PhD in Information Technology and Electrical Engineering
Università degli Studi di Napoli Federico II

PhD Student: Lorenzo De Donato

Cycle: XXXVI

Training and Research Activities Report

Academic year: 2021-22 - PhD Year: Second

Tutor: Prof. Valeria Vittorini

Co-Tutors: Prof. Carlo Sansone, Prof. Francesco Flammini (Linnaeus University, Sweden)

Date: October 30, 2022

1. Information:

- **PhD student: Lorenzo De Donato** **PhD Cycle: XXXVI**
- **DR number: DR995134**
- **Date of birth: 06/07/1993**
- **Master Science degree: Computer Engineering**

  University: Università degli Studi di Napoli "Federico II"
- **Scholarship type: funded by CINI (Consorzio Interuniversitario Nazionale per l'Informatica), partially on the H2020 Shift2Rail RAILS project**
- **Tutor: Prof. Valeria Vittorini**
- **Co-tutors: Prof. Carlo Sansone, Prof. Francesco Flammini (Linnaeus University, Sweden)**

2. Study and training activities:

Activity	Type[1]	Hours	Credits	Dates	Organizer	Certificate[2]
Intelligent Monitoring and Control of Interconnected Cyber-Physical Systems	Seminar	1	0.2	07/12/2021	Artificial Intelligence Doctoral Academy (AIDA)	N
GDPR basics for computer scientists	Seminar	1.5	0.3	14/12/2021	Prof. Piero Bonatti (DIETI)	N
Self-awareness for autonomous systems	Seminar	1	0.2	11/01/2022	AIDA	N
The learning landscape in deep neural networks and its exploitation by learning algorithms	Seminar	1	0.2	21/01/2022	Prof. Michele Ceccarelli (DIETI)	Y
The role of standards for the future of AI	Seminar	1	0.2	15/02/2022	Fraunhofer Institute for Cognitive Systems IKS	N
Towards Trustworthy AI - Integrating Reasoning and Learning	Seminar	1	0.2	22/02/2022	AIDA	N
Who pays the bill when an AI-system causes damage?	Seminar	1	0.2	10/03/2022	Carmen Mac Williams (Grassroots Arts)	N

Artificial visual intelligence: Perceptual commonsense for human-centred cognitive technologies	**Seminar**	**1.5**	**0.3**	**16/03/2022**	**Centre for Robotics and Neural Systems – University of Plymouth**	**N**
Potential and challenges of next generation railway signaling systems: Moving Block and Virtual Coupling	**Seminar**	**1**	**0.2**	**06/04/2022**	**Prof. Valeria Vittorini (DIETI)**	**Y**
Towards a Political Philosophy of AI	**Seminar**	**2**	**0.4**	**11/04/2022**	**Prof. Giuseppe Longo, Prof. Flora Amato**	**N**
Safety First for Autonomous Vehicles: Where Do We Stand? What is Missing?	**Seminar**	**1.5**	**0.3**	**28/04/2022**	**IEEE Standards Association**	**N**
Low-code AI: Making AI Accessible to Everyone	**Seminar**	**1**	**0.2**	**18/05/2022**	**MathWorks**	**Y**
Using MATLAB with Python	**Seminar**	**1**	**0.2**	**18/05/2022**	**MathWorks**	**Y**
Continuous Integration with MATLAB and GitHub Actions	**Seminar**	**1**	**0.2**	**18/05/2022**	**MathWorks**	**Y**
Mind the Gaps: Trustworthy AI for Autonomous Vehicles	**Seminar**	**1.5**	**0.3**	**30/06/2022**	**IEEE Standards Association**	**N**
Impreditorialità Accademica	**Course**	**10**	**4**	**26/05/2022-14/06/2022**	**UNINA**	**Y**
La sostenibilità del trasporto pubblico locale su ferro: elementi di efficientamento	**Seminar**	**3.5**	**0.7**	**12/07/2022**	**Prof. Mario Pagano (DIETI)**	**Y**
Neural Networks and Deep Learning	**Course**	**65**	**10**	**01/11/2022-06/04/2022**	**Prof. Giorgio Buttazzo (Scuola Superiore Sant'Anna, Pisa)**	**Y**

AI with Model-Based Design: Virtual Sensor Modeling	**Seminar**	**1**	**0.2**	**20/09/2022**	**MathWorks**	**Y**
Medical Image Analysis and AI Workflows in MATLAB	**Seminar**	**1**	**0.2**	**29/09/2022**	**MathWorks**	**Y**
Mind The Gaps: Do You Trust AI-Enabled Autonomous Vehicles? – Sessions 2, 3 and 4	**Seminar**	**5**	**1**	**11/10/2022**	**IEEE Standards Association**	**N**

1) Courses, Seminar, Doctoral School, Research, Tutorship
2) Choose: Y or N

2.1. Study and training activities - credits earned

	Courses	Seminars	Research	Tutorship	Total
Bimonth 1	**0**	**0.5**	**7.5**	**0**	**8**
Bimonth 2	**0**	**0.8**	**8**	**0**	**8.8**
Bimonth 3	**0**	**1.4**	**8**	**0**	**9.4**
Bimonth 4	**0**	**0.9**	**8**	**0**	**8.9**
Bimonth 5	**4**	**0.7**	**5.5**	**0**	**10.2**
Bimonth 6	**10**	**1.4**	**8**	**0**	**19.4**
Total	**14**	**5.7**	**45**	**0**	**64.7**
Expected	**30 – 70**	**10 – 30**	**80 – 140**	**0 – 4.8**	

3. Research activity:

Most of the research activities I carried out during this year have been conducted in the context of the H2020 Shift2Rail project RAILS (Roadmaps for AI integration in the raiL Sector), whose main objective is to investigate how to bring Artificial Intelligence (AI) approaches in the rail sector and provide recommendations for their implementation in railway applications including smart maintenance, autonomous train driving, and traffic planning and management.
To be specific, my research activities have been mainly oriented to the study and implementation of Computer Vision approaches based on Deep Learning (DL) to improve current practices in Level Crossing (LC) maintenance and inspection activities and Vision-based Obstacle Detection on rail tracks. Therefore, this year, my research has mainly been two-fold as discussed below.

1. **Smart Maintenance at Level Crossings**
   In line with the research activities carried out during my first year, advancements have been done towards the definition of a suitable architecture of an AI system capable of efficiently and continuously monitoring LCs while being non-intrusive and possibly cheaper than current practices or other solutions. To contextualise the case study, it is worth highlighting that my research focuses on Active Automatic LCs, as they involve all the macro sub-systems that could compose a LC namely the Warning Bell (WB), the Warning Light (WL), and the Barrier (BA) sub-systems.

The aim is to provide a solution that: i) overcomes the shortcomings of scheduled-based inspections; ii) does not introduce complications in terms of intrusiveness (i.e., that leverage sensor that could be installed externally to the systems in order not to run into possible re-approval processes); iii) is more cost-effective than other solutions.
The AI system I am currently working on aims at overcoming these problems by leveraging non-intrusive sensors, particularly fixed cameras and microphones, and analysing these sub-systems as if they were black boxes, i.e., evaluating only their visible and audible behaviour to estimate their deviations from the expected/normal functioning. Worth highlighting, camera sensors also introduce advantages in terms of technology reusability (cost-effectiveness): it would be possible to exploit cameras already installed at LC currently used for, e.g., safety/security purposes.
The AI system is composed of four main modules: (i) a Warning Bell Detection Module and (ii) a Warning Light Detection Module, which focus on detecting WBs and WLs respectively; (iii) a Barrier Analysis Module, which aims at detecting the movement of the barrier(s); and (iv) an Orchestrator which will gather the outputs of all the modules mentioned above to outline the health status of the whole LC.
As discussed below, during this year, I have focused on performing additional tests for the Warning Bell Detection Module (whose implementation is already described in the first year's report) and studying how the Barrier Analysis Module could be implemented.

- *Warning Bell Detection Module.* In addition to what was described in the first year's report, further tests were performed to study the correlation between the dimension of the training set and the accuracy of the model (which is a three-class classifier based on a VGG-like Deep Neural Network), and cross-country and audio-intensity generalisation performances of the proposed solution. Results showed that: i) in general, the larger the datasets the better the accuracy, hence, it might be still room for further improvements if more data will be collected; ii) the model does not perform properly on WBs from a specific geographic area (e.g., United Kingdom) if trained by considering WBs belonging to another area (e.g., Italy), this means that the model must be fine-tuned each time it will be used to detect WBs which are different from those it has been trained on; iii) the model performs better when the intensity of the WBs is above a certain threshold. If the latter is a practical problem depends on whether it would be possible to place the microphone sufficiently near the LC WB. Theoretically, if the WB performs correctly, the nearest the microphone the higher the intensity of the collected audio sample; then, the misclassification based on the intensity could also be seen as a warning indicating that the WB is not functioning properly.
- *Barrier Analysis Module.* The idea was to leverage a DL object detector to identify the barrier(s) within video frames and then, given that the camera is fixed, retrieve the movement of the barrier by considering the heights of the bounding boxes over the video frames. To study the potential of this approach I recorded different LC videos (with different weather and light conditions) by exploiting the Grand Theft Auto 5 (GTA 5) video game. Then, I manually labelled each frame of the videos by exploiting the LabelImg tool. Hence, I split the dataset into train, validation, and test sets (1212, 263, and 263 frames respectively) to train and evaluate a YOLOv5s architecture. On the test set, the model achieved the following results: precision equal to 1; recall equal to 0.996; mean Average Precision (with an Intersection over Union threshold set to 0.5 – mAP@0.5) equal to 0.995; and mAP@0.5:0.95 equals to 0.929. Then, in the future, it would be possible to trace the movement of the barrier by plotting the height of the identified bounding boxes to study the deviation from its nominal behaviour.

Additional details and future improvements could most likely be found in RAILS's Deliverable D3.3 which publication is scheduled for December 31, 2022.

2. **Obstacle Detection and Collision Avoidance**

The aim is to improve the coverage of vision-based Obstacle Detection (OD) systems which typically rely on Supervised DL approaches and, thus, can detect only the obstacles with which the network has been fed during the training phase. Improving the coverage, in this case, means implementing an AI architecture that is capable of also detecting anomalies it has not seen during the training phase. As a case study, it has been selected "obstacle detection on rail tracks"; however, most likely, the solutions developed may also be adopted in other circumstances, e.g., to detect obstacles within the LC area. The experiments discussed below have been performed by leveraging video data provided by researchers from the Scuola Superiore Sant'Anna of Pisa. However, I have already start working on a rail "simulator" by leveraging the MathWorks' editor RoadRunner, originally conceived to design road scenarios, to create different rail scenarios with different obstacles and then capture videos to train and test DL models in the future.

The AI architecture I am currently working on is composed of five modules: i) Rails Detection Module, oriented at detecting the rail tracks (the Region of Interest – RoI); ii) Obstacle Detection Module, which will leverage state-of-the-art DL object detectors such as YOLOv5 to recognise obstacles within the RoI; iii) Anomaly Detection Module, which will be oriented at detecting any kind of possible anomaly within the RoI by leveraging DL approaches trained in an unsupervised mode; iv) Check Detection Module, which will compare the detections made by the Obstacle and Anomaly Detection modules; and v) Distance Estimation Module, which will estimate the distance of the obstacle/anomaly from the train. This year, I have mainly focused on the Rails Detection and Anomaly Detection modules as discussed below:

- *Rails Detection Module*. To realise this module, I leveraged a semantic segmentation approach based on a U-NET architecture. To train the network, I considered frames depicting "free tracks" (i.e., without any obstacles). The challenge was that these frames were not labelled, therefore, instead of manually labelling all of them, I only labelled 10% of them (by exploiting the LabelMe tool) and then realised a self-training approach to automatically label the remaining ones as discussed in the following. First, I leveraged the RailSem19 dataset (which is available online) which contains real images properly labelled to build semantic segmentation networks and customised it by extracting only the labels (i.e., the masks) related to the rail tracks. Second, I pre-trained the U-NET architecture on the obtained data. Third, I implemented a custom self-training approach to automatically label the non-labelled frames and, thus, obtain a labelled dataset which I augmented by simulating darker/brighter illumination conditions, snow, rain, etc. Lastly, I split these data into train, validation, and test sets (12800, 1600, and 1600 frames respectively) to train and validate the U-NET whose Dice Score computed on the test set is equal to 0.9948.

  To conclude, I tested the U-NET on frames containing obstacles. The main shortcoming was that, when the train is approaching an obstacle, the U-NET prediction tends to degrade, i.e., some background pixels are classified as rail track pixels (and vice-versa). Hence, I wrote a post-processing algorithm to "adjust" the prediction and "enlarge" the masks produced by U-NET (which produces masks whose "edges" follow the rails). The necessity to enlarge the mask, i.e., make it a bit wider, come from the fact that an obstacle could also stand near the rail tracks, and not precisely on them, but still be a threat as it could be hit by the shape of the train. At this stage, the time the network takes to detect the rails is, on average: 5.3 milliseconds without post-processing and 58.5 milliseconds with post-processing.

- *Anomaly Detection Module*. The main idea was to implement a Deep Neural Network (DNN) – trained with non-anomaly images only – capable of reconstructing the image in input and, possibly, removing any kind of anomaly. Then, it would be possible to obtain an "anomaly map" by computing the difference or, for example, the Structural Similarity Index Measure (SSIM) map. Preliminary tests have been performed by considering two kinds of autoencoders (AE): a "traditional" deep AE and a Vector Quantisation Variational AE (VQ-VAE).
  To train and evaluate them I took into account the augmented dataset described above and I pre-processed it by masking all the frames (i.e., the frames are composed of all black pixels except for those related to the rail track that were left unchanged). Then, I split the dataset into train and validation sets (14400 and 1600 frames respectively). Results show that the "traditional" AE does not perform properly; differently, the VQ-VAE produced some promising results. Considering the results obtained on the validation set, the VQ-VAE is capable of reconstructing images that are, on average, about 98,92% similar to the original ones.
  Then, I tested how the VQ-VAE behaves when there are anomalies on the rail tracks. For each frame in input, the VQ-VAE produces the reconstructed frame (in 3.5 milliseconds on average); then, an anomaly map is computed between the reconstructed and the original frame. However, results show that the anomaly is poorly identified, and the anomaly maps are characterised by evident noise. Therefore, further investigations are required in this direction.

Additional details and future improvements could most likely be found in RAILS's Deliverable D2.3 which publication is scheduled for December 31, 2022.

3. Other Activities

- *Study on Trustworthy Intelligent Train Control (ITC).* Preliminary studies have been carried out to understand what has been proposed at the European Leven and within the automotive sector in terms of Trustworthy AI systems (and vehicles). As a result of some of these investigations, the paper "A Vision of Intelligent Train Control" (reported below) has been written and published which discusses the possibility of exploiting the concept of the safety envelope (originally conceived in automotive) to potentially introduce AI in a "safe" and "trustworthy" manner within ITC.
- *Collaboration with HITACHI Rail STS.* I have collaborated with HITACHI Rail STS on the investigation of AI approaches to detect obstacles within the area of level crossings.
- *AI4RAILS 2022 Workshop.* I was involved in the AI4RAILS 2022 Workshop (organized in the context of the RAILS project) as a member of the Program Committee.
- *Paper Review.* I have acted and currently acting as reviewer for papers submitted to journals (e.g., IEEE Intelligent Transport Systems) and workshops (e.g., AI4RAIL 2022).

4. Research products:

RAILS project deliverables (available online: https://rails-project.eu and ResearchGate):

- Francesco Flammini, Stefania Santini, Lorenzo De Donato, and Valeria Vittorini, "Deliverable D2.1: WP2 Report on case studies and analysis of transferability from other sectors". Published, 2022 (NOT indexed).

- Nikola Bešinović, Francesco Flammini, Lorenzo De Donato, Ruifan Tang, Zhiyuan Lin, and Valeria Vittorini, "Deliverable D3.1: WP3 Report on case studies and analysis of transferability from other sectors". Published, 2022 (NOT indexed).
- Stefania Santini, Lorenzo De Donato, Valeria Vittorini, Francesco Flammini, and Rob M.P. Goverde, "Deliverable D2.2: WP2 Report on AI approaches and models". Published, 2022 (NOT indexed).
- Francesco Flammini, Lorenzo De Donato, Zhiyuan Lin, and Ruifan Tang, "Deliverable 3.2: WP3 Report on AI approaches and models", Published, 2022 (NOT indexed).

Scientific papers:

- Nikola Bešinović, Lorenzo De Donato, Francesco Flammini, Rob M.P. Goverde, Zhiyuan Lin, Ronghui Liu, Stefano Marrone, Roberto Nardone, Tianli Tang, and Valeria Vittorini, *"Artificial Intelligence in Railway Transport: Taxonomy, Regulations and Applications"*, IEEE Transactions on Intelligent Transportation Systems (IEEE T-ITS). Published, 2021. Indexed in Scopus.
- Ruifan Tang, Lorenzo De Donato, Nikola Bešinović, Francesco Flammini, Rob M.P. Goverde, Zhiyuan Lin, Ronghui Liu, Tianli Tang, Valeria Vittorini, and Ziyulong Wang, *"A literature review of Artificial Intelligence applications in railway systems"*, Transportation Research Part C: Emerging Technologies (TR_C). Published, 2022. Indexed in Scopus.
- Lorenzo De Donato, Francesco Flammini, Stefano Marrone, Claudio Mazzariello, Roberto Nardone, Carlo Sansone, and Valeria Vittorini, *"A Survey on Audio-Video Based Defect Detection Through Deep Learning in Railway Maintenance"*, IEEE Access. Published, 2022. Indexed in Scopus.
- Francesco Flammini, Lorenzo De Donato, Alessandro Fantechi, and Valeria Vittorini, *"A Vision of Intelligent Train Control"*, Reliability, Safety, and Security of Railway Systems. Modelling, Analysis, Verification, and Certification (RSSRail 2022). Lecture Notes in Computer Science (LNCS). Published, 2022. Indexed in Scopus.
- Ruth Dirnfeld, Lorenzo De Donato, Francesco Flammini, Mehdi Saman Azari, and Valeria Vittorini, *"Railway Digital Twins and Artificial Intelligence: Challenges and Design Guidelines"*. European Dependable Computing Conference (EDCC). Dependable Computing - EDCC 2022 Workshops. Communications in Computer and Information Science (CCIS). Published, 2022. Indexed in Scopus.
- Lorenzo De Donato, Stefano Marrone, Francesco Flammini, Carlo Sansone, Valeria Vittorini, Roberto Nardone, Claudio Mazzariello, and Frédéric Bernaudin, *"Intelligent Detection of Warning Bells at Level Crossings through Deep Transfer Learning for Smarter Railway Maintenance"*, Engineering Applications of Artificial Intelligence. Submitted, 2022.

5. Conferences and seminars attended

- *INNORAIL2021: Future of the railway – Railway of the future*. Budapest (Hungary), 16-18 November 2021. I gave an oral presentation titled "*Roadmaps for the Integration of Artificial Intelligence in Railways*".

- *RAILS Mid-term Project Workshop*. Online Event, 25 February 2022. As one of the researchers involved in the project, I also gave an oral presentation titled "Artificial Intelligence for Smart Maintenance: Preliminary Results and Next Steps".
- *MATLAB Expo 2022*. Online Event, 17-18 May 2022.
- *RSSRail 2022: Reliability, Safety and Security of Railway Systems*. Paris (France), 1-2 June 2022. I presented the paper *"A Vision of Intelligent Train Control"*.
- *WCRR 2022: World Congress on Railway Research.* Birmingham (United Kingdom), 6-10 June 2022. I gave an oral presentation titled *"Trustworthy AI for safe autonomy of smart railways: directions and lessons learnt from other sectors*".

6. Periods abroad and/or in international research institutions

I am currently carrying out my research at Linnaeus University (Växjö, Sweden), under the supervision of Prof. Francesco Flammini. The research period abroad began on 1 September 2022 and its end is scheduled for 22 December 2022. Being the Federico II and the Linnaeus University partners in the context of the RAILS project, I am continuing my research on the project's tasks and activities while supported by Prof. Flammini and accessing computing resources to train and test some of the networks discussed above.
In the current year, I have spent two months (September and October) at Linnaeus University.

7. Tutorship

None

8. Plan for year three

Future research activities will be mainly oriented at implementing and optimising the modules of the AI architectures discussed above for Level Crossing smart maintenance and Vision-Based Obstacle Detection on rail tracks. The idea would be to provide a suitable solution for these problems or, at least, a comprehensive analysis of the AI approaches that could be useful to address these tasks. Perhaps, Explainable AI approaches will be studied to understand if these could contribute to increasing the trustworthiness of AI systems in railways.

In line with what discussed in this document, the objective of my PhD thesis would be to investigate how AI could support dependable railway systems to improve the maintainability of railway assets and the safety of autonomous trains. Specifically, it will discuss how vision-based AI applications could be valuable in the contexts of smart maintenance, with particular focus on the Level Crossing case study, and autonomous trains' environmental perception, with particular emphasis on obstacle detection on rail tracks.

To conclude, I will continue my research period at Linnaeus University (Växjö, Sweden) until 22 December 2022.