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Habilitation à Diriger des Recherches

de l'Institut Polytechnique de Paris

Préparée à l'École Nationale Supérieure de Techniques Avancées

École doctorale n° 626

Spécialité Informatique, Données, et IA

par

ZHI YAN

Robot Perception and Learning

A Human-aware Navigation and Long-term Autonomy Perspective

Mémoire présenté et soutenu à Palaiseau, le 18 juin 2025

Composition du Jury :

CHEN LIMING	Professeur à l'École Centrale de Lyon, France	Rapporteur
HUGEL VINCENT	Professeur à l'Université de Toulon, France	Rapporteur
MENEGATTI EMANUELE	Professeur à l'Université de Padoue, Italie	Rapporteur
LAUGIER CHRISTIAN	Directeur de Recherche (émérite) à l'Inria, France	Examinateur
FILLIAT DAVID	Professeur à l'ENSTA, France	Examinateur
TAPUS ADRIANA	Professeure à l'ENSTA, France	Examinatrice

Hommage à Simon Lacroix

Simon Lacroix a été la première personne à qui j'ai demandé de rapporter sur mon HDR et qui a immédiatement accepté.

Simon Lacroix était un véritable spécialiste de la robotique mobile.

Simon Lacroix était une personne très gentille et je garderai toujours en mémoire son sourire.

Le candidat souhaite attirer l'attention du jury sur les contributions méthodologiques et pratiques du candidat dans le domaine de l'intelligence embarquée en robotique, notamment à l'**apprentissage en ligne des robots**, accompagnée de ses projets de recherche, ainsi que les recherches doctorales du Dr. Rui YANG et du Dr. Iaroslav OKUNEVICH, encadrées par le candidat, conformément à l'**article 1** de l'arrêté du 23 novembre 1988 relatif à l'habilitation à diriger des recherches :

> *"L'habilitation à diriger des recherches sanctionne la reconnaissance du haut niveau scientifique du candidat, du caractère original de sa démarche dans un domaine de la science, de son aptitude à maîtriser une stratégie de recherche dans un domaine scientifique ou technologique suffisamment large et de sa capacité à encadrer de jeunes chercheurs."*

Ce document a été établi dans le respect des exigences de l'**article 4** de l'arrêté du 23 novembre 1988 relatif à l'habilitation à diriger des recherches :

> *"Le dossier de candidature comprend soit un ou plusieurs ouvrages publiés ou dactylographiés, soit un dossier de travaux, accompagnés d'une synthèse de l'activité scientifique du candidat permettant de faire apparaître son expérience dans l'animation d'une recherche."*

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Last but not least, I thank my family, especially my wife Fanfan, my son Tony and my daughter Cindy, for their love.

À Cindy, Tony et Fanfan

Contents

1

INTRODUCTION

Nous allons changer un petit peu. Non pas pour nous adapter à nos machines, mais parce que nos machines vont nous faire changer.

Patrick Greussay

1.1/ RESEARCH BACKGROUND

My interest in mobile robotics, or rather, mobile robotic intelligence, began with my exposure to the RoboCup[1]. This is thanks to Prof. Nicolas Jouandeau, my doctoral research supervisor. At the same time, it can also be seen that I am a recipient of RoboCup's concept of attracting young people to learn and explore Science, Technology, Engineering, and Mathematics (STEM), so that our community can always inject new blood to maintain vitality. On the other hand, my systematic understanding of Artificial Intelligence (AI) comes from Prof. Patrick Greussay, the father of VLISP[2]. His inspiration has been influencing the establishment of my view of AI (in knowledge representation and reasoning) from my undergraduate studies to my doctoral research, and has actually become the original driving force for my pursuit of embodied-AI in robotics.

So what is embodied-AI? Embodied-AI refers to an intelligent system that perceives and acts based on the physical body, which obtains information, understands problems, makes decisions and implements actions through the interaction between the intelligent agent and the environment, thereby producing intelligent behavior and adaptability. The germination of its ideas can be traced back to the birth of AI, as Alan Turing wrote (Turing, 1950):

"We may hope that machines will eventually compete with men in all purely

[1] https://www.robocup.org/
[2] https://www.artinfo-musinfo.org/fr/issues/vlisp/index.html

intellectual fields. But which are the best ones to start with? Even this is a difficult decision. Many people think that a very abstract activity, like the playing of chess, would be best. It can also be maintained that it is best to provide the machine with the best sense organs that money can buy, and then teach it to understand and speak English. This process could follow the normal teaching of a child. Things would be pointed out and named, etc."

Playing chess can be seen as disembodied-AI, such as what Deep Blue in the last century and AlphaGo in this century presented to people. The example of understanding and speaking English can be seen as embodied-AI, corresponding to the topic that this dissertation wants to discuss. These two different examples actually reveal my understanding of the difference between agents and robots early in my research career (Yan et al., 2013b):

"We should be careful not to confuse multi-robot systems (MRS) with multi-agent systems (MAS) and distributed artificial intelligence (DAI), as MAS usually refers to traditional distributed computer systems in which individual nodes are stationary, while DAI is primarily concerned with problems involving software agents. In contrast, MRS involves mobile robots that can move in the physical world and must physically interact with each other."

Figure 1.1 gives an intuitive impression of the differences between disembodied-AI and embodied-AI. In addition, Turing's second example also brings out two aspects that my research is concerned about: (robot) perception and learning.

Figure 1.1: Disembodied-AI (left) vs. Embodied-AI (right).

So why do we, or rather robots, need embodied-AI? First, as mentioned in the previous paragraph, a robot is an entity that essentially needs to physically interact with the real world (assuming the world we are in is not virtual). From a philosophical point of view, individuals who lack embodied cognition lack actual existence, which is similar to

Descartes's point of view "I think, therefore I am", which is opposite to Heidegger's later "I am, therefore I think". Second, in the physical world, context plays a crucial role in semantic understanding, and the lack of embodied-AI will make it difficult for robots to make informed decisions based on situational awareness. Last but not least, the physical environment in which robots operate changes, slow like the seasons and fast like a pedestrian. The lack of embodied-AI makes it difficult for robots to cope with changes in the real world.

1.2/ Research Positioning

Although my research positioning in different periods remains consistent at the macro level, that is, rooted in computer science to make mobile robots a productive tool for human society, it has experienced some evolution at the micro level, and overall, it can be seen as a transition in my research focus from symbolic approaches to statistical approaches, connectionist approaches, and activist approaches. Not fully converting to connectionism was due to my ongoing interest in mathematical logic and my concerns about the interpretability of connectionist methods. The focus on activism is actually more of an interest in reinforcement learning.

My PhD research was driven by RoboCup's NAO Robot Soccer League (Yan et al., 2011b; Jouandeau et al., 2012) and focused on the coordination strategies required among members of a team of mobile robots working towards the same goal (Yan et al., 2013b). Fortunately, I was mainly studying multi-robot coordination strategies from two aspects: task planning and motion planning, which provided me with valuable experience in robots as actuators for my later research on embodied-AI. Specifically, in terms of task planning (Yan et al., 2012c), my focus was mainly on the decentralized approach, which allows each robot to decide for itself what it should do, based on a rigorous logical structure (Yan et al., 2011a; Jouandeau and Yan, 2011). Additionally, I investigated centralized approaches, where a global agent determines the optimal task allocation strategy based on partially observable information (Yan et al., 2012b). Although the latter is not really consistent with the idea of embodied-AI, it was my first time to study how to incorporate statistical methods into traditional task planning. As for path planning, my research at the time was focused on how to use sampling-based methods which are very efficient in high-dimensional configuration spaces to plan paths for multiple robots with less collision, deadlock and congestion (Yan et al., 2010; Jouandeau and Yan, 2012; Yan et al., 2012a, 2013a). For research on this part, please refer to my doctoral thesis (written in French) (Yan, 2012), which will not be repeated in this dissertation.

My first postdoctoral research did not investigate embodied-AI methods per se, but instead focused on how to effectively test and evaluate these methods and facilitate comparisons between different methods. Specifically, taking the multi-robot exploration problem as the target task, the standardizable system performance metrics (Yan et al., 2014, 2015b), benchmarking process (Yan et al., 2015a, 2016), and testbed construction were studied (Yan et al., 2017b). This systematic study of test and evaluation methods greatly influenced my subsequent research. The latter absorbed the agile development methods in the field of software engineering (as shown in Figure 1.2), implemented rapid closed-loop iterations for the development of new methods, and always prioritized benchmarking when conducting experiments (Vintr et al., 2020; Yang et al., 2021a; Vintr et al., 2022; Yang et al., 2023a; Okunevich et al., 2023). There is a chapter in this thesis devoted to this topic.

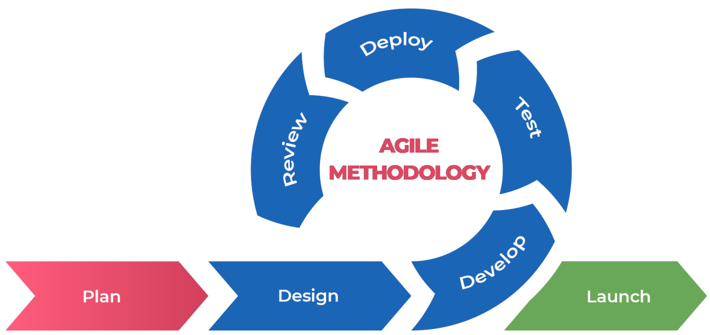

Figure 1.2: Schematic diagram of agile development methodology in software engineering.

My second postdoc returned to research on the methods of embodied-AI and began to focus on statistical approaches while exposuring to connectionist approaches. Scientifically, two issues were being studied. One is how to make a robot aware of the surrounding humans through embodied perception, including their detection and tracking (Bellotto et al., 2018), to ensure that the robot is safe for humans when moving. The other is how to achieve out-of-the-box and long-term robot autonomy by enabling the robot to learn and reason about the environment (Yan et al., 2023), such as predicting the trajectory and the appearance of humans.

Regarding the first issue, my research focused on using embodied non-visual sensors, especially 3D lidar (Yang et al., 2022), to implement large-scale and long-distance human perception (see Figure 1.3 for an intuitive understanding). This sensor can intuitively provide the object distance information needed for the robot to move without collision, and compared with the classic 2D lidar, it can provide more than one plane of laser measurement points, making it possible for the robot to detect objects based on a set of 3D points (called point cloud) representing the environment. Specifically, my research (Yan et al., 2017a) used a tree search-based method to segment the point cloud and then used Support Vector Machine (SVM) to binary classify the segments to determine which points represent humans and which points do not. For human tracking, the Global Nearest Neighbor (GNN) and Joint Probabilistic Data Association (JPDA) methods were used for data association, while the Unscented Kalman Filter (UKF) method was used for state estimation. The above methods for human detection and tracking are all statistical methods.

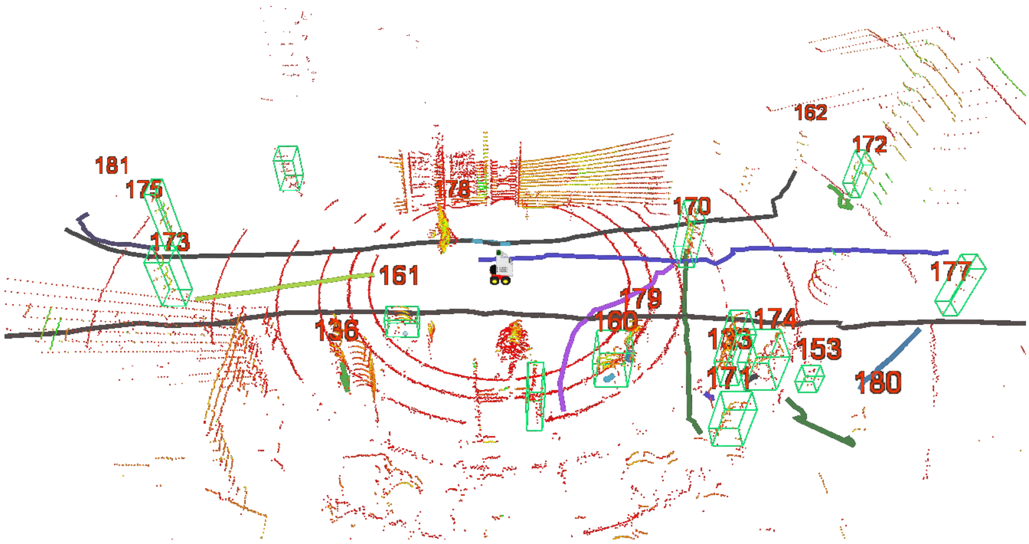

Figure 1.3: Human detection and tracking in 3D point clouds (Yan et al., 2017a). Detected humans are enclosed in green bounding boxes. The colored lines are human movement trajectories generated by a multi-target tracker we developed.

Regarding the second issue, my personal research mainly focused on the robot's learning of the environment, while the robot's reasoning about the environment was researched in collaboration with my close partners Dr. Kevin Li Sun and Dr. Tomas Krajnik. The former forms the core of my research so far, which aims to give robots an **Online Learning (OL)** ability (Yan et al., 2017a) (see Figure 1.4) so that they can absorb some new knowledge in the short term and maintain long-term memory of this knowledge. This kind of robot learning is on-site, on-the-fly, and faces a unique challenge different from traditional machine learning fields: the data that enters a learning system is often unforeseen and unannotated. It is worth pointing out that my research aims to propose a general learning method / framework (with dynamic representation capabilities) rather than a learning model. In other words, the proposed learning method should theoretically be able to incorporate different learning models. The theoretical foundation of robot OL is still statistics.

Regarding the prediction of the appearance of humans at a certain time and place, we still focused on using statistical methods, including heat maps (Yan et al., 2020b) and histograms (Vintr et al., 2018, 2019b,c,a), to build spatiotemporal models of long-term observations of robots. As for the prediction of human movement trajectories, we mainly used connectionist methods including Long Short-Term Memory (LSTM) to learn prediction models from long-term robot deployment data (Sun et al., 2018). In addition, for research on robot learning, I still mainly focused on the use of non-visual sensors, which

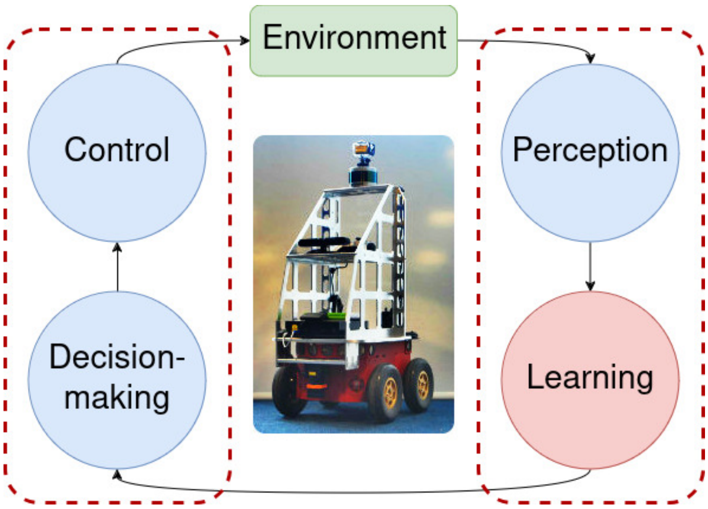

Figure 1.4: Principle diagram of Robot Online Learning (ROL). It is easy to understand that by adding a learning module to the classic operational definition of service robots “sense-think-act”, online learning is established, forming “sense-learn-think-act”. The dashed boxes on both sides indicate that the modules included are closely related and can sometimes even be merged into one module.

are beneficial to the long-term autonomy of the robot as they are not sensitive to lighting conditions.

The research content from my second postdoc to the present constitutes the main body of this thesis (see Figure 1.5), that is, how to build the embodied-AI of robots from the two aspects of robot perception and learning, and the downstream tasks mainly include human-aware robot navigation and long-term robot autonomy. The research after my second postdoc was mainly carried out with my graduate students, doctoral students and postdocs. The main line is still robot OL (Yan et al., 2018b, 2020a, 2023), and branch research around this includes denoising sensory data. As an overview, my graduate student Mr. Filip Majer studied how to use OL to enable embodied millimeter-wave radar to learn human detection capabilities from embodied 2D lidar (Majer et al., 2019; Broughton et al., 2021b); my Ph.D. student Dr. Rui Yang studied how to use OL to enable 3D lidar installed on autonomous vehicles to learn the detection capabilities of road participants from the cameras installed together (Yang et al., 2021a, 2023a), and avoid the problem of catastrophic forgetting of learned knowledge during cross-environment learning (Yang et al., 2024a); my Ph.D. student Dr. Iaroslav Okunevich studies how to combine OL with deep reinforcement learning to enable mobile robots to adapt to different social contexts while navigating over long periods of time and across environments (Okunevich et al., 2025); and my postdoc Dr. Tao Yang studied how autonomous vehicles denoise images in rainy weather (Yang et al., 2020a) and point cloud data in foggy weather (Yang et al., 2020b, 2021b; Broughton et al., 2021a; Yang et al., 2023b).

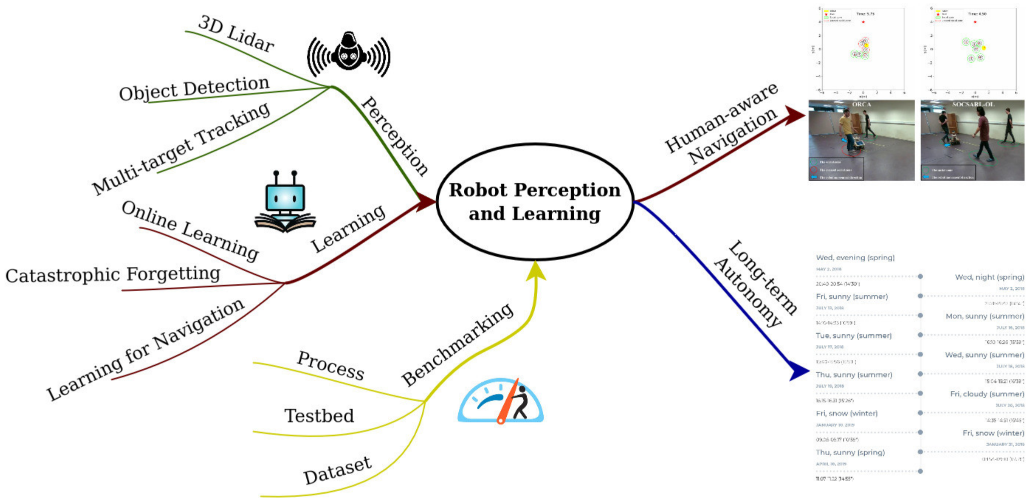

Figure 1.5: Topology of my research content.

1.3/ Industrial Positioning

I work with industry, a lot. This is motivated by my research positioning that is driven by practical problems and oriented to industrial needs. The first example is my second postdoctoral research in the framework of the European project FLOBOT[3], which aims to develop an embodied perception system for a floor washing robot for professional users to ensure that it does not hinder the surrounding humans while working (navigating) (Yan et al., 2020b). Our industrial partners are Fimap, a well-known Italian scrubbing machine manufacturer, and EasyMile, a well-known French autonomous driving system developer. Collaborating with them not only puts forward clear generalization ability and adaptability requirements for my research in method development, i.e., the method should not be targeted at specific scenarios and can adapt to changes in the environment, but also puts forward requirements for the implementation (code) quality of the method, the real-time nature of the implemented system, and the deployability in the wild.

The second example is my research collaboration with Toyota[4], where I needed to lead and implement our research work within a clear contractual framework and confidentiality agreement. The research aims to study robot perception and learning methods and ensure that the developed methods can be deployed on the prototype robot HSR (Human Support Robot) developed by Toyota (Vintr et al., 2020; Crombez et al., 2021; Yan et al., 2021; Zhao et al., 2021a; Vintr et al., 2022). The third example is my collaboration with Renault[5], within the framework of which, together with a partner from industry, we supervised a postdoctoral study. This research aims to model the noise caused by water droplets in the air in lidar data under rain and fog weather to enhance the perception of the

[3]https://cordis.europa.eu/project/id/645376
[4]https://yzrobot.github.io/MACPOLO/
[5]https://yzrobot.github.io/DENOSAU/

environment by autonomous vehicles in adverse weather conditions (Yang et al., 2020b, 2021b). This collaboration seamlessly connects my scientific research topics and methods with practical industrial applications and can be considered a showcase that reflects the industrial orientation of my research.

1.4/ Open Science

Open science[6] has been an important theme in my research career so far. Initially, the "push" on the one hand came from the fact that I struggled to compare with other methods during my Ph.D. because they were not open source, and the "pull" on the other hand came from the fact that my doctoral research benefited from the open source robotics project Player/Stage (Gerkey et al., 2003). Early in my research career I focused on open software and source code. This corresponds to my focus on symbolic approaches, which are not data driven. Later as my research started to focus on data-driven approaches, open research data became part of it. Additionally, as a teacher, I made my educational resources public.

Specifically, the open materials mostly completed by myself are listed below:

- Open research data:
  - L-CAS 3D Point Cloud People Dataset (https://lcas.lincoln.ac.uk/wp/research/data-sets-software/l-cas-3d-point-cloud-people-dataset/) (Yan et al., 2017a): This dataset was collected with a 16-layer 3D lidar mounted on a mobile robot, in one of the main buildings of the University of Lincoln, UK. It includes 28,002 scan frames recorded by the robot while stationary and moving, with a total length of 49 minutes. About 20% of the data was manually annotated to form ground truth.
  - L-CAS Multisensor People Dataset (https://lcas.lincoln.ac.uk/wp/research/data-sets-software/l-cas-multisensor-people-dataset/) (Yan et al., 2018b): This dataset is a supplement to the previous one, adding sensory data from an infrared camera and a 2D lidar.
  - L-CAS Thermal Physiological Monitoring Dataset (https://lcas.lincoln.ac.uk/wp/research/data-sets-software/lcas-thermal-physiological-monitoring-dataset/) (Cosar et al., 2018): This dataset is designed to evaluate human physiological monitoring algorithms based on thermal imagers including body temperature, respiratory rate and heart rate. It consists of a thermal camera recording thermal images of five

[6] https://github.com/yzrobot/Open-Science-UTBM

different faces at 27 Hz for two minutes each. People were asked to remain still for the first minute and then move their heads up and down, back and forth, and left and right, holding each movement for ten seconds.

- FLOBOT Perception Dataset (http://lcas.github.io/FLOBOT/) (Yan et al., 2020b): This dataset was collected using FLOBOT (an advanced autonomous floor scrubber) in public places in Italy and France including an airport, a supermarket and a warehouse. It includes data from four different sensors, including a 3D lidar and an RGB-D camera for human detection and tracking, and another RGB-D and a stereo camera for ground dirt and object detection. Additionally it contains the pose of the robot in the world reference frame.
- EU Long-term Dataset with Multiple Sensors for Autonomous Driving (https://epan-utbm.github.io/utbm_robocar_dataset/) (Yan et al., 2020c): This dataset was collected over a year in Montbéliard, France, in the city center (for long-term data) and in the suburbs (for roundabout data) using a vehicle equipped with 11 different sensors. For long-term data, the driving distance in each round is approximately 5.0 kilometers (including a small loop and a large loop for loop closure), and the length of recorded data is approximately 16 minutes. For the roundabout data, the driving distance of each collection round is about 4.2 kilometers (including 10 roundabouts of different sizes), and the recording data length is about 12 minutes.

• Open software and source code (selected):

  - Adaptive Clustering (https://github.com/yzrobot/adaptive_clustering) (Yan et al., 2017a): This is a lightweight and accurate point cloud clustering method implemented in C++.
  - L-CAS 3D Point Cloud Annotation Tool (https://github.com/yzrobot/cloud_annotation_tool) (Yan et al., 2020a): This tool provides semi-automatic annotation of point cloud data, whereby the point cloud is first automatically segmented and then each segment is labeled by humans.
  - Online Learning for Human Classification in 3D LiDAR-based Tracking (https://github.com/yzrobot/online_learning) (Yan et al., 2017a): This is the code released with the paper, which allows the robot to learn a human model in the point cloud online at runtime without human intervention.
  - Multi-robot Exploration Testbed (https://github.com/yzrobot/mrs_testbed) (Yan et al., 2017b): This testbed allows dozens of mobile robots to be repeatedly deployed in a 3D simulation scene driven by a physics engine to perform environment exploration tasks, and automatically collect various performance data during task execution for later analysis.

- Open educational resources:
  - Introduction to Mobile Robotics (https://yzrobot.github.io/introduction_to_mobile_robotics/): This course is designed to introduce basic concepts and techniques used in the field of mobile robotics. Relevant fundamental problems and challenges are analyzed, and both classic and cutting-edge solutions are illustrated.

The open materials completed primarily by my students and postdocs under my supervision are listed below:

- Open research data:
  - Light Field Raindrop Dataset (https://github.com/cavayangtao/light-field-raindrop-dataset) (Yang et al., 2020a): This dataset was collected using the first-generation Lytro camera, which contains 90 light field images under rainy weather, 50 of which correspond to one round of collection routes of the EU Long-term dataset.
- Open source code (selected):
  - Point Cloud Denoising in Adverse Weather Conditions for Autonomous Driving (https://github.com/cavayangtao/lanoising) (Yang et al., 2020b, 2021b), (https://github.com/cavayangtao/lanoise_pp) (Yang et al., 2023b): These are the source codes that my postdoc Dr. Tao Yang released with the papers during his postdoctoral research.
  - Online Continual Learning for 3D Detection of Road Participants in Autonomous Driving (https://github.com/RuiYang-1010/efficient_online_learning) (Yang et al., 2021a, 2023a), (https://github.com/RuiYang-1010/lstol) (Yang et al., 2024a): These are the source codes that my Ph.D. student Dr. Rui Yang released with the papers during his doctoral research.
  - Online Context Learning for Socially-compliant Navigation (https://github.com/Nedzhaken/SOCSARL-OL) (Okunevich et al., 2025): This is the source code that my Ph.D. student Dr. Iaroslav Okunevich released with the paper during his doctoral research.
- Open software and hardware:
  - Human-aware Robot Navigation System (https://github.com/Nedzhaken/human_aware_navigation) (Okunevich et al., 2023, 2024): This is the source codes and hardware models that my Ph.D. student Dr. Iaroslav Okunevich released with the papers during his doctoral research.

1.5/ Thesis Organization

As my research experience grew, I gradually became accustomed to narrating my research results as a story. There are two advantages to doing this. From the author's point of view, the content introduced is systematic. And from a reader's perspective, the manuscript may be more readable. The remainder of the dissertation is therefore organized as follows.

Chapter 2 introduces my work so far in mobile robot software engineering, which mainly includes benchmarking of robot performance including evaluation methods, metrics, construction of testbeds and datasets, etc. In addition, some insights and thoughts on how to integrate AI into testing tools, benchmarking ethics, and data privacy, which are some of the aspects involved in modern AI development, will be given. Although the latter are not the focus of my research, it may be interesting to share some of my experiences and give some of my opinions as we are increasingly unable to avoid these issues in today's research activities. Starting the main body of the thesis with the topic of benchmarking is a bit like the idea of "testing before development" in the field of software engineering, that is, we need to understand how to evaluate them before we really discuss the methods for realizing embodied-AI. Moreover, this also happens to be consistent with the actions of the European Commission, that is, it would be a good choice to formulate a standard before vigorously developing AI to prevent its development from being uncontrolled and unregulated, which would lead to disastrous consequences (aiact).

Chapter 3 introduces my research work on robot perception. In a systematic way, the research motivation is first introduced, which is to use embodied sensors and onboard computing for large-scale human detection and tracking in public (non-home) environments. Then the contemporary 3D lidar adopted as an embodied sensor, from its basic working principle to its relevant applications in the field of mobile robots, is introduced. Next, the "adaptive clustering" method I developed during my postdoctoral period will be introduced, and the advantages and limitations of the proposed method will be illustrated by comparing its performance with other popular methods at the time. Then, several hand-crafted features extracted from point clouds with proven performance for human model training are introduced. Finally, a multi-target tracker optimized for deployment in point clouds is introduced.

Chapter 4 introduces my research work on robot learning, including a systematic study of Robot Online Learning (ROL) frameworks. First, what is ROL and why robots need OL are explained. Then, two ROL frameworks are introduced, one based on P-N learning and the other based on knowledge transfer. The advantages and disadvantages of the two methods are analyzed. The former does not require external help but will produce self-bias. The latter can avoid self-bias but requires external help. In addition, the latter also needs to resolve conflicts between internal and external parties. Next, the issue of how to alleviate catastrophic forgetting in the long-term process of ROL is addressed. Finally, how to leverage ROL to improve the performance of socially-compliant robot navigation in long-term and cross-environment deployments is introduced.

Chapter 5 summarizes the full text and gives prospects for future research.