Development of a Multi-Sensor System for Smart Quartier Mobility Applications

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Abstract: The negative impact of global urbanization is most evident in the field of mobility. Inner city individual traffic, in particular, is on the rise. The mixed and increasingly unpredictable traffic conditions result in more and more accidents, to the chagrin of vulnerable road users (VRUs). The use of existing infrastructures is unbalanced and no longer meets the needs of all road users. By transforming public areas into pedestrian-only zones, a balance is slowly being restored. The deployment of autonomous mobile systems (AMSs) creates new problems that exhibit similarities to those in automotive mobility. Within the project Test Area Intelligent Quartier Mobility (TIQ) at the Hamburg University of Applied Sciences (HAW Hamburg), a multi-sensor system (MSS) is developed. This platform aims to facilitate the integration of AMSs into quartier mobility.

1 Introduction

The growth of the world population witnessed in recent years and the consequent increase in urbanization exhibit exponential character. The rate of urbanization and population growth go hand in hand. Together with demographic changes, this ultimately leads to an increase in the distances that many employees have to travel to work in cities with significant growth, leading to an increase in mobility.

Interurban and intraurban individual traffic is inevitably on the rise and becoming an increasing burden on the currently existing infrastructure to the point that it can no longer meet the various mobility participants' needs. Similarly, the unpredictability of traffic is rapidly growing, resulting in a whole new range of problems. It is not surprising that Smart City and Urban Mobility topics are becoming more prominent in research and development. After all, innovative and efficient solutions are required to address this challenge in the future. The topics of autonomous driving and collision avoidance are currently receiving considerable attention in research and society. Accidents occur more frequently in traffic-intensive areas that different road users use. Collision avoidance technologies have emerged, giving the vehicle the ability to detect pedestrians in the immediate environment, predict its movement, and take proactive measures. Overall, the advent of intelligent sensor technology (IST) in the automotive world has led to a significant improvement in preventing accidents. This trend is particularly beneficial to inner-city mobility. While this approach may reduce some negative impacts of automotive traffic in mixed-use infrastructures, it does not deal with the different needs of road users and the fair use of existing infrastructures. Contemporary cities are beginning to pedestrianize more and more public space. Similarly, researchers are exploring ways to let AMSs interact with intelligent infrastructure.

2 Related Works

As modern cities worldwide become digital, more and more research projects explore ways to integrate smart sensors into existing infrastructures. Such sensor platforms (Khalifeh et al., 2021) come in various forms and are primarily deployed for environmental monitoring. Typical for these devices is a self-sustaining, wireless, low-power and cost-effective design. A network of wireless sensors enables the coverage of larger urban areas and allows significantly more data to be collected. Other research projects take a different approach. A range of sensors is being experimented with in search of the ideal way to capture traffic events as accurately as possible. Though, the automotive industry does not exclusively benefit from recent scientific advances in object detection, tracking and motion prediction. These technologies are also finding their way into other areas of mobility.

In pedestrian and vehicle detection research, optical sensors are predominantly used in single. In projects involving surveillance cameras, LiDAR sensors often come in as support. In this case, accurate calibration is crucial. Only when knowing the sensor's exact location and orientation, an absolute reference point is given for measurements (Klöker et al., 2020b). The ongoing research project HDV-Mess (HDV, 2021) at the RWTH Aachen University experiments with deploying several 3D-LiDAR sensors (Klöker et al., 2020a; Klöker et al., 2020b) to precisely detect broader areas of traffic. This approach uses four 64-layer LiDAR combined with a real-time point cloud fusion-based algorithm, making a conventional calibration unnecessary.

The application of intelligent sensor systems (ISSs), autonomous vehicles or complex algorithms in public space assumes a reliable operation. Extensive testing and validation are essential to rule out potential sources of error in advance. As a result, some research projects deal exclusively with the development of suitable test areas. In project CERMcity (Kopacz and Heberling, 2016) at the RWTH Aachen University, a vehicular test environment was built. Specifically, V2X communication using the ITS-G5 and 3GPP-LTE standards was thoroughly tested. CERMcity serves as a platform for controlled field tests of networked mobile systems. The test area accommodates smart traffic lights, roads, buildings and even a short highway.

Hamburg, belonging to Germany's smartest cities, has two significant projects regarding the development of test environments. Project HEAT (Heat, 2021) is a joint research project of the City of Hamburg, the local public transport company HOCHBAHN and several other project partners. It aims at integrating autonomous electric minibusses with a level 4 autonomy into regular traffic. These minibusses that reach 50 km/h in speed are extensively tested under real conditions over an extended time. For testing, a large public test area near the port is set up.

The TAVF-project (TAFV, 2021) is a test track for automated and connected driving. It has several kilometers equipped with IST, such as smart street lights, enabling the testing of intelligent services and automated driving functionalities within real traffic scenarios. Data exchange is based on V2X and I2X communication via the IEEE 802.11p standard.

Ubiquitous cities (Jang and Suh, 2010) represent large test areas for smart applications in the size of a city. In the case of fully ubiquitous smart cities, entire cities are built from scratch and designed to be smart and connected to a large extent. These cities exhibit a highly advanced energy efficiency, sustainability, and connectivity level due to integrating the latest IST. A leading and successful example of such a smart city is Songdo in South Korea (Kshetri et al., 2014). Founded in 2007, this city of more than 1,500 acres near Incheon is now home to more than 30,000 residents. Total costs in 2016 amounted to around $ 39.5 billion. Compared to other cities of similar size and number of inhabitants, it produces 70 % fewer carbon emissions.

Fujisawa Sustainable Smart Town (Sakurai and Kokuryo, 2018) is a privately funded smart city project in the Japanese prefecture of Kanagawa, led by the company Panasonic, and was developed with urban sustainability in mind. Renewable energy production, high energy efficiency and sustainable use of water resources are the main goals. This city features housing for 3,000 residents. It manages to reduce its water consumption by 30 % and produces 30 % of its energy through solar energy. These mentioned precautions, among others, result in a carbon footprint reduced by 70 %.

3 Quartier Mobility in Smart Cities

Smart City projects explore ways to make cities more resource-efficient, sustainable, connected, safe, and socially inclusive to counteract urbanization's adverse effects such as traffic congestion, air pollution, and inefficient resource utilization. Infrastructure-based ISSs that collect, generate and provide data play a crucial role in improving mobility. Smart applications typically depend on communicating with such systems, that continuously provides data about their immediate environment and any activity that occurs within it. Urban mobility usually exhibits a characteristic dynamic of its own, which can be understood as a highly dynamic system of complex processes, many of which run concurrently and independently of each other. It helps to look at this system on a smaller scale by focusing on a smaller section that still qualifies as a good representation of the city's dynamics.

Quartiers represent an independent social reference system distinguished from others both by geographical and social means. The highest density of interaction is typically located in the infrastructural center of the quartier. Quartier mobility refers to the transportation of people and cargo within its public space with traveling distances less than 3 km. A quartier can be represented by a residential district, shopping street, pedestrian area, park, school or university campus. Mobility participants such as pedestrians, cyclists, scooter riders, disabled pedestrians or pedestrians with limited mobility are referred to as vulnerable road users (Sewalkar and Seitz, 2019). A promising approach to optimize mobility is a close network and cooperation between various mobility participants and a dynamic exchange of data with infrastructure-based ISSs. The usual approach includes data acquisition, exploration and integration with heavy use of AI-based algorithms. Last, acquired and preprocessed data is distributed among mobility participants. The development and evaluation of algorithms for ISSs require vast amounts of data and a test environment.

4 Project Test Area Intelligent Quartier Mobility (TIQ)

4.1 Background

In mobility, conflicts tend to arise where some road users' needs cannot be accommodated with those of other equally entitled. This circumstance is due to the limitations and the growing mixed-use of existing infrastructure. Project TIQ started in 2020 at the HAW Hamburg and is researching different areas of quartier mobility. It aims at actively shaping the mobile change and intended to find ways of improving the quality of life out of a quartier perspective. Within its framework, innovative applications and use cases of AMSs within quartiers are studied. This project works on the interaction between VRUs and AMSs using IST. The contiguous university campus belonging to the Faculties of Computer Science, Mechanical Engineering, Business and Social Sciences serves as a test area. This region has a high density of population and mobility due to its proximity to the larger faculties and is therefore particularly suitable for our purposes. Furthermore, the city's official authorization for realizing this project is not required since it is private property.

4.2 Objective and Planning

A MSS is developed to detect mobility events within the test area's most suitable region using a range of sensors. Methods for detecting and predicting the movements of individual VRUs will be extensively explored. It is worth noting that the sensor's design and construction specifically focus on Privacy-by-Design to ensure that acquired data does not conclude individuals. Image-based sensor equipment should be avoided in public space since it can be used for identification purposes. To comply with data privacy and protection regulations, installed cameras that are part of the proposed MSS will solely be used for evaluation purposes.

Besides developing the MSS, innovative functionalities are developed and tested using the mobile platform Husky from Clearpath and the 6-DoF manipulator UR5 from Universal Robots. Examples of smart applications are cleaning of door handles, use of elevators, or the transport of packages combined with in-house navigation. Based on the analysis of acquired and locally processed data, trajectories can be generated for AMSs, preventing them from becoming an obstacle for other road users or even posing a threat. It is envisioned to cooperatively map the environment using the perceptual data of each AMS. A closer inspection of the environment from multiple perspectives opens up new opportunities for infrastructural services such as quality management, repair services or optimization.

Simultaneously, this project aims at developing a prototype of an innovative mobile system for transporting people and cargo. This system will be designed for optimal usability within quartiers. Its electric drive is also being developed entirely new. It is scheduled that this research project will finish by the end of 2023 and should lay the foundation for many other research projects of this kind. This paper deals exclusively with the development of the MSS.

4.3 Methods

Quartier mobility faces challenges that are quite similar to those in autonomous driving. Consequently, this enables a viable application of state-of-the-art methods for pedestrian and cyclist detection, object tracking, behavior and motion prediction, localization and mapping, dynamic path planning and obstacle avoidance. In a highly dynamic environment such as an urban pedestrian zone, it is challenging to detect and track VRUs reliably. Although many research projects use monocular RGB cameras (Masalov et al., 2019) for this purpose, the latest approaches of 3D pedestrian (Fei et al., 2020; Wang et al., 2016) and cyclist detection (Saleh et al., 2017) take advantage of depth data provided by 3D-LiDAR sensors. CNN-based deep learning algorithms such as SSD (Ahmed et al., 2019), YOLO (Lan et al., 2018) or Faster-R-CNN (Chen et al., 2019a; Saleh et al., 2017) are commonly used to classify objects within data in real-time. Using thermographic cameras in combination with depth cameras has proven to be significantly advantageous when visibility deteriorates (Chen et al., 2019a; Rangel and Soldan, 2014). Predicting intentional or reactive movements of VRUs represents a more difficult task. The commonly used method is based on a constant velocity and turn model (Schöller et al., 2020; Westhofen et al., 2012), similar to motion prediction in autonomous driving approaches. There are camera-based methods that predict the pedestrian's intention, for example, by estimating the head pose (Schulz and Stiefelhagen, 2012). Considering a scenario in which AMSs such as UGVs are also moving among VRUs, the topics of multi-agent path planning, obstacle avoidance, and SLAM become more significant. Here, it is essential to avoid a collision with other VRUs and ensure that these systems are not perceived as a hindrance. The ultimate goal is to achieve the path with the least possible interference. The centralized processing of all collected environment data is required to dynamically compute the most optimal and efficient path for each system with minimal latency (Chen et al., 2019b). Commonly used deterministic algorithms for this purpose are D*, A* and other variants. However, newer approaches (Sartoretti et al., 2019) are based on deep learning algorithms.

5 Concept, Design and Construction of a Multi-Sensor System

Sensing platforms, such as those currently deployed in many smart city projects, are typically designed for compactness, low power consumption and cost-effectiveness (Khalifeh et al., 2021). In many cases, these platforms are deployed for environmental monitoring and do not require costly sensors. The use of wireless sensor nodes on a large scale enables a broader and, thus, more representative reflection of the environment to be obtained. Naturally, the simplicity of these devices is also a limiting factor in terms of functionality. Our approach towards developing a MSS addresses the limitations of existing platforms.

5.1 Basic Concept

A considerable amount of effort was put into the conceptual design of the MSS. Robustness, durability, maintenance, repairability, reproducibility, and safety was prioritized in its development. The choice of materials and components fell on commercially available standard materials and stock parts. A simplistic design and mindful choice of materials significantly reduced the system's complexity and, therefore, overall shorter construction time. The materials chosen are aluminum, plexiglass, thermoplastic and stainless steel. The individual components can be constructed from commercially available aluminum sheets and angle sections with a minimum effort. A handful of parts such as the sensor flanges are custom made by 3D printing. Easy maintenance and repairability were considered during assembly. The MSS is self-contained. Since it is intended for year-round operation and exposed to various weather conditions, it is equipped with a climate control system. It is meant to regulate the internal temperature and humidity by utilizing active cooling, heating and ventilation. As a positive side effect, this climate control system reduces the potentially harmful formation of condensation within the system.

Figure 1: Model of the Multi-Sensor System

A splash-proof design guarantees protection against damages caused by heavy rain and thunderstorms. Sensors can be swapped out individually or as a sensor configuration via built-in module slots without effort, similar to (Tiedemann et al., 2015). The MMS operates under mains power. An internal power supply generates specific voltages required by other components. Existing infrastructural features such as building walls or street lamps can serve as a basis for the installation. Although the system's aesthetics are of secondary importance, an unobtrusive design that seamlessly integrates into its surroundings is reasonable.

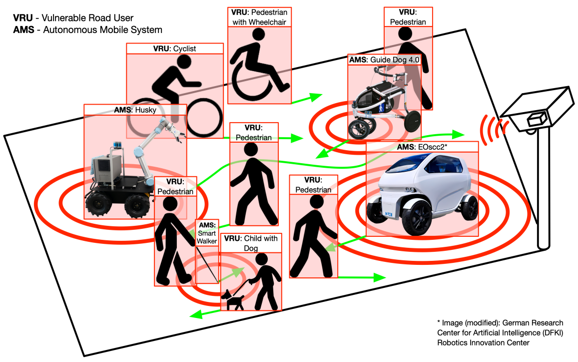

Figure 2: Use Case Scenario of the Multi-Sensor System

5.2 Design Decisions Regarding Construction and Sensor Selection

For the design of the MSS and the sensor selection, specific requirements were defined in advance. These requirements regarded the field of view and horizontal resolution of individual sensors, protection class of housing and components, operating temperatures of each component and power supply.

Table 1: Specified Requirements for Sensor Selection

Type	Requirement
FOV	detection area of at least 10 m $\times$ 10 m
IFOV	horizontal resolution of 5 cm $\times$ 5 cm at 1 m height over ground
Protection Class	at least IP 43 protection against particles smaller than 1 mm in diameter and spraying water up to a vertical angle of 60°
Operation Temperature	year-round operation with temperatures from $-20°$ C to 40° C
Power Supply	mains supply at 230 V / 16 A @ 50 Hz

5.3 Final Sensor Selection

Sensors of different types are used to detect VRUs. The commonly used sensors for this purpose are based on LiDAR, RADAR, TOF, ultrasonic and mono-/stereoscopic or thermographic vision. These sensors differ in reliability, accuracy and speed, among other things, and have their advantages and disadvantages. They may not reach their potential for detection in all circumstances. Therefore, most sensors are only suitable for a specific application.

Table 2: Selection of Components

Sensor Type	Model
QSS 3D-LiDAR Sensor	Blickfeld Cube 1
2D-LiDAR Sensor	Slamtec RPLIDAR A3
TOF Sensor	Basler Blaze-101
Thermographic Camera	FLIR A35
Area Scan Camera	Basler Ace 2
Surveillance Camera	Abus ICPA72510
Embedded PC	OnLogic Karbon 700
Ethernet Switch	Cisco SG-350-10P
IMU	Xsens MTi-630

After intensive research and evaluation of suitable sensors, a selection was made according to the defined requirements. Most suitable sensors for intended purposes and applications have already been extensively tested in other research projects, proven reliable. In the first revision of this MMS, optical sensors such as LiDAR-based sensors, TOF sensors, thermographic cameras and monocular cameras were considered. An IMU is also an integral part of the MMS's equipment. A later version will include a RADAR sensor as well. With this selection, the majority of state-of-the-art detection and tracking methods are realizable. It is of particular interest to determine each sensor's potential situational advantage or disadvantage compared to others, what these advantages and disadvantages are, and which sensors are dispensable. Besides these sensors, the system requires other essential components. These include an embedded PC with sufficient computing power, a power supply and an ethernet switch, providing power over ethernet.

Figure 3: Overview of Selected Sensors

Since available sensor nodes are mainly focusing on environmental monitoring, many track temperature, humidity, ambient pressure, weather status, and sometimes air quality with its particulate pollution. Such measurements are desirable when searching for correlations between measurements and mobility or to monitor certain developments over time. Thus, environmental sensors are also installed as secondary sensors in our MSS.

5.4 Communication Architecture

In a smart city, all mobility participants continuously exchange data with each other. Depending on the participant from which the data exchange originates, the communication is either called vehicle-to-everything (V2X), infrastructure-to-everything (I2V) or pedestrian-to-everything (P2X) (Bersani et al., 2020; Dominguez et al., 2019). AMSs and other connected vehicles are grouped in this case. Depending on which road users share data, the communication type is further specified, e.g., the data ex-

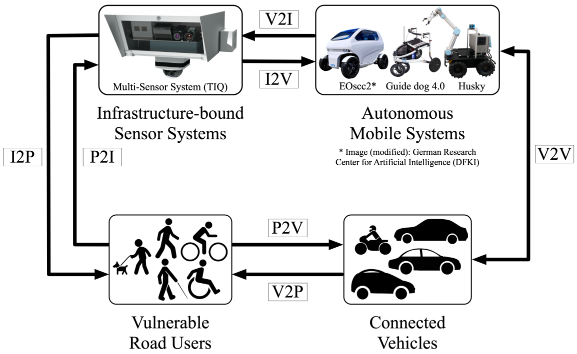

Figure 4: V2X, I2X and P2X Communication

change between vehicles and VRUs (V2P) or MMSs and AMSs (I2V) (Dominguez et al., 2019). The same applies the other way around, hence P2V and V2I. The IEEE 802.11p standard is commonly used for this purpose. Some examples of AMSs which this system is planned to interact with are the Husky, the Shared Guide Dog 4.0, the Smart Walker and the EOscc2 from our partner DFKI (EOscc2, 2019). The second and third are aids for pedestrians with physical disabilities and also developed at the HAW Hamburg.

6 Conclusion and Outlook

This paper proposes an MSS for use in quartier mobility, developed in the scope of project TIQ. It is equipped with several optical sensors to detect VRUs and AMSs under different mobility conditions. A particular focus is placed on Privacy-by-Design, which prevents the improper use of data. Mobility participants can exchange data using V2X, I2X and P2X communication via the IEEE 802.11p standard. The campus of the HAW Hamburg serves as a test environment. It is also planned to extend the MMS by a RADAR and IMU sensor, a DGPS, and several environmental sensors for further functional expansion. Collected data will be used to develop and evaluate algorithms for pedestrian detection and tracking, movement prediction, and path planning for AMSs. Evaluating the latest algorithms will also determine the sensors' suitability in specific applications. Future results will show if sensors are dispensable without compromising in functionality.

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