planner from a PEMFC durability enhancement point of view, and also, introduce motion planning information in the PEMFC control.
EMS: choose and implement the algorithms in the energy management system to interconnect the fuel cell control with the path planner
Test the energy system/planning control architecture in simulation.
Hardware design: define the parts and systems for the physical implementation of the designed scheme.
Built the physical platform, which encompasses the mobile robot, the fuel cell, BoP, electrical energy storage unit, energy management system and motion planning system.
Implement and validate the control architecture in the physical platform.
Write and present the PhD thesis.

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