# RESEARCH STATEMENT | DONGYAO CHEN

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My research focuses on designing, developing, and evaluating novel ubiquitous sensing and machine learning technologies to address real-world challenges, including automotive, behavioral biometrics, and Internet-of-things (IoT) networks. My thesis is based on applying new approaches to construct accessible and interactive systems that promote seamless interaction between *humans* and *mobility systems* (e.g., automobiles and road infrastructure) to achieve safe, efficient transportation. My Ph.D. training has prepared me as a system researcher with interdisciplinary expertise (in mobile computing, machine learning, and cyber-physical systems) for discovering and tackling pressing world challenges. In this statement, I summarize my thesis research and outline my future research directions.

## THESIS RESEARCH: INTRODUCTION

Mobility systems have recently undergone a period of rapid and profound change. Although new technologies offer unprecedented benefits related to on-road transportation, most rely on several additional devices and/or services. For example, advanced driving assistance systems (ADAS) require specialized sensing modules (e.g., cameras and radar) to realize promised features, such as lane-departure warning. Mapping services, including Google Maps, largely depend on heavily instrumented mapping vehicles to collect road information. Supplementary units/services can be costly (in terms of money and/or time), thus contributing to a bottleneck that throttles widespread deployment of these advances. This bottleneck will likely continue to narrow as mobility technologies become more sophisticated, further limiting the accessibility of smart mobility systems.

Quickly evolving ubiquitous and IoT devices present unique opportunities to implement mobility applications on a large scale thanks to their unprecedented high penetration rate. However, existing options, such as navigation apps, are often *less interactive* and unable to perceive and react to *implicit* cues from user input (e.g., a driver's driving pattern) and environmental changes (e.g., risks at road intersections). These limitations can severely undermine the usability of mobility applications and may ultimately hinder transportation safety.

The main objective of my thesis research is to democratize *accessible* and *interactive* mobility systems. I approach this goal on two fronts: 1) exploring the potential of the sensing capabilities of off-the-shelf devices (e.g., smartphones); and 2) discovering novel computing paradigms to support real-world needs. I frequently build and evaluate my systems with data collection campaigns via different computing platforms, such as customized software and crowdsourcing platforms (e.g., Amazon Mechanical Turk). Over the last few years, I have gathered approximately 5,600 miles (with more than 200 accumulated driving hours) of on-road data from 28 different vehicles via a customized data collection app and on-board diagnostic devices. To assess our systems from the user's perspective, I have also conducted user studies and surveys with hundreds of users under comprehensive IRB protection.

My thesis research demonstrates a continuous effort comprising significant original works to investigate implicit natural driving behavior through novel ubiquitous sensing and machine learning systems. My research output indicates that nuanced, highly accessible systems can be achieved using off-the-shelf mobile devices to advance various real-world applications. I have published papers featuring these systems at top mobile computing, human–computer interaction, and wireless networking venues, including MobiSys, UbiComp, and CoNEXT. The fruition of my work has resulted in several patented technologies, with two issued [6, 7] and several more filed.

## THESIS RESEARCH: CONTRIBUTIONS

The main thread of my thesis research enables real-time steering behavior detection (V-Sense [1]) on ubiquitous sensory platforms, which is essential for analyzing (a) individual users' microscopic characteristics (e.g., a driver's behavioral characteristics via Dri-Fi [2]) and (b) macroscopic contextual information within the environment (e.g., risks at road intersections via TurnsMap [3]).

**V-Sense: Sensing Vehicle Steering Maneuvers in Real Time without Cameras**. Understanding vehicle dynamics is a prerequisite for various ADAS, such as lane-departure warning. Detecting how a vehicle is steered and then alerting drivers in real time is essential to vehicle and driver safety because fatal accidents are often caused by dangerous steering. Existing solutions for detecting dangerous maneuvers tend to be implemented either solely in high-end vehicles or on smartphones as mobile applications. However, most solutions rely on cameras, the performance of which is seriously constrained by high visibility requirements. Moreover, over- or sole reliance on cameras may distract drivers.

To alleviate these problems, I developed a vehicle steering detection middleware called V-Sense, which can run on commodity smartphones without additional sensors or infrastructure support. Rather than using cameras, the core of V-Sense (demo: https://youtu.be/OwgWmU_cgj4) senses a vehicle's steering by using lightweight inertial measurement units (IMUs), such as non-vision sensors, on a smartphone. I designed and evaluated algorithms to detect and differentiate various vehicle maneuvers, including lane changes, turns, and driving on winding roads. As V-Sense does not rely on cameras, its practicability is *not affected by the device's posture* (e.g., mounted vs. in a cupholder) or by the (in)visibility of road objects or other vehicles. To evaluate V-Sense's efficacy, I experimentally examined its performance in two prevalent use cases: camera-free steering detection and fine-grained lane guidance. Extensive evaluation results show that V-Sense can accurately determine and differentiate various steering maneuvers and is suitable for a range of safety-assistance applications without additional sensors or infrastructure.

**Dri-Fi: Modeling Drivers' Driving Patterns from Mobile Sensors**. When a person drives a car, the vehicle's dynamics leave *distinct* traces that can reflect the driver's behavioral pattern. This implicit information is highly meaningful for various applications. For example, drivers' unique driving behavior can be used to verify ride-sharing drivers, thus protecting passengers' safety. However, it is difficult to model this behavioral feature via *quantifiable* metrics. Even human passengers may be able to only vaguely differentiate implicit *riding experiences* (e.g., reckless vs. prudent) among drivers.

I addressed this challenge and proposed an accessible mobile-based driver fingerprinting system called Dri-Fi (demo: https://youtu.be/erYxTDTXO4M). It explores driver–vehicle interactions and presents a new approach that enables mobility apps to identify the person behind the wheel by only using mobile sensors. Dri-Fi contains several novel designs in mobile sensing and feature engineering. I discovered that the driver's left and right turning maneuvers are *strong* features reflecting the driver's behavioral pattern. Furthermore, turning data captured by the V-Sense scheme provides sufficient input bandwidth for characterizing driving behavior. Based on these findings, Dri-Fi's core algorithm extracts three new features from raw IMU data and feeds them to train a machine learning model for driver identification. The evaluation shows that Dri-Fi can achieve up to 95.3%, 95.4%, and 96.6% accuracy across 12, 8, and 5 drivers (typical of an immediate family or close-friends circle), respectively. By applying Dri-Fi's capabilities, mobility apps (e.g., usage-based auto insurance, Apple CarPlay, and Android Car) and ride-sharing services can personalize their services/assistance to greatly enrich their usability.

**TurnsMap: Mining Safety-critical Information via Crowdsourced Ubiquitous Sensing**. While V-Sense and Dri-Fi unlock promising opportunities to aid individual and small groups of drivers, TurnsMap explores the feasibility of harvesting ubiquitous sensing and novel machine learning algorithms for the greater *social good*.

Left turns are the most *dangerous* driving maneuver at intersections due to interrupting traffic and crossing pedestrians. The danger of left turns can be effectively mitigated through a protected traffic phase intended exclusively for left turns, such as left-turn lights (left-oriented arrows). Despite the enhanced safety of such a scheme, its presence at intersections is not yet available to the public and/or automotive apps (e.g., navigation systems).

To extract such safety-critical information, TurnsMap infers left-turn information powered by two main components: 1) a mobile crowdsensing front end, which uses V-Sense to extract sensor data for left turns from mobile devices carried by the driver/passengers in a moving car; and 2) the data analytics back end, used to infer left-turn information from crowdsourced IMU data collected from many users. To power the machine learning algorithm at the back end, I built a dataset with crowdsourced ground truth labeled by 231 annotators recruited on Amazon Mechanical Turk. I evaluated this framework using real-world driving data collected through our customized mobile app, demonstrating TurnsMap's ability to identify left-turn information with high accuracy at low cost.

My Ph.D. research also extends beyond motion-based ubiquitous sensors to explore other computing modalities. My CoNEXT' 17 work [4] investigated the practicability of using several Bluetooth low-energy (BLE) beacons (demo: https://youtu.be/556Io5MoJso) to collaboratively locate a BLE device at a fine granularity. This technology can be used to enhance the usability of various BLE-based in-car applications, such as interactive apps that require the location of the driver's smartphone.

## FUTURE RESEARCH AGENDA

As a faculty researcher, I am excited to expand my thesis research to examine how novel sensing and machine learning can foster my envisioned mobility ecosystems of the future. I also plan to explore how my expertise can be applied to address other real-world problems, such as in biomedicine and healthcare, in collaboration with other researchers and students from interdisciplinary backgrounds.

**Privacy-preserving Sensing Technologies**. Users' privacy is crucial in ensuring the integrity of different computing frameworks. I plan to investigate new research challenges around user privacy protection while preserving the usability of novel sensing technologies. This is a challenging task because enhanced sensing technology may be intrusive, whereas privacy-preserving sensing technologies may undermine its usability. For example, Dri-Fi and TurnsMap have demonstrated usability in real-world applications. Although they provide a pathway to various helpful applications, one must not overlook how their capabilities could be misused (i.e., misuse of driver identification and location tracking), thus raising users' privacy concerns. To address these considerations, I plan to investigate a privacy model to protect users' privacy by adding noise systematically, such as via a differential privacy model.

**Breaking the Barrier between Sensing Modalities**. I plan to move beyond the scope of my thesis research by investigating emerging computing modalities. Within the rapidly evolving computing paradigm of advanced mobility technologies, new accessible sensing modules can generate context-rich data that can be used to broaden the information bandwidth. As cars become smarter and more connected, modern vehicles are being equipped with a growing number of electronic control units, many of which can produce rich data reflecting vehicle dynamics, engine health, and other contextual information. However, the control area network data format is proprietary to original equipment manufacturers, and reverse engineering may involve prohibitive time and effort. To address this challenge, LibreCAN [5] was recently developed to automatically translate most control area network messages. This automated translator of proprietary data can be used to *break the barrier* of remote in-vehicle data access and render car-based data flow transparent to developers. As a short-term task, I would like to evaluate the feasibility of using translated in-vehicle data to develop new applications based on reverse-engineered vehicular data. In the long term, I plan to continue pursuing this research direction by exploring (a) other 'edge' computing paradigms (e.g., sensors in roadside infrastructure) and (b) novel applications that can be enabled by increasingly advanced ubiquitous sensors.

**Understanding the Collaborative Model of Different Transportation Modalities**. Moving forward, I would like to explore how interactive mobility applications can facilitate the coexistence of self-driving and human-driven cars. For example, humans needed more than a century to upgrade the mobility ecosystem from horse carriages to modern motorized vehicles. This historical transition represented an arduous process requiring decades of experiments and adjustments to new technologies/infrastructure, including vehicle components, traffic regulations (e.g., traffic signs/signals and lane markers), road infrastructure (e.g., roundabouts and pedestrians crossing bridges). As we are in a profound transition period from legacy automobiles to advanced mobility modalities (e.g., ADAS systems and self-driving cars), I believe interactive mobility applications can play an essential role in enabling *accessible* and *nuanced* systems and data analytics approaches for finding implicit pain points in our transportation systems, thus expediting the processes of inventing and/or refining modern mobility technologies. Achieving this goal needs orchestrating vibrant research and technology-driven industrial efforts.

**Exploring Challenges Beyond Mobility.** Ubiquitous sensing can unlock unique opportunities in many future domains. I am particularly interested in applying my expertise to the healthcare field; for instance, by enabling accessible computing arms on IoT devices, patients can receive at-home healthcare services. Reducing overhead associated with patients' costs and hospital visits is essential for various healthcare applications, such as identifying early disease symptoms without a time-intensive hospital appointment-scheduling process. My training in ubiquitous sensing and machine learning can contribute to the development of accessible and interactive systems to accomplish related research goals.

## REFERENCES

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