PRINCETON UNIVERSITY

Senior Thesis Project
Digital Twin for Intelligent Traffic Management

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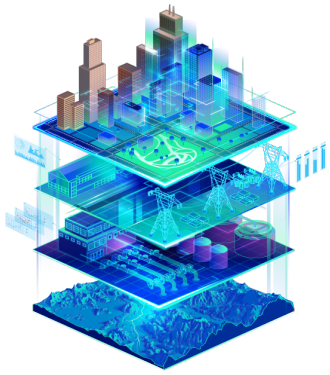
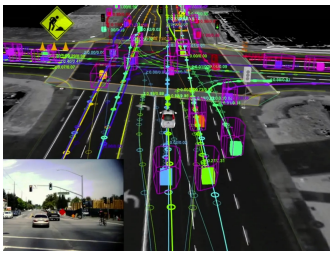
Department
Civil and Environmental Engineering

Term
Fall 2023

Document Version
2023-02-05-v1





Every 12 minutes, a person dies on US roads [1]. Pedestrians are particularly at risk, as a collision with a vehicle is usually fatal or results in serious injuries. The risk of injury is also disproportionately higher for younger pedestrians. Modern technology can significantly increase road safety and improve the performance of the transport system.

One promising technology to foster this change are digital twins. A digital twin is the combination of computational models and real-world systems with the aim to provide a realistic digital representation. The ability to model complex system interactions is an essential feature of a digital twin. Modelling and simulation allow exploring the system behaviour quickly, safely and inexpensively without resorting to real experiments. Researchers and analysts can create synthetic environments that are comprised of other modular components, perturb them, and then gather insights, which allow them to study and solve issues before they occur.

The aim of this project is to develop a digital twin of a road crossing with traffic light control. The project should introduce the problem, describe the implementation of the solution, and show the results of a numerical example. The code of the implementation should be documented according to common software engineering standards and has to be included in the final report. The hosting group offers regular meetings in which the current progress of the work will be discussed and in which any potential problems or issues can be raised.

The concrete tasks of the project are as follows:

1. The first task is to develop an agent-based simulation model for pedestrian crossing and traffic flow at a simple road section. I.e. pedestrians and vehicles are represented as individual agents moving along the road or crossing it (e.g. [2],[3]).
2. In a second step, data must be collected from the ”real world”. As continuous measurements might be beyond this project’s scope, video recordings have to be made from an intersection in Cambridge. These video recordings will serve as a proxy for potential CCTV streaming data.
3. The third task involves extracting information from the recorded data. Computer vision and AI algorithms are used to determine, for example, the position, speed and field of view of the cars. (e.g. [4],[5])
4. In this task, the ”real” pedestrians and vehicles are displayed in the previously generated simulation environment. This means that the movement pattern of the agent no longer corresponds to the simulation but to the observations on the street.
5. A fifth and final task is to document the findings and deploy the code. Good engineering requires proper documentation so that peers can follow your steps and reproduce the results. In the spirit of Open Science, the findings and software of this project should be disseminated in such a way that it is accessible to all levels of an inquiring society, amateur or professional.
6. Bonus Task A: Use the observations to train the agents in the simulation so that the simulated agents behave similarly to real road users. (e.g. [6],[7])
7. Bonus Task B: Use reinforcement learning to find the optimal traffic light operation in the simulation environment. (e.g. [8])

[1] NHTSA
[2] Simulating Traffic Flow in Python
[3] Simulation of Urban MObility
[4] OpenCV Vehicle Detection, Tracking, and Speed Estimation
[5] Making Road Traffic Counting App
[6] Using machine learning as a surrogate model for agent-based simulations
[7] Application of Machine Learning Techniques to an ABM
[8] Reinforcement Q-Learning from Scratch in Python

PRINCETON UNIVERSITY

Senior Thesis Project
Machine Learning on Networked Systems

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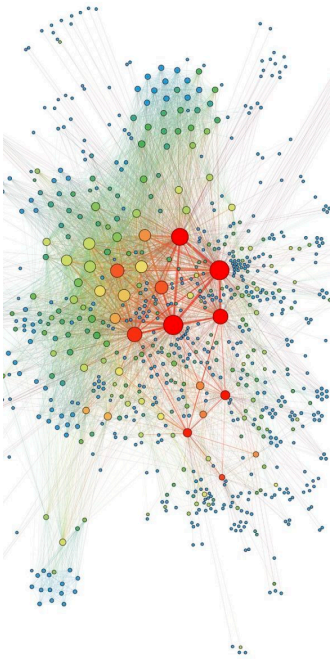
2023-02-05-v1



Infrastructure systems are essential for social development and economic growth. They play a fundamental role in the use and distribution of spatial services, including transportation and communication. Recent historical natural hazard events have shown that the analysis and understanding of large-scale infrastructure systems are essential for research, engineering and society. Especially due to the complexity and interdependence of these systems, localised failures can cascade dramatically, leading to widespread, unforeseen and often disproportionate disruptions compared to the actual physical damage.

Network theory is often used to describe and analyse such complex systems. Thus, the modelling of complex systems as networks of connected elements has become subject to intense study in various fields, including physics, social science, and engineering, with the goal of analysing the structure and dynamics of large-scale networks of all kinds.

Although complex network theory made its appearance in transportation research through empirical measures, the relationships between dynamic properties patterns and the underlying infrastructure network structures have scarcely been investigated so far. Furthermore, the naive application of the (static) network paradigm in modelling dynamic complex systems might lead to wrong conclusions [1],[2]. One way to address this issue is through the extension to higher-order networks (HONs) representation.

Continuing the problem outlined above, the goal of this project is to implement and apply higher-order network analytics and other GraphML approaches for predicting the behaviour of complex transportation systems. The project should introduce the problem, describe the implementation of the solution, and show the results of a numerical example. The code of the application should be documented according to conventional engineering standards and has to be included in the final report. The hosting group offers regular meetings in which the current progress of the work will be discussed and in which any potential problems or issues can be raised.

The concrete tasks of the project are as follows:

1. The first task is to get familiar with and refresh your knowledge of complex infrastructure systems and network science. To archive this, current literature, lecture nodes and online material will be provided.
2. The second task is to investigate a complex infrastructure system (e.g. transportation network) with classical engineering tools (e.g. traffic flow simulation) in order to generate a benchmark model for the following analysis.
3. In the third task, "standard" machine learning approaches are applied to the infrastructure system, with the goal to identify critical elements, classify paths and predict certain features (e.g. traffic flow, route choice)
4. In this task, higher-order networks, as well as other GraphML approaches, are implemented and tested. This should allow accounting for the network dynamics (e.g. traffic flow) and other higher-order effects during the assessment. Both the standard and the higher-order results are compared with the benchmark engineering model.
5. A fifth and final task is to document the findings and deploy the code. Good engineering requires proper documentation so that peers can follow your steps and reproduce the results. In the spirit of Open Science, the findings and software of this project should be disseminated in such a way that it is accessible to all levels of an inquiring society, amateur or professional.

[1] From networks to optimal higher-order models of complex systems
[2] Analysis and Visualisation of Time Series Data on Networks with Pathpy

PRINCETON UNIVERSITY

Senior Thesis Project
AI Solutions for a Resilient Water Distribution

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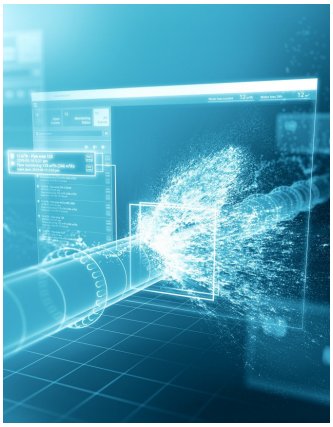
Term
Fall 2023

Document Version
2023-02-05-v1

To ensure that customers have access to clean drinking water at any time, well-maintained water distribution infrastructure is needed. Rapid urbanisation and the effects of climate change will put even more strain on the infrastructure - especially the pipes - in the future. This comes at a price: millions of pounds are spent on maintenance and renewal of the facilities and infrastructures every year. Infrastructure provider thus ensures that the substance of existing facilities such as pipes, pumps, and valves are maintained.

The determination of optimal intervention programs for a portfolio of pipes requires, among other things, a reliable prediction of the deterioration and expected bursts of the pipe assets. A detailed description of this process enables appropriate measures to be taken to reduce the probabilities of bursts and maximise the effect of monitoring, maintenance, repair and renewal expenditure.

The condition of the pipe asset is assessed in the scope of historical data. Since 1900 a UK water provider has maintained a database documenting these condition assessments. There are over 500k pipe assets in this database and 60k records of failures.



This project aims to determine **burst behaviour for water distribution pipes** from available data using novel data-driven approaches such as AI and machine learning. The project should introduce the problem, describe the implementation of the solution, and show the results from the data. The deterioration mechanisms of the water pipes should be documented according to conventional engineering standards and have to be included in the final report. The hosting group offers regular meetings in which the current progress of the work will be discussed and in which any potential problems or issues can be raised.

The concrete tasks of the project are as follows:

1. Preparation of the data – In order to be able to estimate the burst process, the data must be cleaned and structured. This enables the application of different machine learning algorithms. Furthermore, this point includes the preparation of the state evolution so that a comparison with the given observations and currently used engineering models becomes possible.
2. Analysis of the data – Before the burst model is developed, the processed data is analysed to gain important insights into the deterioration and burst process and show possible inadequacies of the current burst model used. This point includes comparing the recorded observations with the predictions of the recent deterioration model and a static evaluation of the data.
3. Burst model – Different machine learning approaches should be trained on the given data to predict potential bursts of the pipes. The different methods should be compared ageist each other and with the currently used model of the infrastructure provider. Furthermore, the models should be used to predict the degradation of the whole water distribution system.
4. Optimal interventions – Knowing potential future bursts, an optimal maintenance strategy should be developed to support the decision-making process of the infrastructure owner and to increase the resilience of the water distribution system.
5. Writing report – The work will be summarised in a report consisting of a description of the methods used, presentation of all burst models, and recommendations on how to move forward with making better predictions of pipe failures in the future.

PRINCETON UNIVERSITY

Senior Thesis Project
The Digital Future of Kyoto's Water Distribution

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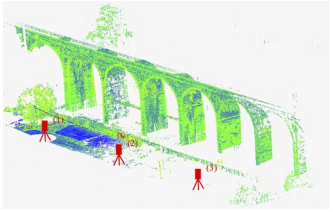
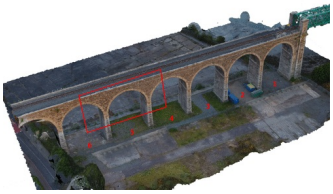
Term
Fall 2023

Document Version
2023-02-05-v1





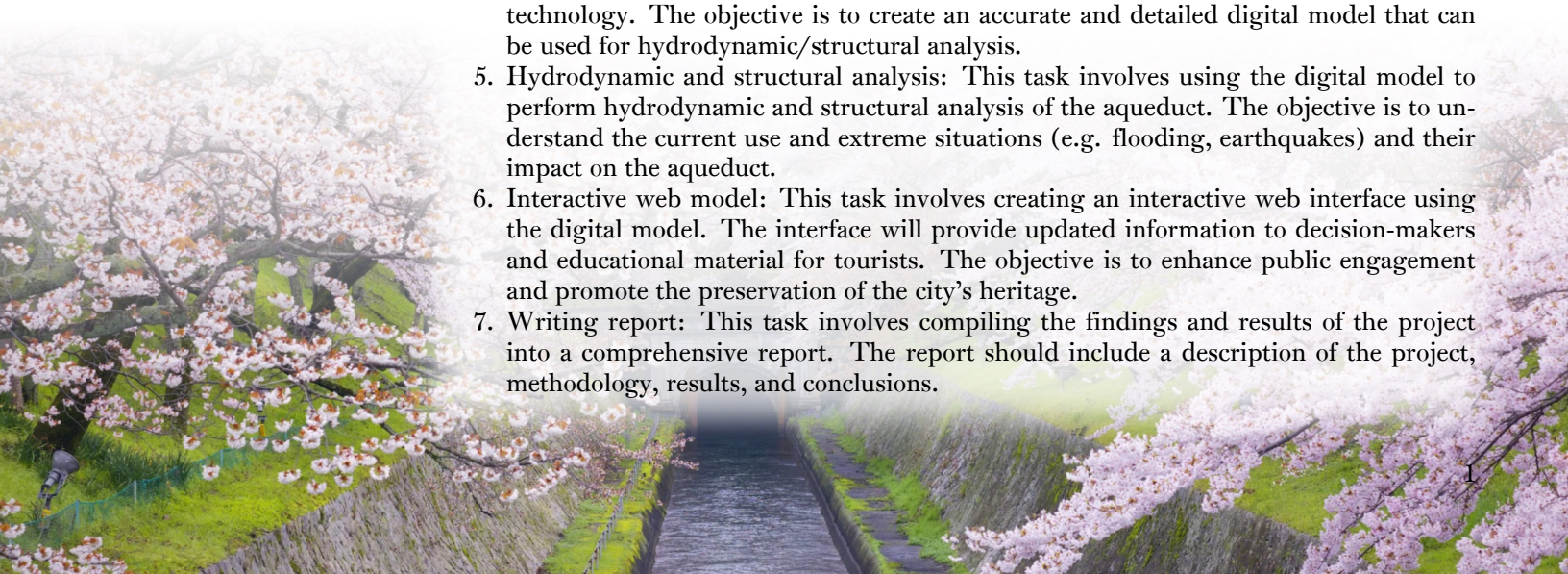
Water infrastructure systems play a critical role in providing clear and healthy drinking water for communities. One such example is the Kyoto water distribution system, which was built in 1885 and initiated a new era in the development of the city. The system still serves 98% of Kyoto's population and is considered a key asset in the city. In particular, the Suirokaku Aqueduct of the water distribution system is an important tourist attraction and a symbol of the city's history. The goal of this project is to digitize the historic aqueduct and use it to perform hydrodynamic/structural analysis and to enhance public engagement.

The aim of this project is to create a digital replica of the Suirokaku Aqueduct in Kyoto using Building Information Modeling (BIM) technology. The digital model will be used to perform hydrodynamic/structural analysis of the current use and extreme situations (e.g. flooding, earthquakes), and to provide updated information to decision-makers and educational material for tourists. The project will be conducted in cooperation with the Chair of "Architecture, Construction, and Innovation" from the Kyoto Institute of Technology. A two-week field trip to Kyoto will be conducted for data collection and site observation. The collected data will be used to create a digital replica of the aqueduct using BIM technology. The digital model will then be used to perform hydrodynamic/structural analysis and to create an interactive cloud interface that will provide updated information to decision-makers and educational material for tourists.

This project presents a unique opportunity to digitize a historical and important infrastructure in Kyoto and to use it to perform hydrodynamic/structural analysis and to enhance public engagement. The project will provide valuable experience in digital modeling, hydrodynamic analysis, and public engagement, and will contribute to the preservation of the city's heritage.

The concrete tasks of the project are as follows:

1. Review of historic water distribution systems in Japan: This task involves researching and studying the history of water distribution systems in Japan, with a focus on the Kyoto water distribution system and its aqueducts. The objective is to understand the significance and historical importance of the Suirokaku Aqueduct and the water distribution system.
2. Familiarization with surveying technologies and digitization methods: This task involves gaining knowledge and experience in various surveying technologies such as photogrammetry, laser scanning, and total stations, as well as the digitization methods used to create a digital replica of the aqueduct, such as Scan2BIM.
3. Field trip to Japan to digitize the historic aqueduct: This task involves conducting a two-week field trip to Kyoto to collect data and perform site observations of the aqueduct. The collected data will be used to create a digital replica of the Suirokaku Aqueduct.
4. BIM modeling: This task involves using the collected data and digitization methods to create a digital replica of the aqueduct using Building Information Modeling (BIM) technology. The objective is to create an accurate and detailed digital model that can be used for hydrodynamic/structural analysis.
5. Hydrodynamic and structural analysis: This task involves using the digital model to perform hydrodynamic and structural analysis of the aqueduct. The objective is to understand the current use and extreme situations (e.g. flooding, earthquakes) and their impact on the aqueduct.
6. Interactive web model: This task involves creating an interactive web interface using the digital model. The interface will provide updated information to decision-makers and educational material for tourists. The objective is to enhance public engagement and promote the preservation of the city's heritage.
7. Writing report: This task involves compiling the findings and results of the project into a comprehensive report. The report should include a description of the project, methodology, results, and conclusions.



PRINCETON UNIVERSITY

Senior Thesis Project
Indie Game Development: ”Infrastructure Tycoon”

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Fall 2023

Document Version
2023-02-05-v1

Infrastructure systems are the backbone of our society. They are an integral part of our lives. Without roads, electricity, freshwater or the internet, our lives would not be the same. Although we use them daily, we hardly think about how they work and what measures are necessary to maintain their functions.

In this project, you will develop a game that deals with the maintenance and management of our infrastructures and brings this closer to the player. As an infrastructure manager, the player has to manage a given water supply system. He has to choose from various maintenance measures and find the optimal strategy to allocate his limited resources to different assets.

As a game developer, it is your task to develop realistic assets with which the player can interact. Your primary focus is on different degradation processes and failure mechanisms that the player has to fight successfully. Besides the graphics, you also have to develop animations and interactions to bring the game to life.

The concrete tasks of the project are as follows:

1. Develop game concept and design – This task involves creating the overall concept and design of the game, including the goals, rules, and mechanics that players will follow. This includes deciding on the storyline, objectives, and game features, as well as creating a game plan to guide the development process.
2. Asset design – This task involves designing the different assets in the game, such as the water supply system components, the degradation processes and failure mechanisms, and any other elements that the player will interact with. This should include a visual representation of the assets, as well as an understanding of how they will work within the game.
3. Asset modeling – This task involves creating a 3D model of the assets, including any animations and interactions that will bring the game to life. This includes creating a digital representation of the assets, and developing any necessary code or programming to control their behavior and movements in the game.
4. World modeling – This task involves creating a representation of the world in which the game takes place, including any physical and environmental elements that the player will encounter. This should include creating a digital representation of the environment, including terrain, weather, and any other relevant factors that impact the player’s experience.
5. User Interface – This task involves designing and developing the user interface for the game, including all the buttons, menus, and screens that the player will interact with. This should include creating an intuitive and user-friendly interface that makes it easy for players to navigate the game and interact with its elements.
6. Writing report – This task involves writing a comprehensive report about the game development process, including the design decisions, development challenges, and overall outcomes of the project. This should include an analysis of the game mechanics, graphics, and other elements, as well as any lessons learned during the development process.

PRINCETON UNIVERSITY

Senior Thesis Project
SmartDrivers: AI Racing Challenge

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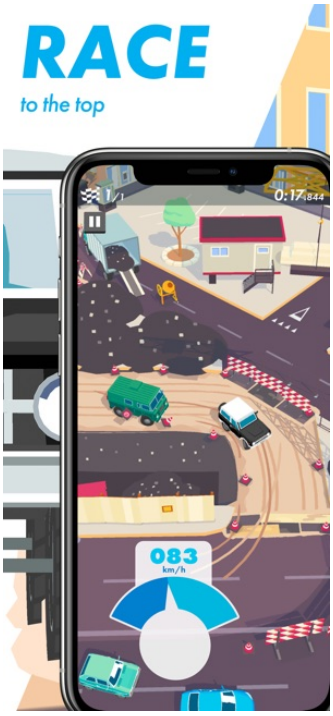
2023-02-05-v1



Self-driving cars are a promising technology that has the potential to revolutionize the way we travel and commute. They use advanced sensors, computer vision, and machine learning algorithms to navigate roads and highways with little or no human intervention. By eliminating human error, self-driving cars have the potential to greatly increase road safety and prevent accidents caused by driver distractions, fatigue, or impairment.

In this project, you will develop a racing game where the car is controlled by an AI using deep reinforcement learning. The aim of the game is to drive fuel efficiently, avoid obstacles, and follow speed regulations. As a game developer, your task will be to design and build an AI system that can learn how to control the car in the game based on feedback from the environment. You will use deep reinforcement learning techniques to train the AI, so that it can make decisions about how to control the car based on the situation it is in. In addition to building the AI system, you will also be responsible for creating the game environment, including the track, obstacles, and speed regulations. You will need to design the graphics and animations, and develop the user interface, to bring the game to life.

The ultimate goal of the project is to demonstrate how deep reinforcement learning can be used to control a racing car in a game environment, and to evaluate the performance of the AI system in terms of fuel efficiency, obstacle avoidance, and compliance with speed regulations.

Provide descriptions to the following tasks:

1. Develop game concept and design – This involves defining the overall idea and goals for the racing game, including the AI system and game environment. The game concept and design will outline the objectives, gameplay mechanics, and other elements that make up the game.
2. Create a simple game without AI – This involves building the basic game environment, including the track, obstacles, and speed regulations. This initial game will not include the AI system, allowing the player to control the car manually.
3. Implement deep reinforcement learning – This involves designing and building the AI system that will control the car in the game. The AI will use deep reinforcement learning techniques to make decisions about how to control the car based on feedback from the environment.
4. Training and adapting the algorithm – This involves using the game environment to train the AI system, and continually adapting and refining the algorithm based on its performance in the game.
5. Writing report – This involves documenting the process of developing the racing game and AI system, including the design, implementation, and evaluation of the algorithm. The report should also provide an overview of the results and a discussion of the challenges and limitations encountered during the project.