# Research Statement

Living in a new era where human beings and computers are seamlessly connected, my research passion lies in enhancing the **synergy** between human beings and computers with works in three phases: **sensing**, **prediction**, and **decision-making**. Over the past six years, I have intensively investigated **human-centered urban cyber-physical systems**, integrating wireless network, data mining, and machine learning. I also gained unique experience in building **nationwide** systems for millions of workers in the on-demand delivery industry. This statement summarizes my research vision, contributions, and future directions.

## 1 Research Vision

Since the Coca-Cola machine was first connected to the Internet, scientists and engineers have developed this idea into a concept called *Cyber-Physical Systems (CPS)*, or *Internet of Things (IoT)*. Nowadays, with billions of heterogeneous devices connected to the Internet, we are one step away from a world of connectivity. Mckinsey & Company envisions the future of connectivity as one of the top trend technologies, where hundreds of promising use cases could increase global GDP by $1.2 trillion to $2 trillion by 2030 in four sectors, i.e., **mobility**, **healthcare**, **manufacturing**, and **retail**. However, human beings – a key element in the system – are less studied than physical and cyber components. With the increased interaction between human beings and systems, I am motivated to study Human-centered Cyber-Physical Systems (HCPS), featuring various applications like human robots interaction, intelligent transportation, smart health, and gig economy.

One of the essential challenges in HCPS is the **complex** and **implicit** human behavior that disrupts the interaction between the system and human beings. For example, human beings do not behave as the system predicts, or the reported information from human beings is inaccurate. This mismatch between human behaviors and system perception may lead to undesirable consequences, especially when human drivers and autonomous cars drive on the same road.

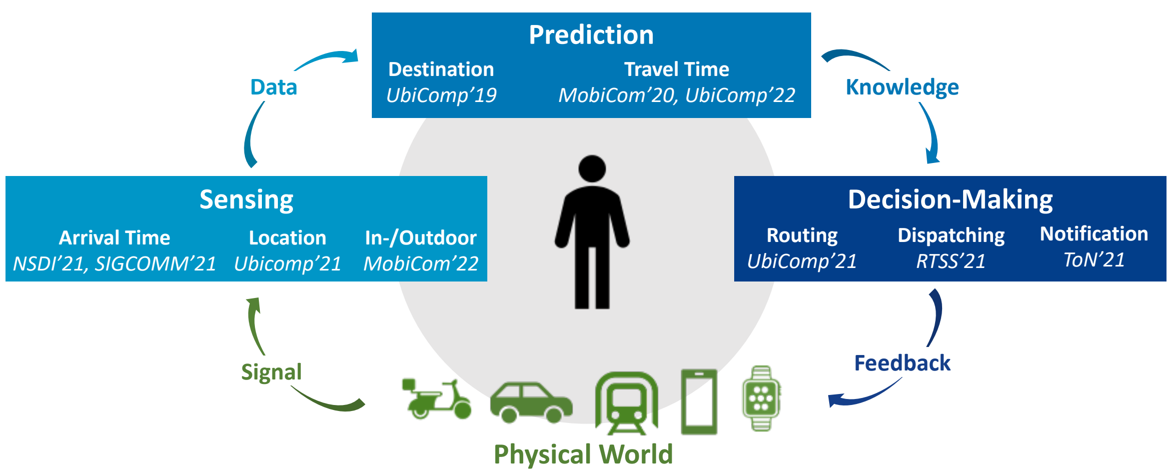


Figure 1: Research Vision

In my vision, as shown in Figure 1, I would like to solve the challenges from all the three phases in HCPS, i.e., sensing, prediction, and decision making. In the past six years, I have done considerable works on on-demand delivery systems, a typical urban HCPS, where gig workers deliver online orders (e.g., food) within a short time (e.g., 30 minutes) from merchants (e.g., restaurants) to customers. I have led a group to build a citywide hardware-based [1] and a nationwide software-based arrival detection system [2]. Both use

Bluetooth sensing technologies on couriers' smartphones to acquire couriers' state information. With the state information, I have designed learning algorithms to predict the couriers indoor travel time [3] and the route choices [4]. With the sensing and prediction results, I have also designed algorithms to dispatch the delivery orders in a concurrent manner [5] or via public transportation [6].

Although my past works are focused on on-demand delivery systems, the underlying challenges and potential solutions are generally applicable for all HCPS problems in my future endeavors. In the following years, I plan to work on HCPS with unreliable human input, privacy and security in HCPS, and group behavior. While my long-term missions in HCPS are three-fold: (1) wellbeing of human beings, where both physical and mental health can be perceived and improved when closely connected with computers; (2) efficiency and equality, where high efficiency can be achieved through human-system synergy, and equality can also be achieved; (3) explainable AI, where human beings rein algorithms, not the other way around.

## 2 Technical Contribution

As shown in Figure 1, my works involve all three phases in the HCPS framework, i.e., sensing, prediction, and decision-making. Focused on the interaction between the couriers and the delivery system, I have solved multiple essential problems in on-demand delivery. More importantly, all of the works are evaluated on the real-world platform (i.e., Ele.me, the on-demand delivery company in Alibaba Group) at the scale of malls [3], citywide [1, 5, 6], and nationwide [2]. Especially, the **citywide** and **nationwide** beacon systems [1, 2] have been deployed as **critical components** in Alibaba Group, serving **1 million** couriers, **3.3 million** merchants, **150 million** customers with 3.8 billion orders in 364 cities in China, and saving more than **$8 million**. The works on travel time prediction and order dispatching also help reduce couriers' detour and improve the delivery efficiency. In the following, I will introduce one representative work of mine in each phase.

### 2.1 Arrival Time Detection based on Smartphone Bluetooth (SIGCOMM'21)

Obtaining accurate state information (e.g., location, mobility, activity, emotional state) of human beings is a fundamental task in HCPS, which can provide online feedback or train AI models. One of the most important state information in on-demand delivery is the couriers' arrival time at the merchants, which is used to update order status, dispatch new orders, and train learning models. Existing solutions are inapplicable for nationwide deployment due to limited accuracy, high monetary cost, or high energy consumption. Especially, manual reports from couriers suffer from intentional or unintentional human errors (i.e., early/late reports).

To address the challenges, I explore using merchants' smartphones under their consent as a virtual infrastructure to detect the couriers' arrival automatically in real-time at an extremely low cost. I elaborately designed the system with a Bluetooth advertising module on merchants' smartphones and a scanning module on couriers' smartphones, with time-based encryption to protect merchant privacy and platform security.

I led a team to build, deploy, and operate a Bluetooth-based beacon system from in-lab conception to nationwide operation for 30 months. I show that the system has high reliability (80% arrival events detected), low energy consumption (2% additional battery drain), high participation rate (85% merchants joined), great utility (0.7% absolute order overdue rate reduction), significant monetary benefit ($8 million saved), and strong privacy protections (0.03% simulated re-identification risk and no actual cases reported).

I also summarize three important lessons learned from the 30-month practice in the wild that can inspire future HCPS works: (1) A participatory software-based "virtual" beacon system evolves more robustly compared to a dedicated hardware-based "physical" beacon system; (2) The reliability of a large-scale wireless system suffers from factors like heterogeneity of device hardware/software and human behavior in the wild that seldom studied in the lab environment; (3) The synergy between the system and couriers improves both the system's and couriers' performance but to different degrees due to human behavior complexity.

### 2.2 Travel Time Prediction with Graph Learning (UbiComp'22)

Based on the state information acquired in the sensing phase, I designed a map-free localization system named SmartLOC that employs merchants' smartphones as anchors to predict couriers' travel time to nearby merchants in the mall. The travel time is critical information for the platform to conduct order dispatching and navigate couriers in an indoor environment, but existing solutions needs physical anchors or human effort.

I solve the problem based on the key idea that the encounter event between merchants and couriers can be used to aggregate spatio-temporal information, and this information can be propagated. I built a system named SmartLOC with three modules: (1) An encounter detection module based on smartphone Bluetooth; (2) A graph embedding method where merchants are nodes and travel time are edges to extract the inherent topology of merchants with the encounter information; (3) A transformer-based method using the merchant embedding and the encounter information as input to predict the travel time.

The evaluation in two malls shows that SmartLOC improves the travel time estimation by more than 40% compared with baselines. I also conducted additional experiments to show the effectiveness of SmartLOC under different encounter densities and system penetration, detection failures, device heterogeneity, and label scarcity. The simulation also shows that SmartLOC can reduce detours by 12%, improve dispatching efficiency, and save $176,800 each year in a single city.

Although SmartLOC is designed for on-demand delivery, the idea of "smartphone-based anchors" can be generalized to generic location-based services like restaurant recommendations and social networks.

### 2.3 Order Dispatching with Reinforcement Learning (RTSS'21)

The sensing and prediction results lay the foundation for order dispatching, one of the most critical functions of the delivery platform. To fulfill the increasing demand for food and groceries delivery in the urban area, we must design a highly efficient order dispatching process. Although many works have been done in ride-hailing, two unique characteristics make the delivery of food and groceries more challenging: (1) Concurrent dispatch scheme, where new orders will be dispatched to a courier before she completes her current delivery tasks; (2) Strict time constraints to guarantee the food is fresh.

We designed a reinforcement learning algorithm to solve the problem with two modules: (1) An actor-critic scheme trades off between the existing orders and future revenue; (2) An action pruning module filters out the actions that may lead to overdue orders based on couriers' destination and travel time predictions.

The evaluation on one month of 36 million orders with 42,000 couriers shows that our algorithm achieves 22.9% of the increase in total revenue compared with baselines. Although the algorithm is not fully adopted in the commercial process, the work sheds light on the potential of learning-based decision-making compared to operation-research-based methods. Moreover, the algorithms and intuition in solving time-constrained HCPS problems can be generalized to other applications like self-driving and ambulance dispatching.

## 3 Future Directions

I divide my future research directions into two stages. Short-term interests are specific problems that I want to solve to advance the state-of-the-art. Long-term missions are topics I find important and interesting, so that I would like to devote myself to them throughout my career.

### 3.1 Short-term Interests ($\leq$ 3 years)

**HCPS with Unreliable Human Input.** Human input in HCPS (e.g., couriers' report in delivery, patient's statement in healthcare, customers' answer in retail) essentially plays two roles: feedback information to facilitate the process and label information to train AI models. Human factors like cognitive diversity or physical factors like sensor heterogeneity may cause the human input to be unreliable (e.g., inaccurate, delayed). Mining the historical interaction data for the factors is the key. I can propose solutions to detect and compensate for the reliability issue or build robust systems tolerant to error input.

**Privacy and Security in HCPS.** With the rapid growth of data-drive methods, a huge amount of data is used and released in the HCPS community. Based on my own experience in releasing four data sets, I found it quite difficult to tradeoff between the privacy and the usability of the data-set. Although privacy and security have been widely studied in many fields, I am motivated to solve specific sensing and mobility data problems where existing solutions fail.

**Group Behavior.** I became interested in group behavior problems with one of my observations in the nationwide beacon project. In the project, we pop up notifications to those couriers who we believe reported inaccurate information and ask them to either "confirm" or "cancel". I found that couriers' feedback tends to be homogeneous after several weeks. One possible reason is that couriers communicate and use collective intelligence to wrestle with the system. Group behavior widely exists in large-scale HCPS, such as couriers, drivers, and passengers, so a better understanding of group behavior can lead to more efficient and equitable designs. By cooperating with other teams with more experience in human behavior, I can propose novel integrated solutions in sensing, prediction, and decision-making.

### 3.2 Long-term Mission (5-10 years)

**Wellbeing.** With ubiquitous smart devices and advanced learning algorithms, physical and mental health can be monitored, predicted, and promoted. I want to contribute to this mission by answering two questions: (1) How does the system impact the wellbeing of human beings in large urban HCPS? (2) What can we do to promote wellbeing in the process of human-system interaction?

**Efficiency and Equity.** Ever since Dr. Licklider proposed the idea of "Man-Computer Symbiosis" in 1960, great works have been done to liberate human beings from repetitive routines. However, research can still be done to fully take advantage of advanced network and AI technologies to pursue efficiency further. Moreover, the consideration of social welfare like equity introduces new objectives. I hope my future works on human-system synergy can advance the studies in this field, especially for the decision-making problems like dispatching and recommendation.

**Explainable AI.** The conflicts between human workers and AI exist not only for Gig workers but also for many professional workers. Many countries, including the U.S., China, and European countries, are making an effort to rein in algorithms. I want to contribute to this big topic with works on HCPS.

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