MERC PhD Project Proposal

Title of the research project

Automatic Detection, Classification and Prediction of Collective Behaviors in Network Dynamical Systems: Application to Epileptic Seizures

Keywords

Dynamical Systems, Machine Learning, Network Science, Time-Series Analysis, and Neuroscience

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Project description

The automatic detection of collective behaviors is an open problem in network science, and has several fallouts in diverse application fields. For instance, in engineering problems, detecting the onset of collective behaviors is of potential interest for the coordination of robotic swarms (Khan et al., 2020), whereas in the study of animal behavior it has been used to pinpoint the similarities and peculiarities in the patterns of coordination across the animal kingdom (De Lellis et al., 2014). Ideally, one would either use data-driven (model-free) approaches, or obtain a fully calibrated model of the network system under analysis. Unfortunately, both methods are seldom viable when studying complex systems, since they would require qualitatively rich datasets. In applications, instead, our ability to detect, classify, and predict the emergence of collective behaviors is often hindered by the limitations on the available data. Specifically, the time series we are able to collect are affected by noise, and characterized by limited spatial and temporal resolution. For instance, in medical applications, when analyzing electroencephalography (EEG) signals, we must cope with the inherent noise, which give rise to artifacts, and with the limited number of signals we can collect, which are bounded by the number of electrodes.

In this project, we propose to cope with this data limitations by avoiding the reconstruction of the full dynamics of the signal, and rather performing a recurrence analysis that captures the main features required to identify the onset of collective behaviors. More specifically, we will leverage an alternative approach toward recurrence quantification that we recently introduced. Such an approach combines classical and symbolic recurrence to mitigate measurement noise that is known to plague classical recurrence analysis and avoid crude coarsening due to the limited alphabet of a symbolic representation (Caballero Pintado et al., 2018; Porfiri and Ruiz Marín, 2019). We showed how this notion of ε-symbolic recurrence can be used to successfully construct a recurrence network, whose topological characteristics were utilized to enhance the discrimination between ictal and non-ictal activity from scalp EEG recordings.

The objective of this doctoral project is to push forward these promising results and lead to the automation of collective behavior detection, enhancing our ability to analyze and predict the behavior of complex systems under limitations on the available data. The main technical step to be undertaken by the student involved in the project is the extension of the ε-symbolic recurrence network into a multilayer recurrence network, where each layer is associated to each unit in the complex system. Our theoretical findings will be experimentally validated for the automatic detection of epilepsy, a common and chronic group of neurological disorders, from EEG signals. Indeed, despite optimal medication management, about 30% of the 65 million persons affected by epilepsy worldwide will continue to have uncontrolled seizures and will eventually need a presurgical evaluation in an epilepsy monitoring unit. Visual scanning of long-term-EEG recordings by expert epileptologists is the conventional approach to seizure detection, but the complexity of the EEG manifestations of epileptic events (desynchronization, decrease in amplitude, appearance of moderate or high amplitude rhythmic activity, high amplitude electromyogram, irregular paroxysmal activity) constitutes a significant hurdle to manual analysis of EEG recordings, which could often lead to errors even when conducted by highly trained physicians. Automatic seizure detection systems offer a promising alternative to efficiently and accurately analyze EEG recordings. Although many attempts have been made to automate the analysis of EEG recordings, results have

been limited and to-date epileptologists are still relying on visual scanning when it comes to seizure detection (Gotman, 1982; Baumgartner and Koren, 2018).

This project brings forward a transformative, interdisciplinary approach across complex systems, information theory, and dynamical systems theory, which promises a breakthrough in the automatic detection and prediction of emerging behaviors. In demonstrating our approach on seizure detection from EEG, we will benefit from the successful collaboration among the team of supervisors in this field (Ruiz Marín et al., 2020), who integrated tools from traditional statistics in the time domain to state-of-the-art complexity measures. Within this project, the student involved will associate each layer of a multilayer recurrence network to a different electrodes, and use ε-symbolic recurrence analysis to i) reduce the number of false alarms by information fusion across electrodes, ii) infer the network dynamics across electrodes to recognize the typo of epileptic seizure, and iii) obtain short-term, data-driven prediction of epileptic seizure toward personalized device that could be improve well-being and independence of patients. The project validation will be based on real data gathered in a hospital Epilepsy Unit in the region of Murcia, Spain. The data for training the detection, classification, and prediction algorithms will be manually analyzed by clinical experts, and afterword tested without clinical supervision. Finally, the algorithm will be implemented in the Santa Lucia Hospital Epilepsy Unit in Cartagena (Spain) to be tested in a clinical setting.

Relevance to the MERC PhD Program

This projects ideally fits the spirit of the MERC PhD program, with respect to its criteria of excellence, interdisciplinary nature, and transformative potential. The team of advisors involves experts from three different countries (US, Spain, and Italy) with a proven record of collaboration and mentorship of doctoral students. The expertise of the team spans from highly theoretical dynamical systems to data-driven methods and experimental brain research. The mathematical and statistical tools upon which the project is based are at the frontier of knowledge in complex systems, thereby offering an invaluable learning basis for students and an empowering opportunity to contribute to the state of knowledge. Dynamical systems, machine learning, network science, time-series analysis have a central role in the proposal, all topics that ideally fit with the training and curricula of the PhD program. The students will be guided through the challenges of interdisciplinary research, learning how to cope with the different languages and tools used across the disciplines. Beyond enriching their skills in fundamental science, the project will also offer opportunity for students to apply their knowledge on a specific application, with potential impact for early diagnosis of epileptic seizures. Also, the algorithm that the students will develop during the project will be implemented in a clinical trial at the Santa Lucia Hospital in Cartagena.

Key references

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Joint supervision arrangements

The supervisors are close friends who are excited about the project and discuss science on a regular basis, multiple times per week. As such, students will be part of a vibrant team, where discussions continuously happen in an organic and natural manner. Hence, the frequency of meetings will depend on the stage of the research carried out by the student and on the very need they will have. We expect that there will be periods when meeting twice per month with the all group will be sufficient, for instance, when the student is learning and studying some methodology or the state of the art, and other periods when one-on-one meetings with any of the supervisors should happen two or three times per week, for example, when dealing with the development of new models or algorithms. For the mathematical, statistical, and modeling aspect of the project, Professors Porfiri, Ruiz, and De Lellis will take the heaviest lift in mentoring the student. When dealing with specific aspect of the clinical part of the project, like the morphology of the signal prior, during and after the epileptic seizure, Dr. Villegas will be the key supervisor.

Location and length of the study period abroad (min 12 months)

The New York University (NYU) Tandon School of Engineering is the engineering and applied sciences school of NYU. Tandon is the second oldest private engineering and technology school in the United States. Located in the Brooklyn Tech Triangle, ten minutes walking to the Brooklyn Bridge and connected with subway or NYU to any of the other NYU schools in the City. Prof. Porfiri is an Institute Professor (the highest distinction at NYU Tandon), with tenured appointments in Biomedical Engineering and Mechanical and Aerospace Engineering. Prof. Porfiri's laboratory, the Dynamical Systems Laboratory (DSL), was founded fifteen years ago with the vision of creating an interdisciplinary space with fundamental research in dynamical systems with clear societal impact. The laboratory is housed between the Center for Urban Science and Progress (CUSP) and the Department of Mechanical Engineering. MERC students joining the project will have office space in the newly renovated CUSP building and access to any of the DSL facilities. At the DSL, they will be fully integrated in any of the lab activities, such as seminars, workshops, focused courses for professional developments, and collaborative efforts within and outside the group.

Technical University of Cartagena (UPCT) offers several different study programs across engineering, economics, and business sciences. The historical city of Cartagena belongs to the autonomous province of Murcia. Cartagena is located in the southeast of Spain, right at the Mediterranean Sea. The combination of tradition and modernity gives UPCT a vibrant, adventurous and innovative character. Prof. Ruiz is the principal investigator of the excellence research group Economic Modelling and Non-Parametric Statistic (EMODs), an interdisciplinary research group specialized in the analysis and applications of nonlinear time series, complex networks and spatial processes. MERC students joining the project will have office space and access to any of the UPCT facilities.

Ideally, we would like the student to spend 18 to 24 months abroad to ensure ample opportunities for training and full integration with the supervisors' research teams. How to split the time between US and Spain will be discussed based on student preferences; we also anticipate that, under normal circumstances, Prof. Porfiri visits UPTC regularly and so does Prof. Ruiz visits NYU.

Any other useful information

Prof. Porfiri is also a faculty member of the Department of Biomedical Engineering, bringing along access to a number of related learning opportunities in health-related research. For example, he is one of the key investigators of two National Science Foundation Projects on telehealth, machine learning, and rehabilitation between Tandon, the School of Medicine, and the private sector (Facebook and Microsoft). MERC students will be welcome to be involved in these activities, participate in related meetings, and attend lectures and seminars.

Santa Lucía Hospital, where Dr. Villegas works, cares for a population of 280,000 inhabitants. The prevalence of epilepsy in this area is around 1%, therefore 2,800 epileptic patients are attended and followed by the Neurology Department, both in outpatient's clinics, emergency room and hospitalization. Neurology's staff consists of ten neurologists including two experts in Epilepsy. In the Epilepsy Unit we have a video-EEG for long term EEG monitoring and an electroencephalograph for standard EEG recordings. In addition, the Neurology Department of Santa Lucía Hospital is highly committed with clinical research and new technologies. It was granted in 2018 with a European project (Horizon 2020, InDemand project) to develop a communication tool that improved epileptic patients' follow up (EPICO), and again in 2021 to co-create a technological solution to prevent progression in patients with multiple sclerosis.