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Reimagining urban infrastructure through design and experimentation

Autonomous boat technology in the canals of Amsterdam

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Introduction

What it is a "smart city"? The term is now so widely used that its meaning has become convoluted and often obtuse. However, its raison d'être is unquestionable: conceptually "smart cities" result from broad technological phenomena that have been unfolding over the last two decades and are now undergoing a dramatic acceleration. Advancements in robotics, the use of machine learning techniques to mine and analyze unprecedented amounts of data, and the infiltration of information technologies into physical space have ushered in a series of unprecedented possibilities in how we can understand, design, and live in a city and make it "smart" (Duarte & Firmino, 2009; Ratti & Claudel, 2016).

Although frequently promoted in a prescriptive way, smart cities entail such a multitude of complex, exciting, and uncertain technological and social challenges that imagining the future of cities in a formulaic fashion is fruitless. The city of the future is not a model, but rather a framework for experimentation. Novel approaches to smart cities arise from the explorations of the integration of the data currently generated in cities and the presence of robots in our daily lives; explorations that create urban experiences that could define the way people, institutions, nature, and infrastructure will interact in the city of the future.

This requires approaches to science, technology, and design where disciplinary boundaries are removed and the future of the city is envisioned through experiment-based proposals. Indeed, the literature on smart cities has stressed such an interdisciplinary approach (Angelidou, 2014; Stratigea et al., 2015). However, what seems to be missing is empirical evidence on how this would actually work. Much of the smart cities literature focuses on a critical reading of the management of urban planning, forging strong links with technological companies, and using a normative approach (Luque-Ayala & Marvin, 2015). Design and experimentation are largely neglected, mostly because the literature is focused on reacting to large projects developed by cities or companies, seldom with researchers participating actively in the conception or deployment of smart cities initiatives. The literature has missed opportunities to develop insights into the iterative and complex process of designing and developing these projects.

On the other side, design projects that endeavor to reshape cities leave details underdeveloped: how might sensors and technology work to create a new urban ecosystem? By cherry picking technologies such as drones to render into promotional photos, but leaving unexplored the logistics of such systems, designers miss the rigor offered by an experimental process and risk superficiality.

In this chapter, we focus on a research project that combines robotics and artificial intelligence, environmental sensing, and design, driven by a clear experiment-based quest: how will autonomy reframe the way we conceptualize urban mobility and urban services? More specifically, how can the development of a fleet of autonomous vehicles in an urban water system unlock new potentials? In this chapter we show how Roboat, an ongoing interdisciplinary design project, addresses both autonomy's technical challenges and imagine its urban applications beyond the form factor of the car dominating the existing self-driving literature (Duarte, 2019). The Roboat project aims to deploy a fleet of autonomous boats in Amsterdam's canals which will eventually be used to provide transportation for people and goods, monitor water quality, and enable the self-assembling of urban infrastructures such as bridges and stages. The project is part of a research collaboration between the Amsterdam-based Advanced Metropolitan Solutions (AMS) Institute and the Massachusetts Institute of Technology (MIT).

The Roboat project integrates many disciplines, from robotics to environmental sensing, from computer-based perception to industrial design. But within the context of this book on smart cities, after a brief description of the Roboat project, here we discuss some urban services that can be provided by Roboat. After all, the future needs to be imagined and built.

Roboat and Amsterdam

Computer science, artificial intelligence, robotics, environmental engineering, urban studies, design: many laboratories at MIT and AMS, involving dozens of researchers, are joining forces to develop a fleet of autonomous boats that will be navigating Amsterdam's canal in a few years, in a project called Roboat. The decision to focus on autonomous boats is not trivial. A rich body of work exists about autonomous vessels and underwater vehicles (Wang & Xie, 2015; Xiang et al., 2017). However, little research has been done on autonomous boats navigating urban waters, such as Amsterdam, where the large network of relatively narrow canals are used daily for a wide range of purposes—but mainly for leisure and tourist boats, moving thousands of people. The challenges involved in this endeavor require an interdisciplinary approach. The complexity increases when we aim to use these autonomous boats to transport people and goods, provide urban services, and create temporary infrastructures, all while continuously sensing the environment (water and air quality, and canal wall infrastructure). Within this context, interdisciplinary researchers feed each other with challenges and solutions.

Amsterdam is uniquely situated as a test site for autonomous boats. Its urban structure is based on rings of canals, which were first built as we know them in the sixteenth century, and are an UNESCO World Heritage site. Although "there is almost nothing on Amsterdam's canals that is not of importance or does not have an interesting history" (Spies, 1991: 15), the main canals—Singel, Herengracht, Keizersgracht, and Prinsengracht—have played the key functions of delivering goods and transporting people for most of their history.

However, since the late nineteenth century and early twentieth century, roads started to be widened, blocks of houses pulled down, and canals backfilled in order to make room for an expanding city. Amsterdam was becoming "dreadfully overcrowded" (Kahn & van der Plas, 1999). Covering and abandoning the canals as a daily infrastructure had two main purposes: to control waterborne diseases, due to the use of the canals as open-air sewers, and to accommodate a higher demand for road traffic (de Haan, 1991). The area of Amsterdam's canals has halved over the years, giving space to an increasing road-based transport system that has resulted in soaring emissions and noise pollution.

According to a Kennisinstituut voor Mobiliteitsbeleid Mobility report, the modal split in Amsterdam for home to work trips is 21% of trips by private motor vehicles, 48% by bicycle, and 16% by public transport, which encompasses buses, 15 trams, and 4 subway lines (a fifth is under construction). Despite being one of the most bike-friendly cities in Europe and having one of the lowest rate of inhabitants per vehicle (3.65, according to Gemeente Amsterdam, 2016a), traffic and related emissions are still a concern. In addition to resident traffic, the city receives 271,000 commuters daily (Eurostat, 2016a), and an average of 45,000 tourists, for a total population of 850,000—all using underground and ground transport (including 2,300 taxis) to move around.

Adding to the movement of people, the transport of goods is a major contributor to traffic. In Amsterdam, there are 20,000 freight trips daily to 40,000 delivery and service points in the city center. Furthermore, 80% of the loading and unloading process happens on Amsterdam's narrow and sinuous streets, impeding the general flow of traffic (van Duin et al., 2014). The accelerating phenomenon of online shopping and home delivery is putting an additional pressure on urban freight. In the Netherlands more than 80% of goods are delivered directly to homes (Weltevreden & Rotem-Mindali, 2009). From 1998 to 2011, in the Netherlands the annual home market for internet shopping grew from EU€41 million to €9 billion, and went from a 2.8% market share, in 2005, to 10% in 2011 (Visser et al., 2014). The Netherlands has the highest waterborne freight transport rate in Europe, transporting 47% of the freight share—similar to the road transport (Eurostat, 2016b). Nevertheless, freight transport was absent from Amsterdam's canals in recent decades until 1997, when DHL began transporting goods by water. Today their boats serve as distribution centers from which bicycles collect and then distribute the parcels (Erdinch & Huang, 2014). In 2010, Mokum Mariteam started operating its first electric freight vessel in the city, using the waterways to deliver goods to shops (Maes et al., 2015).

Although 100 kilometers of canals still cover 25% of the city, their ability to transport people and goods has lost its relevance. Currently, the canals are mostly used by leisure and tourist boats. Since 2017, the city of Amsterdam enforces a maximum speed of 6 kilometers per hour (km/hr) in the canals, and the maximum size of boats in the central canals is 4.25 meters wide and 20 meters long. Since 2018, the use of radio frequency identification (RFID) is mandatory for all boats entering the city, which will allow a better monitoring of the boat traffic. By 2025, canal cruise boats must produce zero emissions, and in the next few years all boats must be electricity powered. These measures would help to address the current exposure to pollutants to the significant population residing close to Amsterdam's canals (van der Zee et al., 2012).

With one of the most extensive canal networks in the world, Amsterdam has the unique opportunity to reclaim the canals, rather than keep saturating its road system and ground transport. In the following sections, we introduce three use cases in which autonomous boats could play a role in Amsterdam: first, we address the use of the canals as a transportation network, comparing it with existing modalities such as cars, bicycles, tramways, and subway. Next, we propose the use of autonomous boats to deliver goods and to tackle one of the critical problems in the historical district of Amsterdam: waste collection, and compare the performance of the proposed systems with the current situation. Finally, we explore the use of Roboat to create temporary urban infrastructures, such as bridges, stages, and floating markets. In discussing both the research methodologies and the physical design of the Roboat units, we hope to show how the interdisciplinary nature of this team allows for unique lines of inquiry and results in novel solutions.

Moving people

As any city, motorization has been increasing in Amsterdam—and despite the pervasive use of bicycles and an extensive transit network including tramways, trains, buses, and subway, traffic has become a problem for the city. While the road network is congested, the canals of the city have been abandoned as a transit infrastructure. We used network analysis to study the possibility of regaining Amsterdam's canals for the movement of people, comparing the performance of autonomous boats with other existing modes, analysis that informed the design of the use cases, which in turn led to further research questions.

In order to assess the feasibility of deploying autonomous boats for the transportation of people and goods using Amsterdam's canals, comparing their performance (coverage area and travel times) with other motorized modes, we divided Amsterdam into a 500 x 500 meter cell grid, totaling 907 cells. Considering only those cells which are traversed by or adjacent to a single connected canal network, 236 cells can be directly served by boats, covering 60 square kilometers, as shown in Figure 27.1.

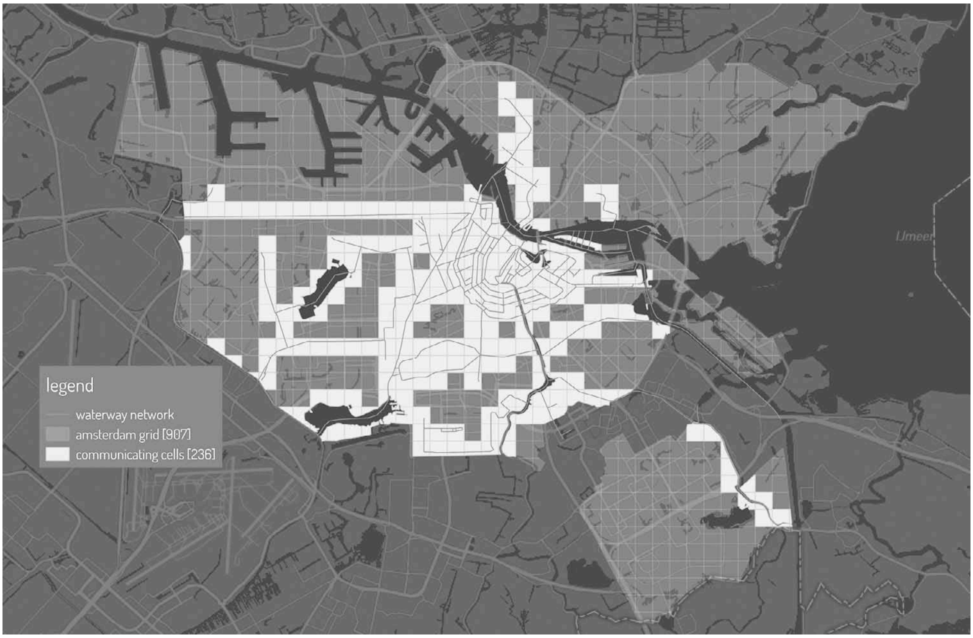

Figure 27.1 Amsterdam's canal network
Source: Chapter author(s)

Cells that can be connected one another through the canals, defining the single largest network of continuous canals in Amsterdam, we call "communicating cells", which include the Ij river and a segment of canal outside city limits. In a city with 850,000 inhabitants, 55% live within the canal network communicating cells. In order to evaluate the use of boats for transport purposes, a test point was established in each cell, using the mean coordinates of the canal segments within each cell, as shown in Figure 27.2. Twenty test points were added manually along the larger bodies of water to ensure realistic points for land transport.

The resulting set of 236 test points were used to calculate travel times across the canal network. For boats, the shortest distance between each pair of test points along the canals was determined using GIS network analysis, specifically an Origin–Destination (OD) Cost Matrix. We used the maximum speed allowed in the canals (6 km/h) to calculate the travel

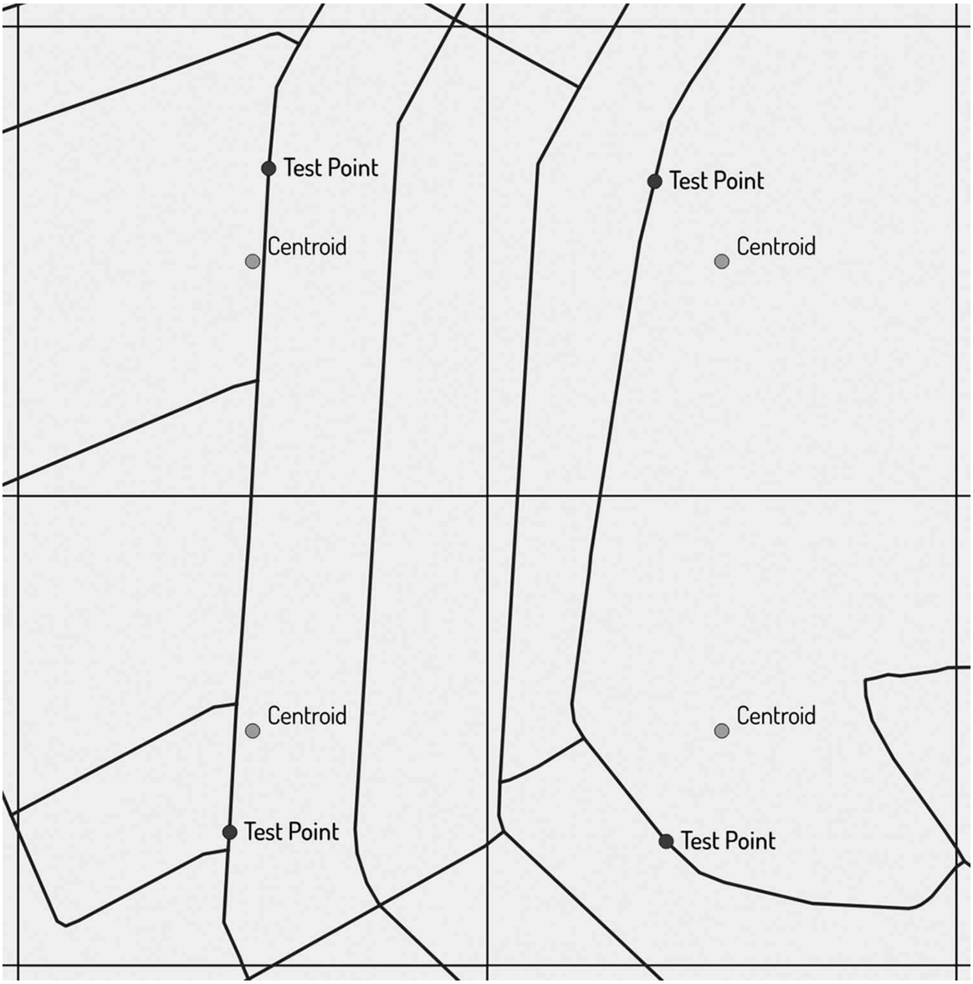

Figure 27.2 To calculate travel times that could be compared across modes, a test point was generated in GIS using the weighted center of the canal segments in each cell

Source: Chapter author(s)

time for each of these possible trips. For the cars and public transport, we developed a script that leverages the Google Distance Matrix web service, which provides travel distance and time for a matrix of origins and destinations. For public transport we used the best combination of buses, trains, trams, and subways.

Combining residents and the 271,000 commuters, daily movements comprise trips to work, shopping, visiting friends and family. We computed travel times from any communicating cell to any other cell in the canal network, for cars, bicycles, public transport, and walking. Not surprisingly for such a bicycle-friendly city, bicycles are the fastest option to almost any trip, any time of the day. Boats, even considering an average speed of 5km/h, can reach a place within a 2 km radius from the origin in less time than the public transport systems in more than half of the trips considered. Boats acquire better results in comparison with cars and public transport if the average speed increases to 10 km/h (Figures 27.3 and 27.4).

Although using boats to move around the city might not be efficient from a travel-time perspective, due to the current low speed limit of 6 km/h, there are other personal and social benefits in using boats. The benefits include reducing on-street parking spaces and decreasing traffic and related emissions, which could be particularly relevant for Amsterdam, where air quality is frequently below European Union standards.

Also, other trips, such as leisure trips, are not sensitive to travel times and thus they consider different parameters. For the 45,000 tourists that visit Amsterdam daily, the city in itself is the attraction; and whereas the routes of existing tourist boats cover, on average, 10 km of canals and only travel on the main canals, the smaller boats we propose in the Roboat project can cover 180 km of canals. Smaller boats could also give more flexibility to tourists wishing to explore farther afield.

Numbers of tourists in Amsterdam are rising rapidly. The resulting issue of congestion and its detrimental impacts on everyday life in the city dominated the mayor's 2016 "Staat van de Stad" (State of the City) address (van der Laan, 2016). A system of boats could also ease congestion in the center of the city by making it easier and more attractive for tourists to visit locations farther away. From anecdotal knowledge, we understand the public transport system in Amsterdam can be confusing for tourists, especially regarding ticket types, costs, and validity on different modes. This confusion serves as a barrier to those seeking to leave the city center —tourists and residents alike are less willing to take multimodal trips, such as a tram and then a bus, and then maybe a regional train to reach their destination. In order to quantify and study this confusion, we measured the number of transfers required to reach attractions from the city center. Here, "transfer" is defined as a switch from one mode or route of transportation to another.

Using OpenStreetMap data for points of interest (POIs), we selected out those related to tourist activities, such as museums, galleries, historic sites, and monuments. Of over 18,000 POIs in the Amsterdam metropolitan region, 4,200 are tourism-related, and over 1,400 of those are within 200 meters of the connected canal system. Then, using Google API, we calculated the number of transfers it would take to travel from the cells with the highest number of hotel beds. On average, it takes 1.1 transfers to reach those POIs within 200 m of the canal system. Autonomous boats could provide an A–B travel system that would allow both tourists and residents to circumvent this problem. While, as discussed earlier, the speed limit in the canals does not allow for fast transport, moving travel back to the canals would add another layer of experience to moving throughout, within, and outside the city of Amsterdam. In the long term, this could aid in the development of museums, galleries, and other cultural facilities outside the core zone, which in turn would diversify the concept of "cultural attraction" in

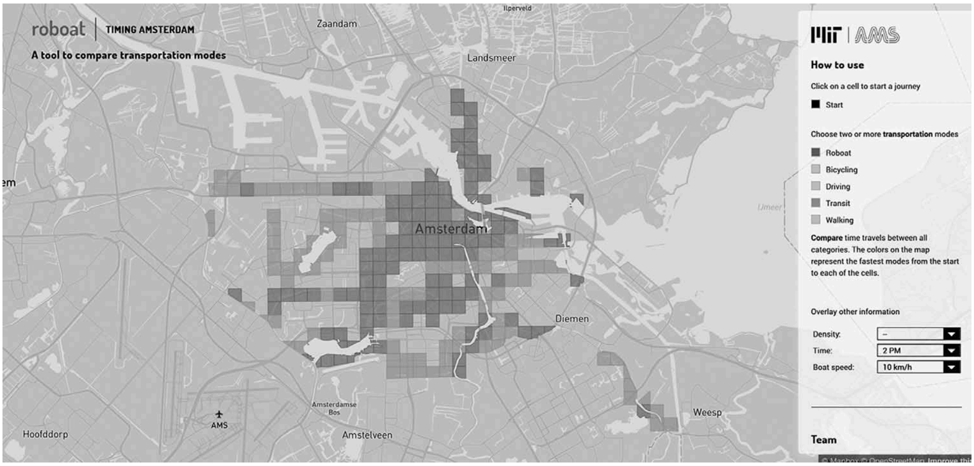

Figure 27.3 and 27.4 Travel times comparison between boats (dark grey) and transit (light grey). The color of the cell shows the best way to reach that location starting from the white cell (Figure 27.3: boat maximum speed 5 km/h. Figure 27.4: boat maximum speed 10 km/h)

Source: Chapter author(s)

Amsterdam. The results from this scientific analysis inform the design of a specific Roboat unit equipped to transport people. An initial design can be seen in Figure 27.5.

Urban services: distributing goods, removing waste

Besides transporting people, autonomous boats could eliminate at least part of the 3,500 trucks and 25,000 vans that drive into Amsterdam daily, consequently decreasing road traffic, and contributing to suit the delivery fleet to the Low Emission Zones enforced in the city center (Teekamp, 2016; Gemeente Amsterdam, 2016b). Moreover, for delivery of goods,

Figure 27.5 Taxi Roboat
Source: Rendering by Pietro Leoni, MIT Senseable City Lab

travel times are generally less sensitive than for people's transport, and rush hour can be avoided by utilizing the canals.

Amsterdam Centraal and the Food Center Amsterdam could serve as potential distribution hubs. Established in 1934 as Centrale Markt, the Food Center Amsterdam initially used canals to distribute goods to the markets and retailers (Gemeente Amsterdam Stadsdeel West, 2014). However, by 1966 those canals were filled in to facilitate the circulation of trucks and other motorized vehicles. Today, there are 70 wholesale companies who operate from the Food Center, selling fruit, vegetables, fish, and meat (Food Center Amsterdam, n.d.). There are plans underway to transform the area into Marktkwartier, a mixed-use district, in which the Food Center Amsterdam continues to be an important distribution hub.

From Amsterdam Centraal and the Food Center, all communicating cells can be reached by boat. As the main destinations, we mapped the supermarkets and restaurants (for larger and smaller deliveries, respectively). Besides these two main hubs, we performed a network analysis to define the most suitable areas along the canals to serve either as intermediate warehouses or boat depots, finding strategic points along the canals that could be developed into distribution centers. Assessing the suitability of cargo boats to supply the demand of restaurants and shops in 21 zones, which cover 2.5 square km in central Amsterdam, van Duin et al. (2014) suggest that just four freight vessels would be enough to supply the total logistic demand in this area during the summer, reducing waiting time for deliveries without interfering with touring boats and pleasure craft.

Waste collection trucks are a particular burden for cities with narrow and sinuous street networks, such as Amsterdam. In the central districts, large trucks collect garbage disposed on the curbside once a week, frequently creating traffic jams while they hoist trash onto the truck. Residents have a 12-hour window to deposit their trash in the designated locations, and face a hefty fine if they place bags in the wrong place and/or at the wrong time. In the peripheral areas of Amsterdam, trucks collect trash from underground refuse containers and bring them to the AEB incinerator. Thus, Amsterdammers have to walk about 100 meters to take their domestic trash to the nearest underground container, as shown in Figures 27.6 to 27.9.

To evaluate the potential for water trash collection we assessed how many buildings in the city were within a convenient walking distance of a canal. Firstly, we have the roads that already run along a canal. Then we took each node in the network of street lines and found the nodes that are on the canals' edge. We then evaluated the shortest walk from each node in the road network to the closest point on the canal. We then redrew these shortest walks from the start point on the canal to the end point in the city, and split the line at the 100 m mark. For the study area chosen, 48% of 37,665 buildings are within 100 m of a canal (Figure 27.10). Therefore, based on the same average walking distances of residents of other neighborhoods, approximately half of the municipal waste in the center of Amsterdam could be collected by boat. This presents some design and logistic challenges, which we have recently addressed focusing on the Centrum district in Amsterdam (Zhang et al., in submission).

Besides deploying autonomous boats as a replacement of trash trucks, the new system could reduce the hazards caused by the plastic trash bags currently left on the curbside, which include being obstacles to pedestrians, attracting pests, and dirtying the streets. Autonomy enables waste collection to operate outside of normal working hours, allows for auto-adjusting based on knowledge of the entire system, and Roboat units might become a key site for data collection on waste and consumption, data which in turn fuel other "smart" aspects of the city. As seen in Figure 27.11, this also has ramifications for the built environment in the design of the garbage modules and their connection to the canal edge. This is one key example of how the diverse experts on the team create feedback loops in the development process, with designers asking questions both formal and functional of the sensors required for autonomy, data scientists identifying optimal locations and re-running models based on feedback from roboticists and designers, and a chorus of voices working together towards the same goal.

Urban services: infrastructure

The goal in developing autonomous boat technology is to realize the potential of Amsterdam's canals to become a responsive infrastructure. As an autonomous system informed by artificial intelligence and machine learning, Roboat can respond in real time to the conditions of the city, such as the ebb and flow of rush hour traffic. Roboat platform units can join together to create temporary bridges, alleviating congestion on Amsterdam's centuries-old bridges and canal-side streets (Figure 27.12). Individual units can also tessellate together to form floating stages and public squares on the canals, a twenty-first century technology enhancing Amsterdam's strong tradition of water-based events. Rather than using autonomy to remove people

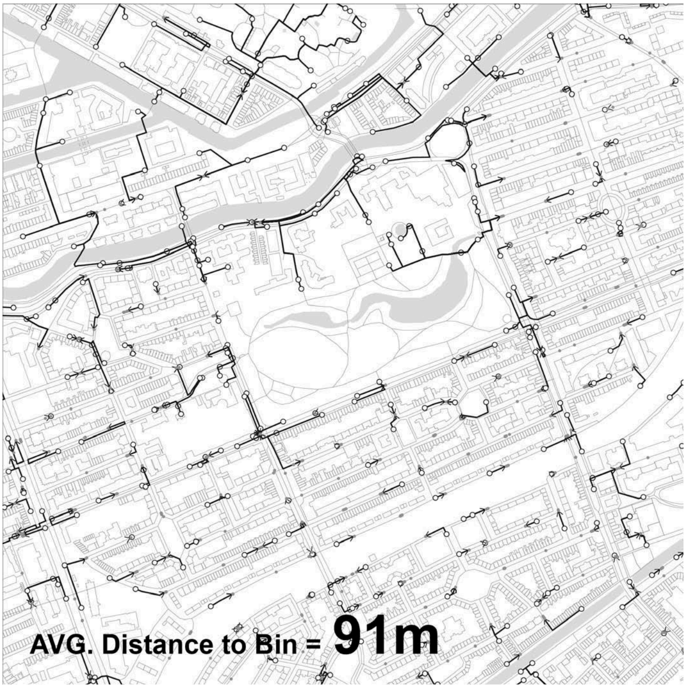

Figure 27.6 Average distance to bin: 91 m
Source: Analysis by Daniel Marshall, MIT Senseable City Lab

Figure 27.7 Average distance to bin: 120 m
Source: Analysis by Daniel Marshall, MIT Senseable City Lab

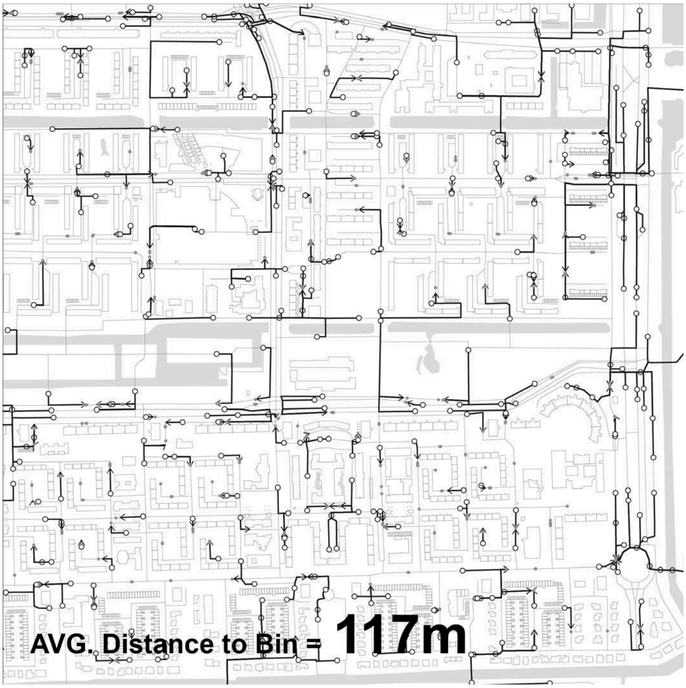

Figure 27.8 Average distance to bin: 117 m
Source: Analysis by Daniel Marshall, MIT Senseable City Lab

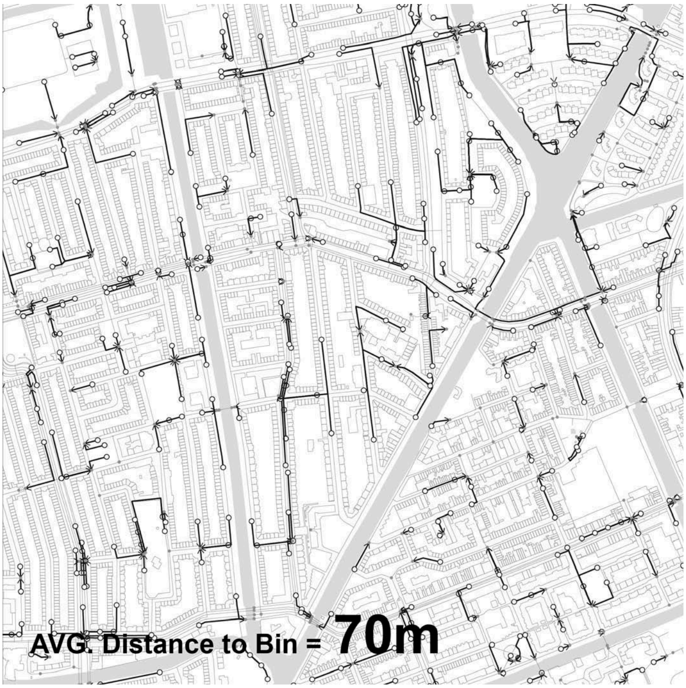

Figure 27.9 Average distance to bin: 91 m
Source: Analysis by Daniel Marshall, MIT Senseable City Lab

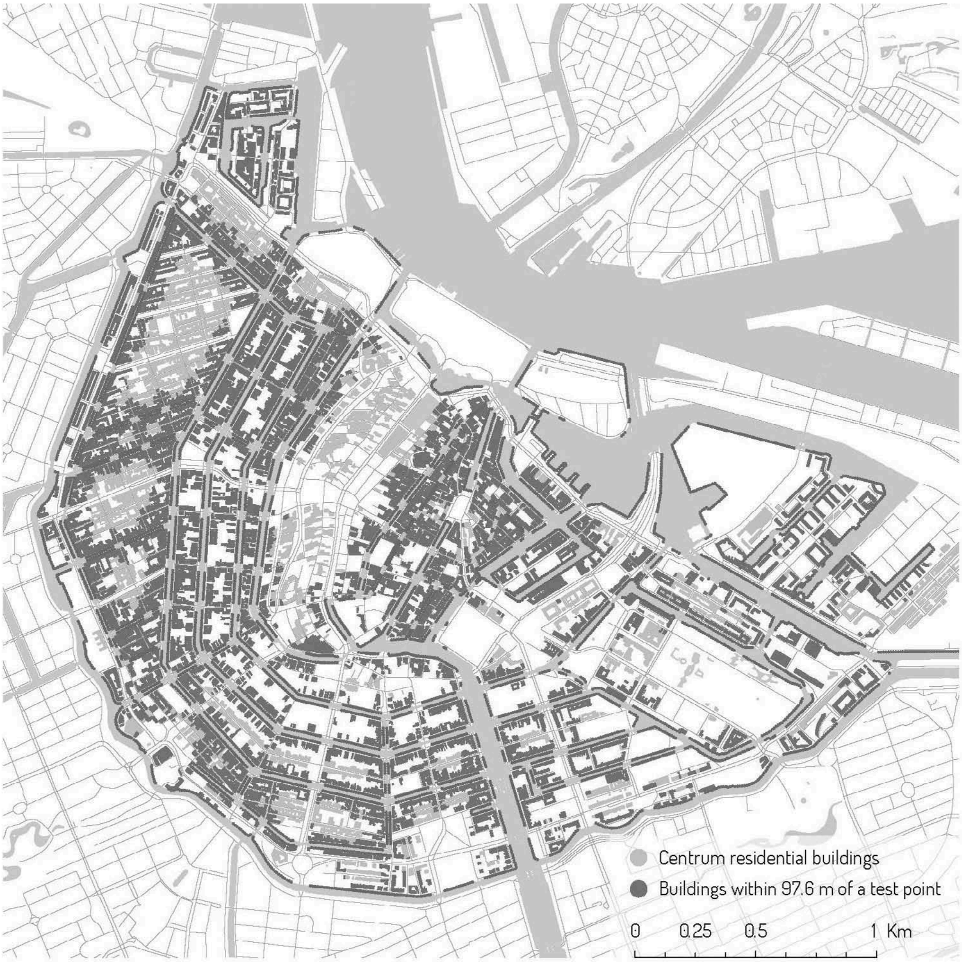

Figure 27.10 Buildings in central Amsterdam that are within a 97.6 m walk of the canal
Source: Map by Snoweria Zhang, MIT Senseable City Lab

from the system, the use of autonomous boats to create novel uses in the important urban space that is Amsterdam's canal network could bring residents and tourists together, creating new shared spaces to exchange ideas, culture, and goods while relieving pressure on roads.

For example, a typical Amsterdam market such as Plein '40–'50 with 150 stalls, it could be estimated that around 150 small vans drive, park, and supply the vendors. This has a huge cost to public space: congestion, as well as noise and CO2 pollution. With this in mind, a system of floating markets could supplement the robust network of markets already present in Amsterdam, highlighting the potential to tap into the greater region's food production. These markets could function as individual stalls, able to dynamically appear on the canal side for Amsterdammers to collect crates of fresh produce or the Roboat markets could combine together to form larger, more typical markets, on the water, as can be seen in Figure 27.13.

Figure 27.11 Roboat units designed for garbage collection can serve the residents of Amsterdam

Source: Rendering by Pietro Leoni, MIT Senseable City Lab

Figure 27.12 Roboat units can join together to create temporary bridges

Source: Rendering by Pietro Leoni, MIT Senseable City Lab

Figure 27.13 Roboat markets
Source: Rendering by Pietro Leoni, MIT Senseable City Lab

Conclusion

As layers of networks and digital information blanket urban space, new approaches to the study of the built environment are emerging. The way we describe and understand cities is being radically transformed—as are the tools we use to design them. Operating at the intersection of design and science, the Roboat project is developing and deploying autonomous boats to learn about cities. By fostering symbiotic working relationships between roboticists, engineers, data scientists, and urban designers, we seek to avoid the mistakes of smart city experts and instead ask challenging and unexpected questions of our urban environment and technology.

By outlining in this chapter our vision of how autonomous boats can transform the urban fabric of Amsterdam, a centuries-old city, we hope to show that innovation comes from an interdisciplinary approach. Over the centuries, technological innovations have changed how people move in Amsterdam, how goods are delivered and waste removed, and, in general, how the city's canals have been used as urban infrastructure. Although still structuring the urban fabric of the city, today the canals are mainly seen as a tourist attraction and used for leisure activities. Autonomy, arguably the most relevant recent breakthrough in transport technologies, can be used to regain important aspects of Amsterdam's canals.

In this chapter we have assessed the feasibility of redeploying utilitarian boats in Amsterdam, initially from a transport standpoint. We argue that balancing transport efficiency with other co-benefits, such as reducing traffic and related pollutant emissions, boats have great potential to become part of Amsterdam's transport portfolio, for both people and goods. We have discussed how Roboat might radically transform Amsterdam's urban services such as waste collection and food distribution by reclaiming the canals as functional space. And in realizing the ability of autonomous floating platforms to tessellate together, the city could gain an entirely new typology of public space. To imagine that a system of autonomous floating platforms could reinvent Amsterdam's canal system takes roboticists in conversation with historians, engineers collaborating with designers, and data scientists asking questions of planners.

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