**PRINCIPAL INVESTIGATOR:** Alexandre Seuret

**TÍTULO DEL PROYECTO (ACRÓNIMO):** SISTEMAS DINÁMICOS HÍBRIDOS: CONTROL BAJO RESTRICCIONES NO LINEALES

**TITLE OF THE PROJECT (ACRONYM):** HYBRID DYNAMICAL SYSTEMS : CONTROL UNDER CONSTRAINTS

## 1. JUSTIFICATION NOVELTY AND OF THE PROPOSAL

*General context of the proposal:* Automatic control, or automation, has immense potential to benefit society [Ast14,Lam17]. It enhances efficiency, productivity, and safety in industries, transportation, healthcare, and daily life. By automating tasks, it frees up human potential for more complex endeavors and drives innovation. With its ability to optimize resource management and promote sustainability, automatic control contributes to a brighter future. *Figure 1* illustrates some applications of automatic control, including industrial automation, robotics, aerospace and aviation, transportation systems, power systems, environmental control, biomedical systems, to cite only few.

*Figure 1. Some examples of applications in automatic control. From left to right, an industrial robot, a spacecraft rendezvous problem from the European Space Agency (ESA), and a simplified microgrid.*

$$\mathcal{H}:\begin{cases} \dot{x} \in F(x), & x \in \mathcal{C} \\ x^{+} \in G(x), & x \in \mathcal{D} \end{cases}$$

*Figure 2: Definition of a HDS with the flow and jump maps F and G and the flow and jump sets C and D.*

*Hybrid Dynamical Systems in Automatic Control:* Among the various topics in Automatic Control, the theory of ***Hybrid Dynamical Systems*** (HDS) is a significant area of study [Goe09]. HDS deals with systems that exhibit both continuous dynamics, characterized by differential equations, and discrete dynamics, represented by logical rules or state transitions. This unique class of systems poses specific challenges and offers distinct opportunities compared to other classes encountered in Automatic Control, as it allows for the representation and analysis of complex behaviors that cannot be captured solely by continuous or discrete models. HDS is particularly relevant in applications involving impulses, such as satellite's propulsors or switches between different operating modes, such as, power grids, and manufacturing processes.

The history of HDS traces back to the development of the Clegg Integrator in 1958 [Cle58]. The nonlinear Clegg integrator introduced the concept of resetting a continuous variable to a specified value when certain conditions are met. This reset action effectively created a discrete event that impacted the continuous dynamics of the system, **which was used to reset the integral action of PID control** [Zac05]. The Clegg Integrator served as a fundamental building block for modeling and analyzing hybrid systems. Following this initial development, researchers delved deeper into the theory of HDS and explored various applications. The study of HDS gained *momentum* in the 1990s with the emergence of new mathematical tools and computational techniques. These advancements enabled a more comprehensive understanding of hybrid systems and facilitated the development of sophisticated control strategies making it a challenging yet exciting research area. Over the years, the field of HDS has expanded to encompass a wide range of applications in fields and researchers have developed mathematical tools to model, analyze and control complex hybrid systems accurately.

The Hy2Con project aims to develop theoretical contributions on HDS, which represents an innovative, attractive, and efficient area in Automatic Control and to confront them with three application fields of great interests for the society. The next paragraphs explain how and why the HDS fits perfectly with these applications.

*Spacecraft rendezvous in Aerospace Science:* A spacecraft rendezvous entails orbital maneuvers designed to bring two spacecraft, depicted in Figure 4, namely the chaser (B) and the target (A), together by aligning their velocities and positions. The target can either be cooperative or uncooperative. Cooperative targets possess navigation markers, whereas uncooperative targets rely on relative measurements obtained from the chaser's sensors, such as an optical tracking camera. Space debris removal operations typically involve uncooperative targets, which arise when satellites lose control and require removal from their orbit.

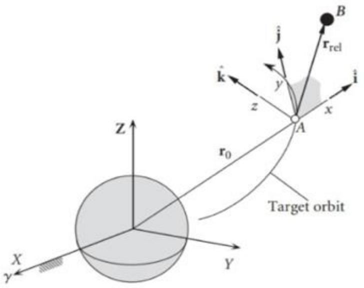


*Figure 3: Orbital Rendezvous*

$$\begin{aligned}\delta\ddot{x} - 3n^2\delta x - 2n\delta\dot{y} &= 0\\ \delta\ddot{y} + 2n\delta\dot{x} &= 0\\ \delta\ddot{z} + n^2\delta z &= 0\end{aligned}$$

*Figure 4: Clohessy-Whiltshire equations [Clo60].*

Interestingly, although the dynamics of each satellite are highly nonlinear, the relative dynamics $\boldsymbol{\delta x}, \boldsymbol{\delta y}$ and $\boldsymbol{\delta z}$ of the two-body problem can be described by a relatively simple linear impulsive model in the relative frame. This is achieved through the utilization of the well-known Clohessy-Whiltshire equations [Clo60], as depicted in Figure 4, with only a minor approximation error. More refined polynomial models can be found in [Luo14].

Behind its simplicity, this model hides quite complicated behaviors that involve mixing two oscillators and an integrator, which ultimately result in unstable dynamics. The control actuators in this system are thrusters capable of instantaneously modifying the velocities of the chaser in all directions or in specific directions, thereby inducing impulsive behavior in the relative dynamics. More precisely, the velocity in the $x$ direction verify $\boldsymbol{\delta\dot{x}(t_k^+) = \delta\dot{x}(t_k) + u_x}$ , only at the impulse instants $t_k$, and the same equation holds for the $y$ and $z$ directions. In this equation, $u_x$ stands for the actions of the thruster in the $x$ direction. In the time-triggered case, the control instants $t_k$ are independent on the system location but only on the frequency of the controller, while in the event-triggered case, they are selected by the control to act only when the state of the system requires an action. Another important issue related to this application is the presence of saturations in the actuators (the instantaneous changes of velocities cannot be of high amplitude), which are well known to affect the stability of the closed loop [Tar11]. Numerous solutions have already been explored in the literature, with most of them relying on the design of Model Predictive Control (MPC) strategies [Cam07, Gav12]. MPC has the potential to provide optimal control inputs, but it comes at the cost of high computation requirements and several assumptions about the models, such as reliance on the model's accuracy, periodic sampled-data, or impulsive control actions. To the best of our knowledge, only a few researchers have sought alternative solutions. Among them, [Bre18] has paved the way for proposing an alternative solution based on HDS in curvilinear coordinates.

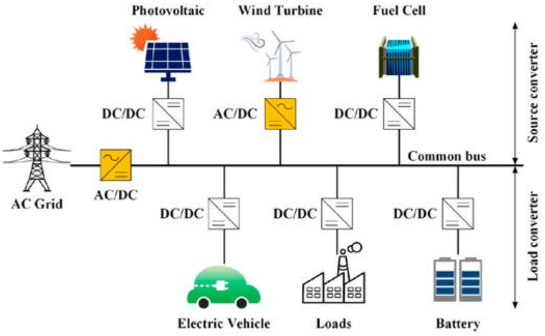


*Figure 5: A microgrid with several sources, loads and power converters.*

*Power Electronics and Microgrids:* The reduction of energy consumption and the management of data are two challenging issues of the 21'st century. Over this WP, we aim to provide new control paradigms for the management of energy generation and consumption in microgrids whose is represented in *Figure 5*. A microgrid is a decentralized group of electricity sources, energy stored systems and loads that can operates connected or islanded to the utility grid in "grid following" or "grid forming" mode

[Ro12], respectively. In this way, microgrids improve the efficiency and security of supply within the microgrid cell reconfiguration with intermittently connected or disconnections loads, batteries and sources, and can also supply emergency power, changing between island and connected modes. Moreover, the connection between the various loads and energy sources is performed through power converters. Hence, there are some control levels in a microgrid. Following the description given in [Oli14]: a primary level controls the power converters; a second level manages the distributed powers (it is known as Energy Management System) to provide efficiency, reliability and security and it can use the concept of droop control. Finally, a tertiary level governs the connections or the disconnections with the utility grid optimizing the market costs. In all these control levels, stability and robustness are mandatory to get high reliability and energy efficiency [Las07].

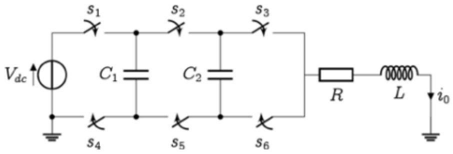


*Figure 6: Example of a power converter.*

$$
\begin{aligned}
\dot{x} &= A_\sigma x + B_\sigma \\
\sigma &= u
\end{aligned}
$$

*Figure 7: Switched affine models of a power converter*

As for general linear and nonlinear systems, power converters, for instance the one presented in *Figure 6*, are very sensitive elements, and require a deep analysis. In addition, power converters models are often badly conditioned i.e., some parameters can be very small and/or very large. Therefore, attention will be paid to the models, the associated analysis as well as the structure of the controllers to better fit with the physical constraints. In particular, these systems have the particularity of having the control input as the selection of the operating mode of the systems i.e., $\sigma = 1,2,3,\ldots$ as shown in *Figure 7*, showing the switching nature of the converters.

As for the first application field, the control input $u$ may be updated at time- or event- triggered instants and remains constant in between, demonstrated the hybrid nature of the system. The main issue with this class of switched systems is that it is not possible, in general, to make their trajectories converge to a desired operating point but rather on neighborhood of it [Alb21a], more precisely to a limit cycle [Ser23], unless reaching an undesirable Zeno i.e., an infinite number of switches in a finite interval of time [Joh99]. Characterizing this region or the optimal limit cycles is the major objective in the context of controlling power converters, and to a larger extend, microgrids.

### *Iterative Learning Algorithms in Artificial Intelligence:*

Artificial Intelligence has already changed our life with, for instance, the recent release of ChatGPT. The impressive performance of these algorithms relies on the learning algorithms together with the increasing computational capabilities. In particular, Machine and Deep learning methods based on neural networks algorithms [Den14], illustrated in *Figure 8*, have already impacted many scientific areas fields such as signal and image processing with breakthroughs in numerous medical applications [Ham17].

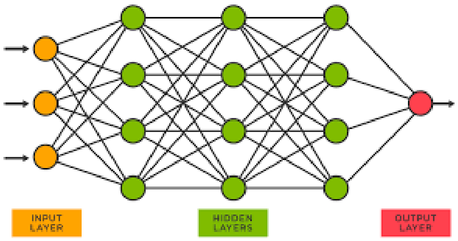


*Figure 8: Illustration of a neural network*

Learning from data is crucial across various scientific disciplines. It forms the foundation of statistics and artificial intelligence and has gained increasing significance in engineering, including the field of control engineering. Although not new in control theory, learning from data has seen significant advancements, such as system identification [Lju99]. The goal is to replace the traditional modeling or identification phases by direct approaches such as data-driven control design [DeP19], [Seu23b], iterative learning control design, based on classical control tools [Bri06] or on neural networks [Hun92].

$$
\begin{cases}
\dot{x} &= Ax + Bu(\tau, j, X) \\
\dot{X} &= 0 \\
\dot{\tau} &= 1 \\
\dot{j} &= 0
\end{cases} \quad (x, X, \tau, j) \in \mathcal{C}
$$

$$
\begin{cases}
x^+ &= x_0 \\
X^+ &= x \\
\tau^+ &= 0
\end{cases} \quad (x, X, \tau, j) \in \mathcal{D}
$$

*Figure 9: Hybrid model for iterative learning control*

The idea of iterative learning is to repeat the same experience several times and to extract from each experiments the data to improve the control actions along the next experiment. A HDS model for these algorithms is presented in *Figure 9*, where $x$ is the state of the system, which is reset to the same initial condition $x_0$, $X$ is a memory of the state, captured by the jump equation, $\tau$ and $j$ are respectively the continuous and discrete timers that account for the duration of each experiment and for the number of iterations. In this model, the objective is to define the control law, which is characterized by $u(\tau, j, X)$ but also the jump and flow sets $C$ and $D$, which has the potential to offer several degrees of flexibility.

## 3. OBJECTIVES, METHODOLOGY AND WORK PLAN

*General objectives:* This project aims at developing new design methods for a wild range of hybrid dynamical systems. As illustrated in *Figure 10*, the main objectives rely on the developments of ***new theoretical tools*** for :

1) ***Efficient modeling of complex systems***
2) ***Innovative hybrid control design***
3) ***Practical constraints***

with a focus on three particular but yet exciting ***applications areas:***

a. ***Aerospace Dynamics***
b. ***Power Electronics***
c. ***Artificial Intelligence***

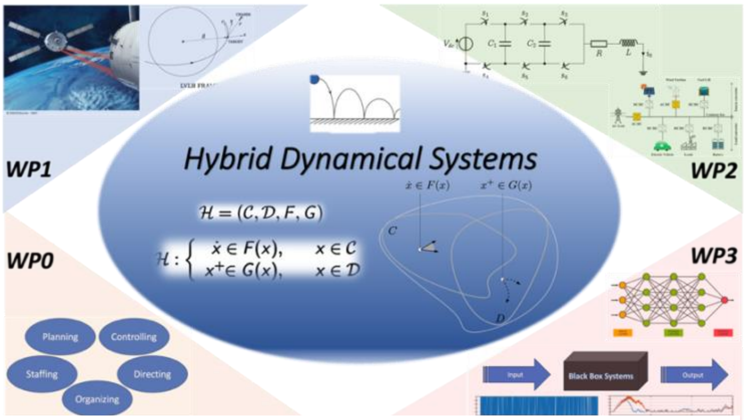


*Figure 10: Structure of the Hy2Con project*

For all these applications, efficient and complete HDS models can be built. With a careful caution when building it, it is possible to ensure the existence of solutions, through the *Well-Posedness theorem* or to assess stability of the closed-loop systems using for instance the *Lyapunov Theorem* for HDS [Goe09]. The success of the project strongly relies on the expertise of the PI on the stability analysis and control of *HDS*, on optimization tools such as the *Linear Matrix Inequality (LMI)* framework [ElG00, Sch00].and on the local partners to complete the theoretic and applicative tasks described in the next paragraphs.

The objectives of Hy2Con align with the *State Subprogram of Strategic Actions* of the *State Plan for Scientific, Technical, and Innovation Research 2021-2023*, specifically in *Strategic Action 4: Digital World, Industry, Space, and Defense*, and *Strategic Action 5: Climate, Energy, and Mobility*. These actions prioritize the following:

- *"Increasing the share of renewable energies in final energy consumption through innovation in technologies in which we already have a competitive position, as well as the technological development of those with great potential for renewable integration and reducing emissions, such as energy storage."*
- *"Increasing renewable energy in the energy system through the development of storage systems and the digitization of the electrical system, aiming for a more decentralized, secure, flexible, and resilient system."*

*Summary of the participants:* The Hy2Con project relies on the expertise of the PI on HDS, but also on his recurrent collaborators. *Table 1* presents a list of personal funded by Hy2Con, and two non-exhaustive lists of local partners (at the University of Seville) and external partners. Note that we have already identified an outstanding Italian candidate for PhD1, after supervising his Master internship jointly with Prof. R. Vazquez.

*Methodology & Working plan:* The project is organized into the four following work packages (WP).

**WP0 – *Organization*.** The management of Hy2Con will be the following: all members will have an orientation meeting every six months; this will be to validate the objectives of each concerning subtask and to adapt the global strategic planning. The report of each task will be delivered periodically. This task will also ensure dissemination policy and agreement of all members for publication in conferences and peer-reviewed journals.

### WP1 – *Time- and event-triggered control for Spacecraft Rendezvous*.

In this WP, our first objective is *to establish a novel generic framework on impulsive and sampled-data systems with constraints*, for instance, on the impulse times or the safety region to approach the target. These theoretical findings will be *consistently examined and evaluated in the context of the spacecraft rendezvous problem*, which introduces its own unique characteristics.

*The following tasks envisioned in this WP are described below:*
*WP1.1 - Time- and event-triggered control of linear sampled-data and impulsive systems: [M0-M24]* In this sub-WP, the objectives are first to extend the existing literature on sampled-data and impulsive systems by introduce new hybrid control structures with the aim of improving the performances of the closed-loop system. While the problem of optimizing the control parameters for linear systems is now well understood, the designing control gain for uncertain systems subject to implementation constraints still represent an open problem in control. Most of the existing methods are based on the ideal parameters for which a robust analysis is performed, and then to evaluate the robustness of the implementation. Here, we aim at improving the co-design method of both the controller gains and the triggering rule. This task will be regarded as an application case of WP3.1 on data-driven control design.
Outcomes: Research papers & D1.1; Participants PI, PhD1, LP1, EP1,5,6.
*WP1.2 – Nonlinear control design and Constraints: [M12-M36]* As a next natural step, we would like to extend the results developed in the previous sub-WP to the case of systems subject to nonlinear constraints, such as input saturations [Tar11] or Pulse-Width Modulated (PWM) input signals [Vaz17]. These two types of nonlinearities refer to real-world implementation problems and in particular on spacecraft rendezvous, that may severely affect the performance or the stability of the closed loop.
Outcomes: Research papers & D1.2; Participants PI, PhD1, LP1,2 , EP1,2.
*WP1.3 – Application to the spacecraft rendezvous: [M00-M48]* As mentioned in the previous section, two-body rendezvous problem can be modeled as linear systems subject to input saturations. The first two sub-WP's already treat these issues. The main constraint brought by this application is the constrain on the localization of the Chaser with respect to the Target. There are regions, that can be modeled as cones in $R^3$ centered at the Target, in which the chaser is not allowed to enter for safety reasons. Again, HDS have the potential to include this constraint without any difficulties by including this information in the flow and jumps sets. The potential is here to derive nonlinear control laws that prevent the chaser to enter these regions, which are much simpler and less computationally demanding than MPC.
Outcomes: Research papers & D1.3; Participants PI, PhD1, LP3, EP2.

### WP2 - *Hybrid control for power converters and microgrids*

Motivated by the application of power converters and microgrids, this WP aims to derive novel hybrid control structures for the generic class of switched systems. This WP is divided into three tasks that comprises between theoretical contributions and applicative research.

*The following tasks envisioned in this WP are described below:*
*WP2.1 -Hybrid control of Switched Affine systems: [M0-M24]* Following our previous contribution [Alb21a],[Ser23], two different strategies can be derived. The first one relies on the characterization of the region where the trajectories of the systems converge to, which is potential larger, while the second provides a precise characterization of the limits cycles to which the trajectories converge asymptotically, at the price of an a priori selection of complex control parameter. *In this task, we aim at presenting new strategies, which provide a more accurate characterization of the trajectories but*

*with only few or without parameters to select a priori.* This tradeoff is envisioned by include the delayed information on the system, allowing then the inclusion of more information about the current state of the system. This task will also be regarded as an application case of WP3.1 on data-driven control design.

Outcomes: Research papers & D2.1. Participants PI, LP1,2, EP3.

*WP2.2 Switched multi-agent systems: [M12-M36]* Microgrids are composed of various loads, energy stored systems and sources joint through power converters. In order to optimize this network of converters, it is necessary to provide a distributed solution that enables the on/off switching in the connections. Up to now, only a centralized solution has been provided in the hybrid systems context [Ser21]. *A first objective of this section is here to extend these preliminary results to a more realistic and flexible solution using consensus algorithms [Olf07] for multi-agent systems.* A second objective consists in exploiting the preliminary results, [Alb21b] and [Alb21c] of a member of the hosting control group *to include more features in the microgrids to account for the variability of the different and heterogeneous components of the microgrid*.

Outcomes: Research papers & D2.2. Participants PI, LP1,2, EP3.

*WP2.3. Application to power converters and microgrids: [M0-M48]* As the PI of the project is not an expert on this application, this research will be conducted with the help of IT1 and two local research that have the experience to prepare the installation, *to implement the theoretical contributions derived in the previous tasks of this WP, and to evaluate the results on the experimental benchmark that is partially deployed at the University of Seville and that will be enriched thanks to the project*.

Outcomes: Research papers, experimental validations & D2.3. Participants PI, IT1, LP1,2, EP3,4.

### WP3 - *Data-driven method and learning for the optimization of neural networks.*

The main objectives of this work package (WP), and data-driven control in general, involve developing plug-and-play algorithms for the systematic design of control laws, surpassing the need for an initial identification phase. This approach presents a contemporary and challenging problem that has gained attention in recent control theory literature, known as data-driven control [Ber20, Bis21, VWa20], and the recent plenary talks of Prof. F. Allgöwer and Prof. S. Hirche during the European Control Conf. and the IFAC World Congress in 2023. It addresses scenarios where only experimental data is available instead of a system model. Such situations arise in large-scale systems, like microgrids, where complex interactions between components make it impractical to construct a tractable model or extract desired properties for efficient control design. Furthermore, data-driven control aims to provide methods for utilizing data to learn about a system. Recently, this problem has been reformulated as convex optimization problems, enabling the application of established control tools such as linear matrix inequalities (LMI) [ElG00, Sch00].

*The following tasks envisioned in this WP are described below:*

*WP3.1 -Data-driven control design: [M0-M24]*: There is actually a big effervescence in Automatic Control about the idea to automatically produce model-free or black-box controllers only based on data. For instance, papers [DeP19, VWa20] already received more than 200 citations over the last two/three years. Indeed, these contributions provides the milestones to design such algorithms. However, there are many aspects to investigate such as the robustness issue with respect to uncertainties and delays. Again, LMI and their manipulations are the perfect tools to provide more advances in this domain. First contributions in this topic have already been initiated at the time of submission of this project [Seu23a]. *The main idea is here to provide an alternative solution for the representation of data-driven systems based on differential or difference inclusion, whose parameter are built thanks to the data and in which a process of the automatic exclusion of corrupted or useless data can be included by using pertinent tools in LMI.*

According to the PI, this topic represents the most important goal of Hy2Con, that will feedback the previous WP's. Indeed, the results on data-driven control design that are expected in this WP will serve the other WPs to design data-driven control law for impulsive and switched systems and their associated applications.

Outcomes: Research papers & D3.1. Participants PI, PhD2, EP1,5.

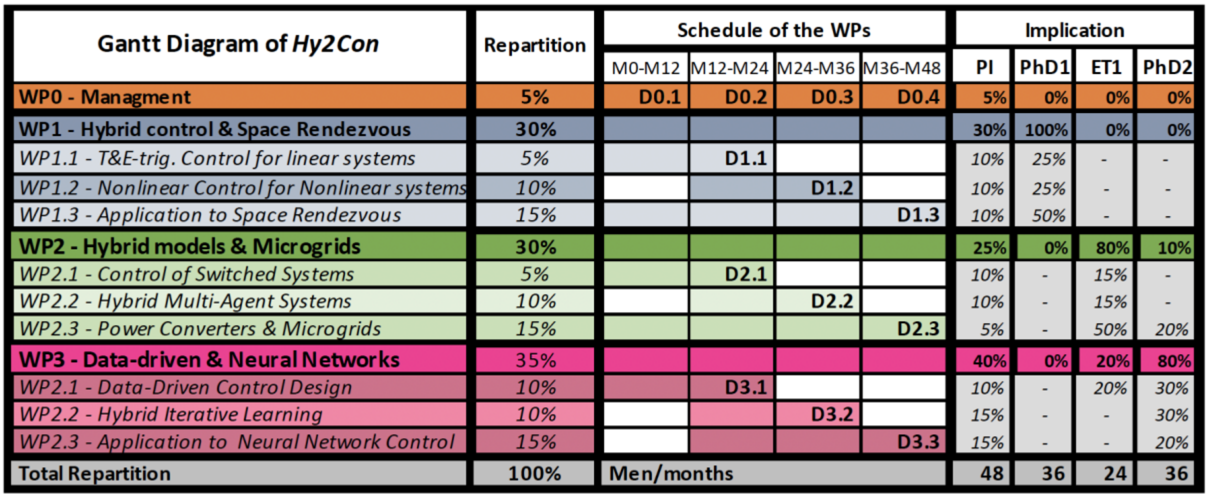
*WP3.2 Hybrid iterative learning control design : [M12-M36]:* In this task, the objectives are to design a complete hybrid iterative learning control algorithm, which presents some originality with respect to the existing structure. First, the constraint of resetting the initial position for each experiment should be removed to propose an online learning approach. Second, thanks to the experience on the PI on Legendre polynomials, the main idea is to propose a new method to build the memory $X$, of the system. *Contrary to the existing method, where* $X$ *only stores the past values of the state (or the output), my idea is to include some convolution of the state into the orthogonal Legendre polynomials and to build polynomial control laws instead of pointwise actions.* Indeed, it has been demonstrated in the fields of approximation, but also in Automatic Control for the stability analysis of time-delay systems that these polynomials can be used to approximate very accurately the desired control law.

Outcomes: Research papers & D3.2. Participants PI, PhD2, LP4, EP1,8.

*WP3.3. Application to the optimization of Neural Networks for learning: [M12-M48]:* This sub-WP represent High Risks / High Gain research. The main motivation for this sub-WP is to derive a generic method for the design and the optimization of Hybrid Neural Networks. *As for the invention of the Clegg's integrator in the , it is expected that including a reset action in a neural network may lead to a breakthrough in learning algorithms for control.* In addition, the goal with also be to include the framework of LMI to the analysis and design of neural networks to present a generic solution to select the optimal weights of the networks to improve the performance of the algorithms.

Outcomes: Research papers, D3.3. Participants PI, PhD2, LP4, EP1,4,6.

*Timelines of the project:* The next table shows the timelines of the project with the granularity of a year. This table summarize the repartition of the efforts among the WP's and sub-WP's, the implication of the PI and the personal funded by the project, and the list of deliverables.



| **Gantt Diagram of *Hy2Con*** | **Repartition** | **Schedule of the WPs** | | | | **Implication** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | M0-M12 | M12-M24 | M24-M36 | M36-M48 | **PI** | **PhD1** | **ET1** | **PhD2** |
| **WP0 - Managment** | **5%** | **D0.1** | **D0.2** | **D0.3** | **D0.4** | **5%** | **0%** | **0%** | **0%** |
| **WP1 - Hybrid control & Space Rendezvous** | **30%** | ▨ | ▨ | ▨ | ▨ | **30%** | **100%** | **0%** | **0%** |
| *WP1.1 - T&E-trig. Control for linear systems* | *5%* | ▨ | **D1.1** | | | *10%* | *25%* | - | - |
| *WP1.2 - Nonlinear Control for Nonlinear systems* | *10%* | | ▨ | **D1.2** | | *10%* | *25%* | - | - |
| *WP1.3 - Application to Space Rendezvous* | *15%* | ▨ | ▨ | ▨ | **D1.3** | *10%* | *50%* | - | - |
| **WP2 - Hybrid models & Microgrids** | **30%** | ▨ | ▨ | ▨ | ▨ | **25%** | **0%** | **80%** | **10%** |
| *WP2.1 - Control of Switched Systems* | *5%* | ▨ | **D2.1** | | | *10%* | - | *15%* | - |
| *WP2.2 - Hybrid Multi-Agent Systems* | *10%* | | ▨ | **D2.2** | | *10%* | - | *15%* | - |
| *WP2.3 - Power Converters & Microgrids* | *15%* | ▨ | ▨ | ▨ | **D2.3** | *5%* | - | *50%* | *20%* |
| **WP3 - Data-driven & Neural Networks** | 35% | ▨ | ▨ | ▨ | ▨ | **40%** | **0%** | **20%** | **80%** |
| *WP2.1 - Data-Driven Control Design* | *10%* | ▨ | **D3.1** | | | *10%* | - | *20%* | *30%* |
| *WP2.2 - Hybrid Iterative Learning* | *10%* | | ▨ | **D3.2** | | *15%* | - | - | *30%* |
| *WP2.3 - Application to Neural Network Control* | *15%* | | ▨ | ▨ | **D3.3** | *15%* | - | - | *20%* |
| **Total Repartition** | **100%** | **Men/months** | | | | **48** | **36** | **24** | **36** |

## 5. PhD BUDGET

***Personal Expenses:***

*PhD Grants:* 240.000€ (40.000€ per year each)

The hiring of two doctoral students for a period of 3 years is considered essential to achieve the objectives of Task WP1 and also of WP2 and WP3 of the project, given the significant workload.

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