DRIVERLESS CITY: THE URBAN POSSIBILITIES OF AUTONOMOUS VEHICLES AND NAVIGATION SAFETY

Abstract

The advent of autonomous and ubiquitous co-robot technologies offers citizens, leaders, and stakeholders the opportunity to recalibrate current automobile transportation infrastructure and, therefore, the morphology of dense urban cores. To do so, we must balance the requirements for navigation safety, functionality, and experiential conditions. This research investigates these trade-offs to understand the impact of driverless vehicles in urban design. The result will be a framework of forecast scenarios that will advise urban designers, policymakers, stakeholders, and the autonomous vehicle industry on critical factors to consider when deploying these technologies and how to achieve valuable social, environmental, and experiential outcomes within the existing road infrastructure. This research will address how cities can leverage upcoming mobility technologies to retrofit late-nineteenth-century automobile transportation infrastructure into human infrastructure for the twenty-first century. Furthermore, how can urban public spaces (roads, sidewalks) be built to promote social equity and environmental performance as the number of autonomous vehicles increases? This research examines the possible implications of autonomous vehicles and navigation safety on State Street (Chicago), a significant commercial artery of the city and with a historical morphology intimately related to mobility and infrastructure innovations.

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Keywords

Autonomous vehicles, driverless cars, navigation safety, geocoded landscape, infrastructure design

There is a clear link between an autonomous vehicle's capability to localize within an environment and that environment's physical structure. Tall buildings can severely compromise GNSS signals due to blockages in line of sight; for landmark-based navigation, landmarks spaced too far apart decrease localization accuracy, and the same landmarks spaced too close together can introduce a higher probability of faulty measurement associations. This research builds a technical framework based on current driverless technologies and IIT's Driverless City project methodology to understand the limitations of GPS availability and landmark-based navigation. Lastly, the final component will incorporate speculative scenarios to increase the localization safety of autonomous cars along the chosen transects from both cities. These operations are devised to address socio-environmental issues such as park accessibility, urban heat island effect, and water management.

The increase in the presence and development of driverless cars urges us to proactively understand the intersection between robotics, navigation safety, and urban design to anticipate outcomes for stakeholders. Historically, cities had to reshape their infrastructure to accommodate disruptive transportation technologies with detrimental consequences. If the deployment of autonomous technologies is left unchecked, we may be on the cusp of a mobility revolution that would exacerbate the precarious conditions of cities. However, the potential for cities to alter their transportation infrastructure due to autonomous cars could result in safer pedestrian paths, better connectivity, the topology of urban spaces, higher tree canopy biomass, increased landscape performance, and regain human and social values.

Introduction

The advent of autonomous and ubiquitous co-robot technologies offers society a unique opportunity to reshape our transportation infrastructure. To properly deploy Autonomous Technologies, we must balance the requirements for navigation safety, functionality, and experiential conditions. This interdisciplinary research investigates these trade-offs to understand the impact of driverless vehicles on urban design and public policy. To do so, this research investigates the challenges of urban navigation for autonomous vehicles on State Street (Chicago). Furthermore, it introduces a method to improve autonomous vehicle (AV) localization safety through an urban design approach. This approach improves current urban practices while ensuring AV's proper function.

Driverless vehicles must operate with safety levels on local and residential streets subject to corresponding accuracies at the centimeter level (Reid et al., 2019). Still, urban environments can degrade navigation sensors' accuracy and, therefore, fault-free integrity. Tall buildings can severely degrade Global Navigation Satellite System Signals (Figure 1) (Nagai et al., 2020). Landmarks spaced too far apart for landmark-based navigation decrease location accuracy. At the same time, close landmarks can introduce a high probability of faulty measurement mis-association (Hafez et al., 2020). One could shape the environment to maximize a robot's localization safety to mitigate safety risks. This could be done by creating ordinances that dictate the appearance of the streetscape so that self-driving cars, drones, and other mobile co-robots can guarantee their trajectory. However, modifying the environment to maximize co-robot safety could have negative and wide-ranging societal impacts if the process does not consider the needs of all the involved stakeholders. This highly interdisciplinary research project studies the relationship between landscape architecture, city planning, and mobile co-robot navigation safety. As a result, it develops a method that transforms passive landscape objects such as trees and light poles into binary error-correcting codes that enhance autonomous vehicle localization safety.

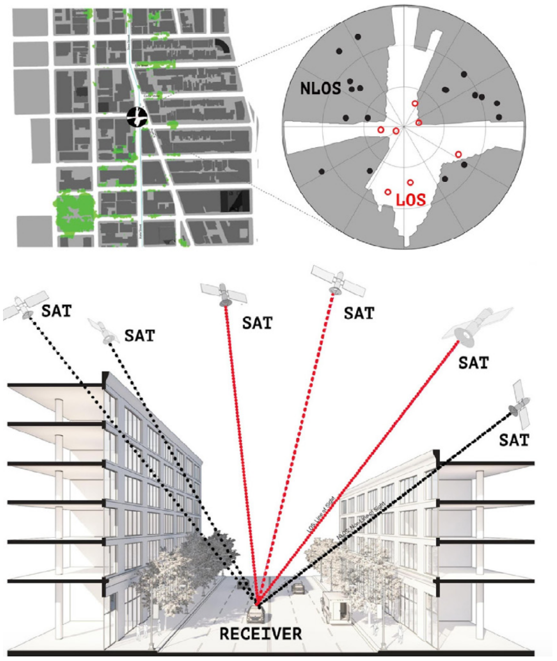

Figure 1: This figure shows an example of how GNSS measurements were formed: a sky map of the GNSS constellation is generated at a given time and given location. The grey areas are buildings in the area and any satellites of PRNs located within the grey area will be considered unavailable due to building blockage. The red dots on the top-right indicate GNSS satellites with a Line of Sight (LOS), while black represents a non-Line of Sight (NLOS). (Source: Alexis Arias Betancourt.)

Methodology

GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS) EVALUATION

The research begins by defining safety requirements for driverless vehicles under fault-free conditions and developing measurement models for multi-sensor integrated navigation systems. The study evaluates satellite availability in 3-D Mapped Urban Environments to understand the limitations of Global Navigation Satellite System Signals Navigation. An array of sensors is utilized to collect data along the 8.9-kilometer State Street transect. This array consists of Lidar sensors, GPS antennas and receivers, IMUs, and other GPS units. The collection of data generated a Point-Cloud dataset of State Street. The sensor array is positioned on top of a test vehicle that ran through the transect multiple times in different weather and time conditions. The team replicated an accurate 3-D Environment with the collected data to evaluate and assess the developed methods.

We started by evaluating GNSS availability. The urban canyon is assessed through shadow matching (Groves, 2011) to identify signal blockages. The availability of GPS-only positioning is determined to be less than 10 percent at most locations on State Street (Figure 2). Using four entire GNSS constellations, availability improves significantly but is still lower than 80 percent at specific points rendering Satellite

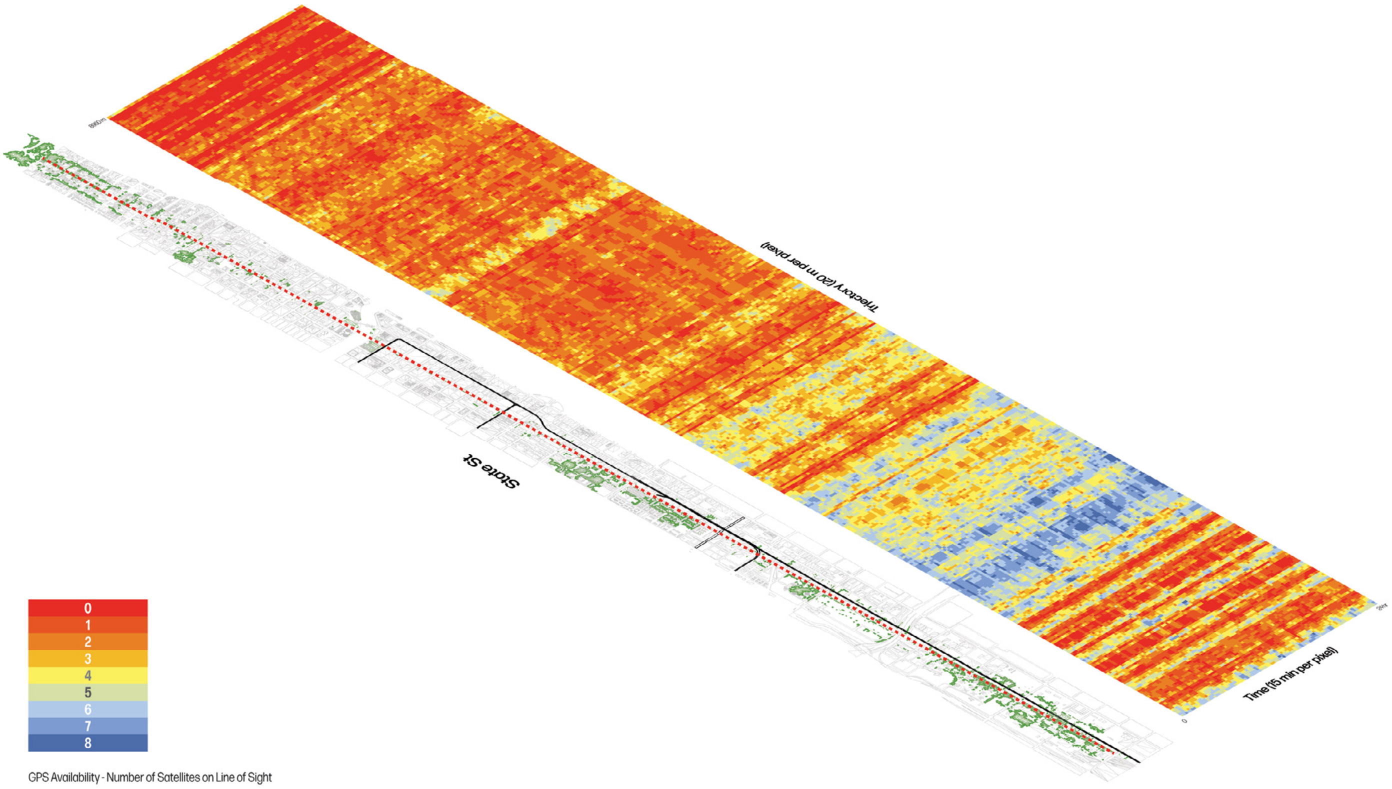

Figure 2: This figure shows an example result of a 24-hour GNSS satellite availability emulation along State Street. The emulation uses high accurate-Ephemeris, together with the 3-D model of buildings along State Street from 35th street to the Golden Coast, to determine the GNSS availability along the mission. A sample point is placed along State Street every 20 minutes. All sample points were re-sampled every 20 minutes for 24 hours. The result forms a heat map on the right: The horizontal axis represents time (with a resolution of 20 minutes in this figure), and the vertical axis represents the distance from the starting point (with a resolution of 15 minutes in this figure). The heat color represents the number of available GNSS satellites. The hotter the "temperature," the more satellites were available to utilize for localization. (Source: Alexis Arias Betancourt.)

Navigation Systems unreliable for Autonomous Vehicles in the selected transect (Nagai et al., 2020).

NAVIGATION SAFETY ASSESSMENT

To test this method, we use the current conditions of State Street obtained through the site survey performed with Navigations Sensors and Ranging Sensors. We evaluate them with Navigation Integrity parameters and define an Alert Limit or maximum allowable error in the measured position. Once the zones with low Navigation Integrity are identified, we modify the transect in a 3-D environment. For instance, this method proposes the addition of 630 landmarks to the 2,558 existent landmarks in the selected nine-kilometer transect of State Street. Then, the 3-D environment of the chosen transect is modified, and its integrity is evaluated under the exact parameters of the beginning of the process.

PSEUDO-RANDOM LANDSCAPE STRATEGY

One approach to solving the deficiency of Satellite Navigation availability is directly extracting navigation information from the local environment, using ranging sensors like LiDAR and RADAR. Unfortunately, the random arrangement of local landmarks makes it challenging to quantify navigational safety. It may be difficult, if possible, to calculate the risk of inaccurate landmark extraction and association in a dense setting (Duenas Arana et al., 2019). In response, the research team combines multiple Ranging and Inertial Sensors with a pseudo-random landscape strategy to provide quantifiable navigation integrity. All objects in urban environments are candidates for external ranging sources for LiDAR. However, we specifically focus on extracting pole-like landmarks (e.g., trees and street lamps) because of their location flexibility, relative ubiquity, and defined shapes (Nagai et al., 2021).

The landscape objects are used in a binary error-correcting code to improve localization safety for autonomous vehicles. Prior research showed that LiDAR measurements using pole-like landmarks improved vehicle localization in urban environments but that "the accuracy of the localization is highly dependent on the number and density of available landmarks at each scene" (Brenner, 2009). In this work, each landmark mapped in the selected transect is assigned a unique identification (ID) with a given geographical area (Figure 3). This results in bidirectionally decodable landmarks so that robots can read the code while traveling in either direction along a given path. To provide a realistic scenario, we included urbanistic constraints on where these landmarks can be set up. The spacing between new landmarks respects the landscape ordinance of Chicago, spacing trees between 6 and 7.5 meters.

Related work includes the use of QR code-based localization methods. These approaches mainly focused on optical-based codes, but the techniques were limited to small-scale indoor applications (Zhang et al., 2015; Lee et al., 2015; Kobayashi, 2012). In contrast, our approach introduces a novel and reliable localization technique that applies to large outdoor environments, such as urban streets. The key benefit to this approach is that, without introducing new instruments to the current environment, through minimal modifications to the urban landscape, the technique can nearly eliminate measurement faults in range measurement-based localization using landmark maps and thus guarantee safe localization.

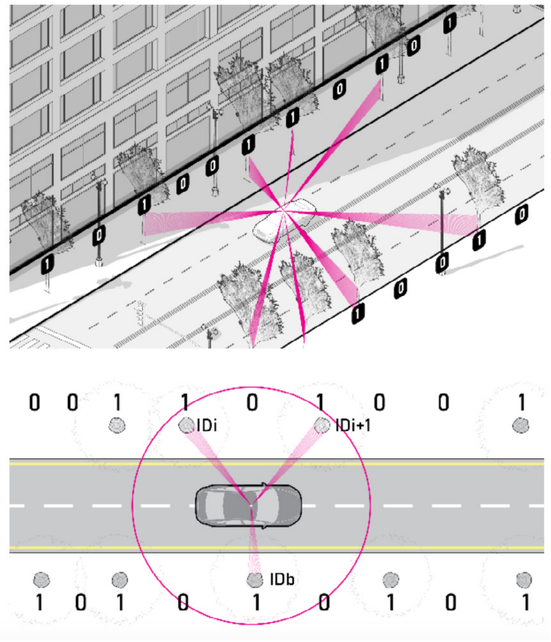

Figure 3: We use trees and their location as bits. With a series of trees' existence and non-existence, we can decode them into identification messages that associate features with pre-mapped landmarks. (Source: Alexis Arias Betancourt.)

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In this step, integrity risk is measured, which is established as a function of the specific sensors the robot is carrying, their availability, noise characteristics, feature extraction algorithms, data association algorithms, monitor detection thresholds, and the density of local landmarks. A monitor developed by IIT's driverless city team is used to evaluate the data integrity of the selected transects. Our monitor considers GPS availability, INS metrics, and extracted data from passive landmarks on the streetscape. We assume as an integrity requirement that the probability of exceeding a 1-meter position estimate error (Figure 4a) must be lower than 10−7 (Figure 4b). Given a position error standard deviation of σpos, the 1-meter integrity alert limit corresponds to approximately 5σpos.

ENVIRONMENTAL AND URBAN IMPACT ASSESSMENT

Once autonomous vehicle navigation is guaranteed, the research evaluates the impact of the added landmarks requested by the binary code approach in the selected transect. From 31st Street to North Avenue, a transect of 8.9 kilometers, there are 2,558 landmarks on State Street. The conditions vary along the transect, where there are areas with a denser number of landmarks. The simulation of the geocode suggested the position of 630 geocoded landmarks located in areas where GNSS is unreliable or unavailable. The geocoded landmarks are prioritized over the existing landmarks to be consistent with the system. The landmarks in the neighboring area must be removed in a radius of 0.40 meters on the X-axis and 5.60 meters on the Y-axis. There are 170 existent landmarks that had to be removed in the total transect. In total, the number of landmarks accounting for the existent and the geocoded landmarks, and subtracting the removed, is 3,018 landmarks, representing an increase of 17 percent landmarks along the transect.

Adding more urban forestry to cities has a positive impact on navigation safety. Chicago's current road infrastructure occupies 39 percent of surface coverage, while parks and public spaces account for only 6 percent (Ibrahim et al., 2018); therefore, there is plenty of room to improve the urban forestry on public roads, exponentially increasing

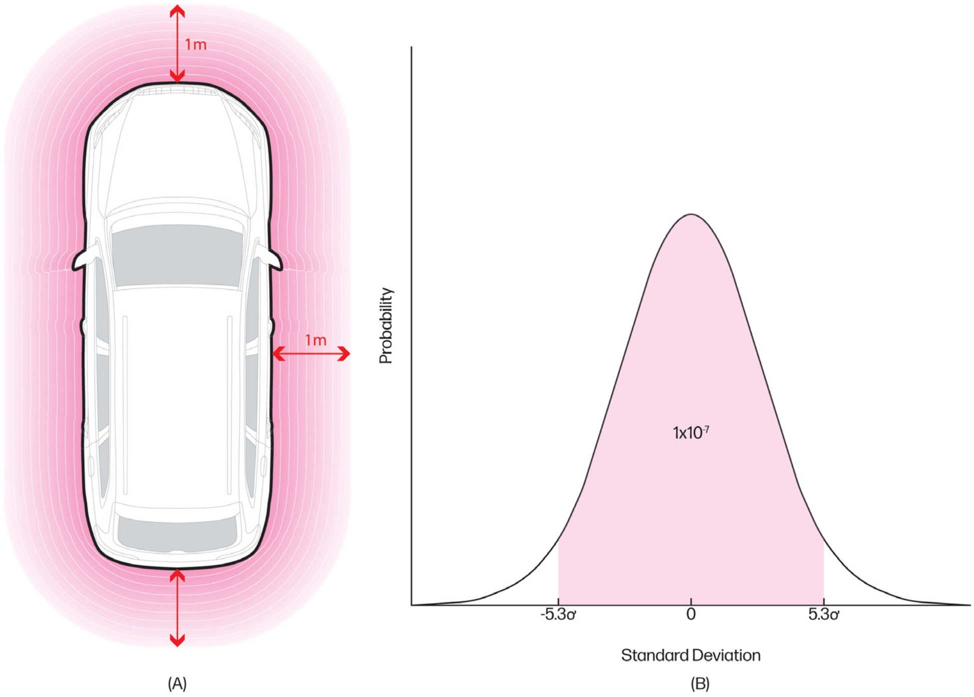
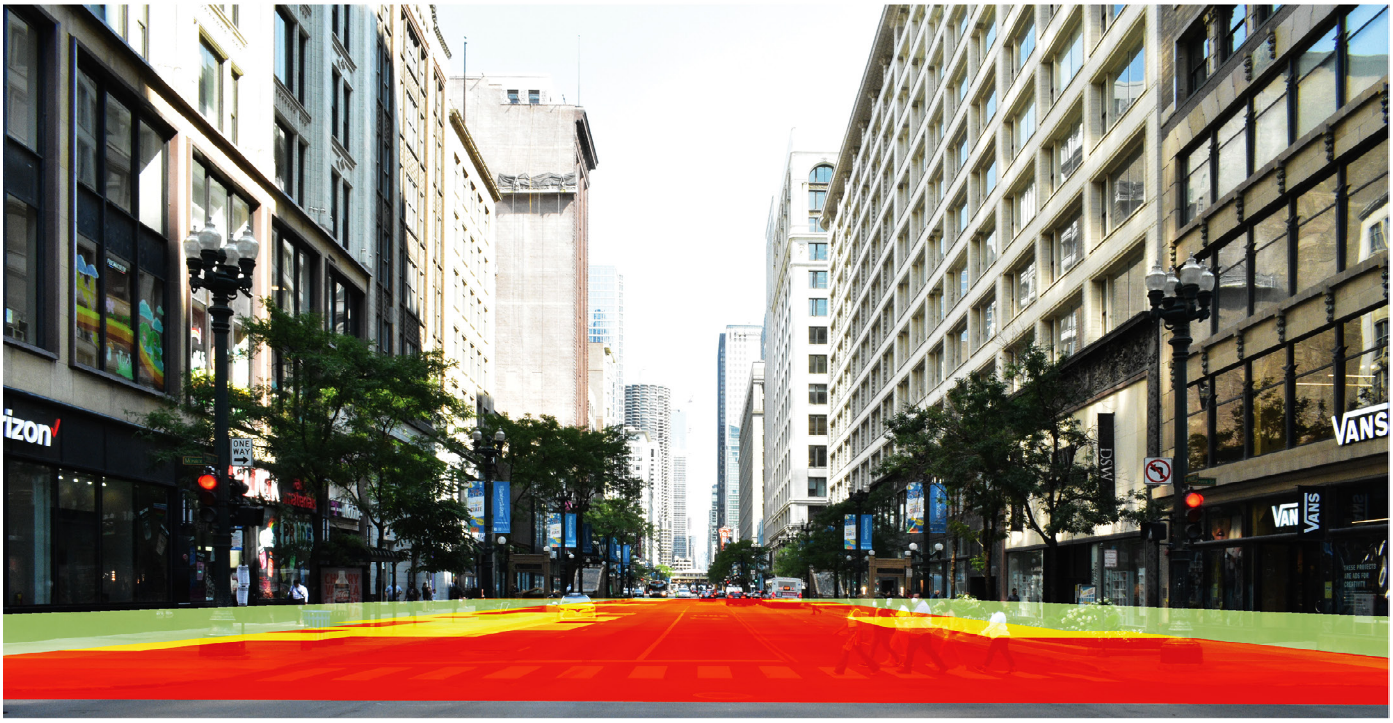
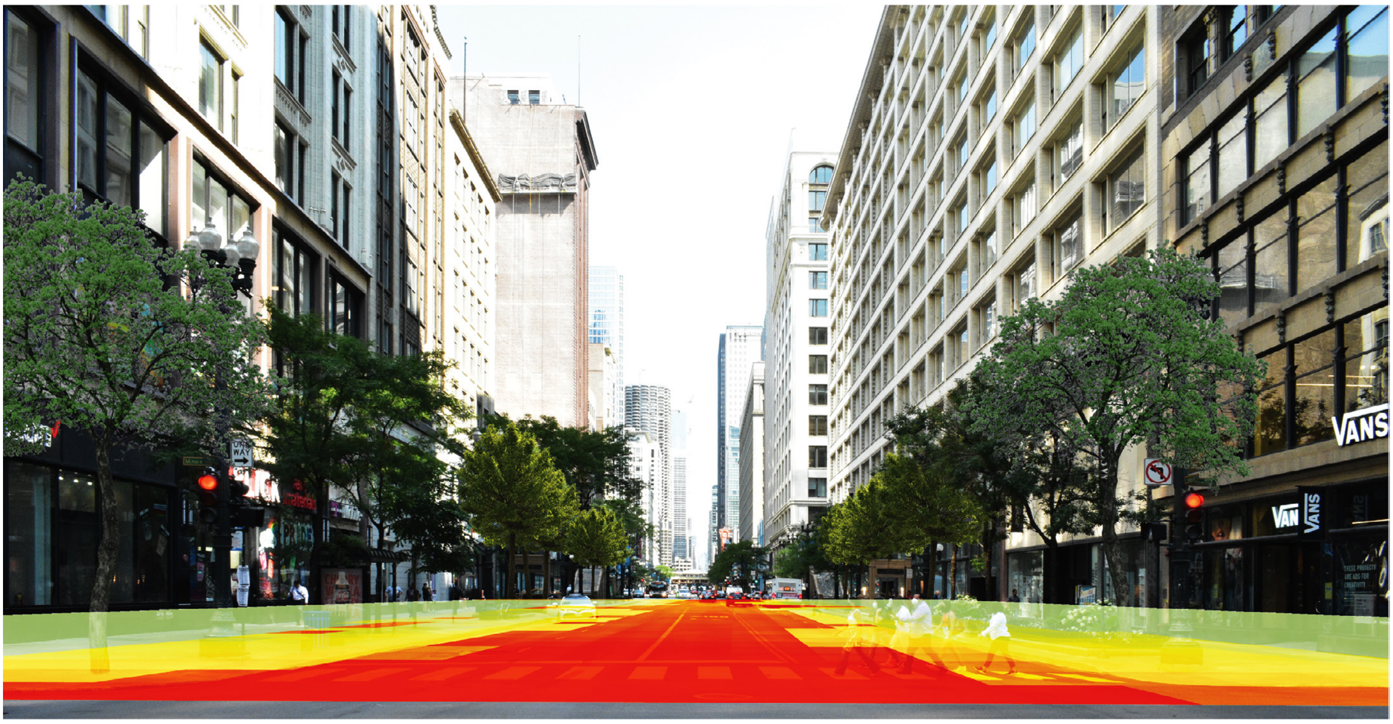


Figure 4: Integrity requirement assumptions for autonomous vehicle positioning. The position domain alert limit is 1 meter in any horizontal direction (a), and the maximum probability of exceedance is 10-7 (b). (Source: Alexis Arias Betancourt.)



A. Outdoor Thermal Comfort - State St - The Loop (Original)



B. Outdoor Thermal Comfort - State St - The Loop (Modified)

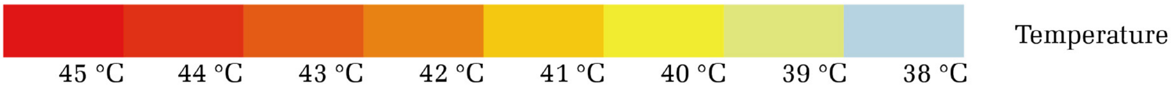


Figure 5: UTCI simulations indicate that State Street could decrease temperatures up to 6º Celsius. (Source: Alexis Arias Betancourt.)

their benefits. An increase from 8\% to 22\% in canopy coverage can help mitigate the urban heat island effect. To assess this, we use 3-D simulated environments of the selected transects. A 10,000 m^2 area has been established on a section of State Street, measuring 125 meters north to south and 80 meters east to west.

These models are subject to thermophysiological evaluations through open-source software called ladybug (Pak et al., 2013). The determined area is divided into small regions of around 2 square meters. Each subdivision is evaluated considering the weather variables obtained from the EPW weather data from O'Hare airport. These variables are air temperature, solar radiation, relative humidity, and wind speed, and they have a combined effect on thermal perception. Buildings' material, shape, morphology, vegetation presence, global radiation, evaporative cooling, and these parameters are determined. Increasing canopy coverage on State Street can lower temperatures from 6º to 9ºC on average across the transect (Figure 5).

We can see from the computed data that the areas with high temperatures are shrinking. The area exposed to 45°C or more decreased by 455.38 m^2. The area was exposed to 44º to 45°C by 607.45 m^2. The area exposed to 43º to 44°C remained constant with a decrease of 40.15 m^2, and the area exposed to 42º to 43°C decreased by 318.322 m^2. There has been an increase in area in the lower ranges. The area exposed to 41º to 42°C expanded by 204.78 m^2, the area exposed to 40º to 41°C climbed by 130.16 m^2, and the area exposed to 39º to 40 °C increased substantially to 1,086.35 m^2.

Conclusion

Streetscape policies rarely considered functional values, let alone using streetscapes to improve navigation safety for ubiquitous robots. Cities like Chicago manifest in their landscape ordinances document the following: The objective of the landscape ordinance is an attractive city of tree-lined streets and boulevards, greener neighborhoods, and enhanced property values. The people of Chicago benefit from a more beautiful city filled with trees, shrubs, and flowers. We all benefit when the high temperatures of the urban heat island are lowered by spreading canopy trees over hot asphalt paved streets and parking lots. Birds and other wildlife benefit from nesting and resting habitats, refuge, and food sources provided by the landscape in what could otherwise be a sterile urban environment.

Although this operation has positive consequences for the integrity of navigation and the environment and society, it would mean a great effort to apply this system on a large scale. The operational and environmental costs of removing mature street trees and planting young trees are high for municipalities like Chicago. New landmarks would take decades to reach maturity, sacrificing their urban benefits in the short term. Likewise, this would require a thorough survey of the road system of already consolidated cities, which could take extensive operating times and costs.

However, systems like the geocoded streetscape can and should be considered in new developments in established cities and emerging cities, where there is greater flexibility to apply these systems and base streetscape ordinances on navigation systems for navigation ubiquitous robots.

The research proposes a solution to the current challenges for autonomous vehicles in urban environments. The importance of this method is the urbanistic design approach as a tool to improve navigation safety. This allows us to propose different scenarios like the increase of urban forestry and the retrofit of street space. Although these technologies are still in the research and development stage, it is essential to discuss the cities' near and long-term future and how we can leverage their needs and capabilities to benefit the stakeholders. This method shows an approach in which the intersection of multi-disciplinary fields can achieve the required conditions for the technology to function and provide positive urbanistic values. If we fail to understand the requirements for technology to coexist with us, we can exacerbate the current urban issues by segregating our infrastructure even more. However, suppose we understood the cooperative essence of technology and provided the meanings for it to function while considering the valuable opportunities it offers appropriately. We could be on the eve of creating sustainable, regenerative, inclusive, and equitable cities.

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