Research proposal for 3-year PhD scholarship since October 2022

Towards an Intelligent Autonomous Prescriptive Maintenance System for Cyber-Physical Systems with Degradation in Context of Industry 4.0

HUYNH Khac Tuan, PhD
Maître de Conférences / Associate Professor
Head of Control and Computer Engineering program
Computer Science and Digital Society (LIST3N) laboratory
Troyes University of Technology
12 rue Marie Curie, 10004 Troyes cedex, France
Phone: +33 3 25 71 85 32 - Fax: 33 3 25 71 56 49
E-mail: tuan.huynh@utt.fr
Website: https://recherche.utt.fr/computer-science-and-digital-society-list3n/tuan-huynh

The project realization requires knowledge in the fields of reliability & maintenance, machine learning, or applied mathematics. We are looking for a PhD candidate who holds an MSc degree and is familiar with one or more of the following topics:

1. Stochastic modeling and simulation (stochastic process, Monte Carlo simulation, dynamic programming, etc.),
2. Machine leaning (reinforcement learning, deep learning, etc.)
3. Applied mathematics (probability, statistics, etc.).

A good level of programing (Matlab, Python, JuliaLang, or R, etc.) is appreciated.

For PhD applicant, please send your CV, cover letter, Bachelor and Master transcript, and other useful documents (two recommendation letters, publications, Master rank, etc.) to **tuan.huynh@utt.fr** by April 24, 2022.

Summary

Maintenance optimization of industrial production systems is a major concern of managers who want to implement the most relevant maintenance policies in terms of technical and economic plans. The dissemination of new digital technologies using connected objects, the Internet of Things, the cloud, artificial intelligence, and more generally data science, are leading to the development of a new generation of production systems, called *cyber-physical systems*, within Industry 4.0. Unlike traditional embedded systems, a cyber-physical system is typically designed as a collaborative network of interacting elements with physical inputs and outputs instead of as standalone devices. This notion allows improving the link between computational and physical elements by means of intelligent mechanisms, increasing the adaptability, autonomy, efficiency, functionality, *reliability*, safety, and usability of cyber-physical systems. However, it also engender new challenges in the maintenance optimization due to the complexity of the operating structure of cyber-physical systems and their dynamic working environment. In this context, maintenance managers have to face with *big data* and numerous scenarios of diverse nature, both at the operational level and at the tactical and strategic level. Traditional *predictive maintenance* models that focus on a very limited number of scenarios are not well adapted to such a challenge. In order to address this important issue for the future industry, this PhD project is dedicated to the creation of new autonomous intelligent maintenance systems that provide advanced autonomy capabilities, from monitoring to decision making for optimizing maintenance policies. *Reinforcement learning* coupled with *artificial intelligence* would be an ideal paradigm to develop these maintenance

systems because this paradigm, unlike a human, can perform thousands of attempts simultaneously via a powerful computing infrastructure. Scientifically, this project contributes to the consolidation of the theoretical basis of deep reinforcement learning in the context of prognosis and decision support in maintenance.

Context and Problem Statement

Inspired from the human process of knowledge acquisition, *reinforcement learning* is able to solve extremely complex problems. This method of machine learning consists of setting up a system of “rewards” and “punishments” through which the autonomous agent (i.e., the artificial intelligence) learns, by successive experiments, to solve a problem by adopting an "ideal" behavior. Situated within a dynamic environment, the autonomous agent is faced with several choices. It begins then to perform actions randomly and receives a reward after each correct decision. In order to maximize the amount of rewards obtained in the long-term, it refines its strategy to improve the sequence of actions, which allows accomplishing the task in an optimal way with respect to a criterion of rewards and punishments. This principle makes reinforcement learning particularly suitable for the development of autonomous intelligent maintenance systems. Reinforcement learning is indeed not new, but its development has accelerated in recent years with the advent of *deep artificial neural networks*. Their combination, *called deep reinforcement learning*, has led to spectacular successes in various fields, including the AlphaGo program developed by Google DeepMind, the AWS DeepRacer racing car created by Amazon, and the open-source Horizon platform designed by Facebook, among others. Notwithstanding, in the literature of maintenance optimization for systems with degradation, the use of deep reinforcement learning is very limited. Especially, it is confronted, on the one hand, with huge amounts of monitoring data, and on the other hand, with very scattered failure data, but essential to characterize the remaining lifetime of systems. Some recent works on this subject are limited only to single-component systems or to systems with multiple independent components with simplistic assumptions (perfect maintenance actions, limited number of states, known degradation model, etc.). Moreover, no requirements related to the resource limit (spare parts, repairmen, etc.) or to the geometrical constraint of the system (layout of a geometrically distributed system, distance between units, etc.) are considered. The constraining academic assumptions should be relaxed to allow an effective implementation on cyber-physical systems whose characteristic is the interdependence and collaboration between the different units.

In this context, this PhD project is dedicated to the development of innovative models based on deep reinforcement learning to allow an optimal prescriptive maintenance of cyber-physical systems presenting degradation phenomena. Such models must be able to detect abnormal behaviors of the system and its components (diagnosis), to predict their lifetime (prognosis) and to provide proposals for prescriptive maintenance (decision support) in an autonomous and efficient way, which is well adapted to the interactive and evolving environment of Industry 4.0.

Position of the PhD project

Within the Computer Science and Digital Society (LIST3N) laboratory, this research project is fully integrated into the “Operational Safety” Axis topics, in synergy with the competences of the “Data Processing” and “Optimization” Axes. The “Operational Safety” Axis is dedicated to the development of stochastic approaches for the modeling of dependability problems of complex systems both in the design phase and in the operation phase. This includes issues related to modeling for reliability assessment, for the development of prognostic process, for the proposal of maintenance strategies, their evaluation and their optimization. The “Optimization” Axis is concerned with modeling, performance evaluation and optimization of systems, whether they be production, logistics, transport, health or simply organizational. Its scientific objective is the development of methods for solving optimization problems that are efficient in terms of performance and fast in terms of computing time. Finally, the "Data Processing" Axis aims at developing emerging methods of data processing and artificial intelligence. This PhD project, which concerns a problem of dependability, is at the interface with the above-mentioned research axes. In addition, it is partially in line with the scientific strategy of LIST3N, which is espectially linked to the WP 4.5 Research of the European University of Technology (EUT+): "*Towards sustainable, integrated and trusted AI*".

At the national and international levels, this PhD project is in line with the research themes of the GDR MACS in *Dependability*, the SAGIP technical committees S3 and H2M, the *Prognostics and Health Management* (PHM) communities: IEEE PHM, PHM society, the *European Safety and Reliability Association* (ESRA), the *International Federation of Automatic Control* (IFAC): TC 5.1 and TC 6.4, the *International College for Research for Production Engineering* (CIRP), etc.

Scientific objectives

As aforementioned, *deep reinforcement learning* is not new and has been experimented in different application domains (autonomous vehicle, industrial automation, finance and trading, natural language processing, video games, etc.). Its exploitation in the context of dysfunctional scenarios (i.e. in the field of system life prognosis and decision-making in prescriptive maintenance of cyber-physical systems with degradation) is still very limited and cruelly lacks fundaments, methods and tools. Therefore, the main scientific objectives of this project are:

i. to consolidate the theoretical basis of deep reinforcement learning in the context of prognostic and decision support in maintenance,
ii. to study to what extent could this machine learning method allows a higher performance maintenance model compared to existing conditional/predictive maintenance models.

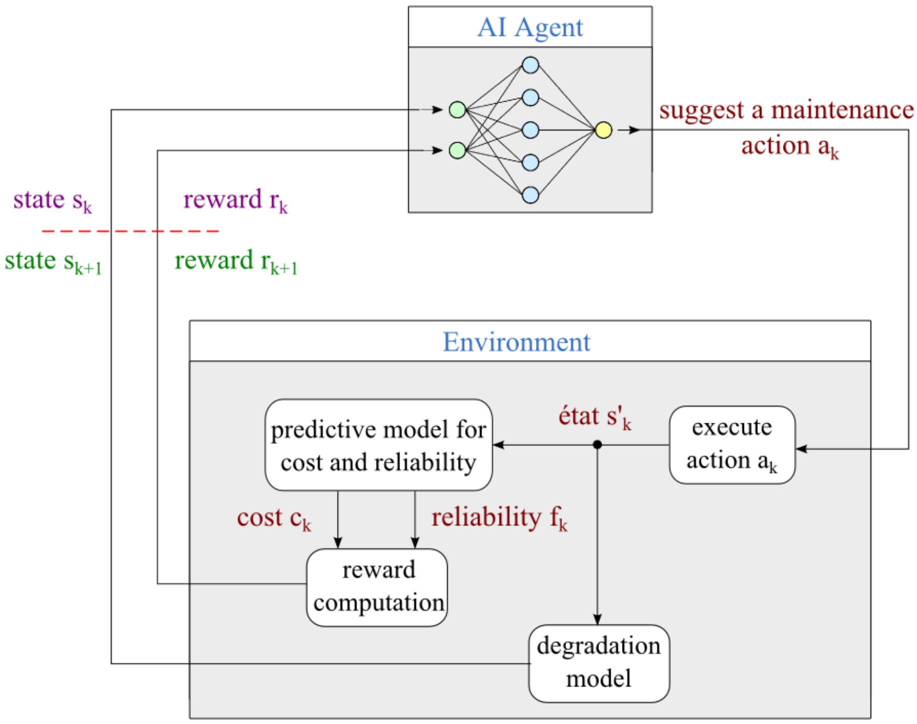

Figure 1: *Basic concept of deep reinforcement learning for maintenance prognosis and decision*

Figure 1 illustrates the basic concept of deep reinforcement learning for maintenance prognosis and decision. At each time step t_k, the agent suggests a maintenance action a_k (replacement, imperfect repair, minimal repair, do nothing, etc.) based on the current state s_k and the perceived reward r_k of its environment. This action a_k modifies the environment and leads to a new state s_{k+1}, which generates a new reward r_{k+1}. Next, the agent uses the state s_{k+1} and the reward r_{k+1} to decide the new action a_{k+1} at t_{k+1}. In this way, the agent learns to improve its decisions in the long-run through evaluation and feedback on the quality of the choices made successively. When applying this concept to degraded cyber-physical systems, several questions arise:

1. Which deep reinforcement learning algorithms (Q-learning, SARSA, Deep-Q-Networks) are best suitable to autonomous maintenance planning?
2. What are the possible mathematical models for modeling degradation (multi-state model, continuous state model, possibly discretized)? How to adapt the concept of deep reinforcement learning when the degradation model is unknown or difficult to develop?
3. What are the relevant decision processes that allow cyber-physical systems to automatically make their optimal maintenance decisions?
4. How to take into account different types of dependencies between the networks of cyber-physical systems in the prescriptive maintenance model?

These questions are the key scientific issues to achieve the main objectives of the project.

Research methodology

The realization of this PhD project requires knowledge in the fields of reliability, prognosis and maintenance, as well as skills in stochastic modeling, probabilistic calculation and deep reinforcement learning. Following a bottom up approach (i.e., from component to system), the project is structured in four phases.

Phase 1 - State of the art (6 months): This phase will be validated by a chapter on state of the art about the deep reinforcement learning algorithms, prescriptive maintenance models and cyber-physical systems with degradation.

Phase 2 - Autonomous models of prescriptive maintenance at the component or single-component system level (12 months): The aim is to exploit the paradigm of deep reinforcement learning to develop autonomous models of prescriptive maintenance adapted to the different contexts of degradation of a cyber-physical system: discrete-state degradation, continuous-state degradation, partially known or unknown degradation. A chapter detailing the different possible models will validate this phase.

Phase 3 - Autonomous models of prescriptive maintenance to the system or network (12 months): The aim is to develop models of collaborative maintenance between different entities of cyber-physical systems presenting deteriorations. Such models are able to take into account the dependency phenomena (stochastic, economic, resource) between systems. For this purpose, a deep reinforcement learning structure with several autonomous agents in interaction could be considered. The developed tracks will be detailed in a written document, in one or several chapters.

Phase 4 - Valuation and writing (6 months): We will validate the developed maintenance models by publishing articles in scientific journals of rank A and presenting the work in national and international conferences. This phase will end with the writing of a PhD thesis.

Supervisor Team and Collaborations

This project is supervised by three qualified researchers of the Computer Science and Digital Society (LIST3N) laboratory, Troyes University of Technology:

1. Khac Tuan HUYNH: Associate Professor - Head of Control and Computer Engineering program,
2. Antoine GRALL: Full Professor - Deputy director of doctoral school "Science for Engineers" ,
3. Yves LANGERON: PhD – RAMS Research Engineer.

The supervisors worked during the last 10 years on reliability problems and predictive maintenance modeling for deteriorating systems, and are qualified researchers of the research field. They already supervised several thesis and their current works motivate the present PhD proposal.

If the quality of the work is correct, the supervisor team motivate Ph.D students to attend national and international conferences and to publish articles in scientific journals of rank A during the thesis.