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Roboat: 阿姆斯特丹自动船系统

ROBOAT: A FLEET OF AUTONOMOUS BOATS FOR AMSTERDAM

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摘要

历史上，在那些拥有发达的、或自然或人工河道网络的城市中，货运和客运都有赖于船舶。近几十年来，城市运输已逐渐由卡车、货车和汽车等工具承载，这一转变损害了城市的环境和宜居性。本文以荷兰阿姆斯特丹城市运河上的自动船系统为例，探索自动驾驶这一新兴技术将如何促进城市基础设施的再利用。研发团队设想通过一组自动化水上平台缓解以上问题，并使之成为一种新型城市基础设施。该计划中既涉及微观尺度的设想（向公众公开水质数据），也包括宏观尺度的宏大愿景（建立汇集了新鲜农产品的自动化平台网络，这些平台可以联合起来形成水上农夫集市）。通过应对城市日常生活中的现实问题，Roboat可成为一个帮助市民营造符合时代需求的美好城市生活的平台。

关键词

Roboat；阿姆斯特丹；水上交通；水上移动工具；智能工具；人工智能

ABSTRACT

Historically, in cities with robust systems of canals and rivers, boats were used for the movement of freight and people. In recent decades, this transport has shifted to trucks, vans, and cars, compromising the environment and livability of these cities. In this article we explore how an emerging technology, autonomous vehicles, can foster the re-appropriation of an urban infrastructure — in this case, the deployment of a fleet of autonomous boats in the city of Amsterdam, the Netherlands, which is imagined not only to serve multiple purposes, but also to become a novel urban infrastructure. The ideas range from the micro scale (public dashboards for water quality data) to the macro (a network of autonomous platforms that collect fresh produce from farms and combine together to form floating farmer's markets). These ideas seek to engage the realities of everyday life in the city and propose Roboat as a platform to help citizens negotiate the 21st century urban life.

KEY WORDS

Roboat; Amsterdam; Water Transportation; Floating Vehicle; Intelligence Tool; Artificial Intelligence

翻译 田晓劼 田乐
TRANSLATED BY TIAN Xiaojie Tina TIAN

1 研究背景

Roboat是美国麻省理工学院感知城市实验室的一个研究计划，旨在探究自动浮船在提升城市服务方面的潜力。通过联合麻省理工学院计算机科学与人工智能实验室和土木环境工程系，以及来自代尔夫特理工大学、瓦格宁根大学及阿姆斯特丹高级大都会研究中心的相关人员，Roboat研发团队旨在突破自动机器技术在城市水环境中的应用局限。

在阿姆斯特丹繁忙的运河中开展自动船项目会遇到感知、动线规划与障碍规避、轨迹规划预判，以及多船协调等诸多挑战。Roboat船体上配备有多种传感器［包括激光雷达、惯性测量装置（IMU）、RGB三通道彩色成像摄像头］、无线路由器和适配器、电池、计算机、微控制器，以及通过机器人操作系统（ROS）的中间运行软件。

激光雷达与拍摄技术的结合可以（通过激光雷达技术）测量船体与物体之间的距离，并（通过具有计算机视觉算法的相机）对这些物

体进行标记。感知技术使得Roboat在航行时能够探测到其他船只和障碍物的信息并反馈至Roboat导航系统，使得该系统可以基于非线性模型预测控制器（NMPC）实时计算出最佳行驶路径，以避免与既有障碍物发生碰撞。除此之外，NMPC还会对船只行进的基准轨道、动态及推力进行综合评估。最后，由于该计划的目标之一是以Roboat为单元创建临时性城市基础设施，因此需要Roboat具备自组装能力，而这需要来自通信、传感和网络等方面的技术支持。在水上设备研究领域，Roboat所具有的变形能力将是具有重要价值的开创性进展。

历史上，在那些拥有发达的、或自然或人工河道网络的城市中，货运和客运都有赖于船舶。近几十年来，城市运输已逐渐由卡车、货车和汽车等工具承载，这一转变损害了城市的环境和宜居性。本文以荷兰阿姆斯特丹城市运河上的自动船系统为例，探索自动驾驶这一新兴技术将如何促进城市基础设施的再利用。作为世界上拥有最大规模运河网络的城市之一，阿姆斯特丹长达数百公里的运河不仅塑造了其城市肌理，也为缓解城市道路交通及陆地运输压力、振兴阿姆斯特丹的水路运输传统提供了独特机遇。

目前，阿姆斯特丹运河上多为休闲观光游船。依照相关规定，截至2025年，运河游船必须实现零碳排放；在未来几年内，所有船只必须由柴油发动机驱动转变为电力驱动，从而实现削减70%温室气体排放的目标。自2017年以来，阿姆斯特丹运河游船一直执行6km/h的最高时速，且中心运河区可通行船只的宽度和长度分别不得超过4.25m和20m。从2018年开始，所有进入市区的船只都必须经过射频识别（RFID）进行登记，以对水上交通状况进行更有效的监控。这些举措都将有助于降低运河沿岸居民接触到污染物的风险[1]。

尽管阿姆斯特丹是欧洲最适宜骑行且人均汽车保有量最低的城市之一（“阿姆斯特丹温度计”的调查结果显示，平均每3.65个阿姆斯特丹市民拥有一辆汽车[2]），但其交通状况和尾气排放问题仍然令人担忧。除了阿姆斯特丹85万居民的日常出行外，该市的交通系统平均每天还需运载271 000名通勤人员[3]和45 000名游客——所有这些都借助地下和地面交通工具（包括2 300辆出租车）运载[2]。

此外，往返于阿姆斯特丹市中心40 000个货物配送服务站点的货运运输频次可达20 000次/日。80%的装卸工作都在阿姆斯特丹狭窄曲折的街道中完成，这也进一步阻塞了当地交通[4]。

城市货运的另一个压力来自互联网购物和送货上门服务的迅速普及。在荷兰，超过80%的商品可被直接送货上门[5]。1998~2011年间，荷兰每年的家庭网购消费从4 100万欧元激增至90亿欧元，网购所占市场份额从2005年的2.8%增长至2011年的10%[6]。有人认为送货上门对于交通量不构成影响，因为送货车辆的增加可以与前往实体商店购物车辆的减少相抵消；然而，住宅区货运量的增加会加剧当地的污染。

上述这些问题使得重新启用运河这一既有基础设施被提上了议题。荷兰是水路货运率最高的欧洲国家，水路运输份额为47%，已大致和公路运输相当[7]。然而，阿姆斯特丹运河的货运业在过去很长一段时间内都处于没落状态，直到1997年DHL快递公司开通水上货物运输。如今，快递船只被当作“配送中心”，包裹的收集和分发通过自行车完成[8]。2010年，Mokum Mariteam水上货运配送公司开始在阿姆斯特丹运营其第一艘电动货船，并利用水路将货物运送至各个商店[9]。J·

1. 阿姆斯特丹城市景观

1. View of Amsterdam

1 © MIT and AMS Institute

H·R·凡·杜因等人[4]对能够满足阿姆斯特丹市中心21个区域（总占地面积2.5km^2）内餐厅和商店的供货需求的船只数量进行了估算，结果表明，在交付货物时不干扰观光游船的情况下，仅需要4艘货船便可满足这些区域夏季的总物流需求。

研发团队设想通过一组自动化水上平台缓解以上问题，并使之成为一种新型城市基础设施。该计划中既涉及微观尺度的设想（向公众公开水质数据），也包括宏观尺度的宏大愿景（建立汇集了新鲜农产品的自动化平台网络，这些平台可以联合起来形成水上农夫集市）。通过应对城市日常生活中的现实问题，Roboat可成为一个帮助市民营造符合时代需求的美好城市生活的平台。

2 Roboat：城市领航者

该计划试图将Roboat单元用作自动化水上出租车或公共汽车，并为游客和当地居民带来全新的体验。每一个Roboat单元都可以作为可租赁的交通工具，用于有明确目的地的出行或作为陆上交通拥堵时的替代选择。这一自动化出行系统有望缓解市中心以外地区的公共交通换乘压力。通过这一水上平台，游客不仅能够近距离感受运河的魅力，而且能方便地抵达较为冷门的博物馆和景点。Roboat还可变身为拖船，为现有的私人船只提供按需搭载服务，使更多的当地居民可以享受水上休闲时光。居民们也可将私人船只停泊在城外，再根据需要随时租用Roboat。

此外，Roboat单元可联结起来形成临时桥梁，以缓解阿姆斯特丹拥有悠久历史的桥梁和沿河街道的拥堵情况。Roboat自动化系统可以实时响应高峰时段的交通流量变化。此外，Roboat单元还可以在运河上联结为水上舞台及公共广场，以重拾阿姆斯特丹的水上活动传统。随着当地居民和游客对运河重新加以利用，这一技术可以构建一种新型城市公共生活的新范式。

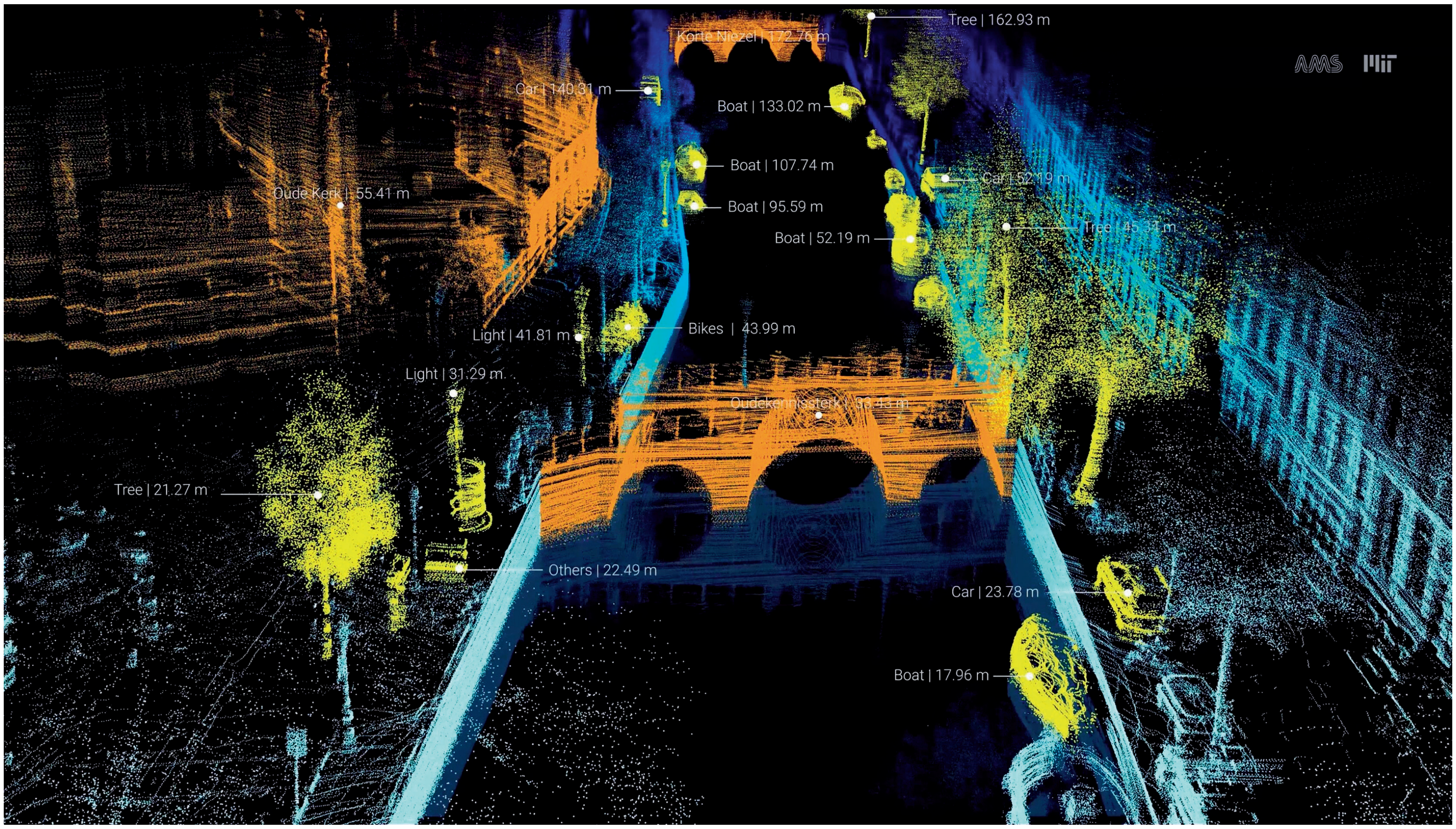
不仅如此，Roboat还可用于解决其他城市基本问题，例如垃圾收集。在阿姆斯特丹中心区，由于当地居民通常将垃圾堆放在路边等待收集，因此这一区域被选为该计划的一处试点。Roboat作为可自动转移垃圾的水上垃圾箱，解决了历史街区中大型垃圾车带来的诸多问题——拥堵、污染、噪音等——服务范围覆盖近70%的试点区域。

研发团队又将视角拓展到阿姆斯特丹周边地区，探索了以Roboat单元构建水上食品市集或快闪式摊位的可行性。这些沿河分布的摊位便于当地居民采购新鲜的农产品。这一尝试的推广将为阿姆斯特丹增加

2 © MIT and AMS Institute

2. 阿姆斯特丹城市鸟瞰激光雷达探测图（2017年）。阿姆斯特丹作为世界上拥有最大规模运河网络的城市之一，长达数百公里的运河形成了其城市肌理。
3. 阿姆斯特丹运河及桥梁激光雷达探测图（2017年）

2. LiDAR aerial scanning of Amsterdam, 2017. With one of the most extensive canal networks in the world, Amsterdam enjoys hundreds of kilometers of canals that are the formative structure of the city.
3. LiDAR scanning of Amsterdam's canals and bridges, 2017.

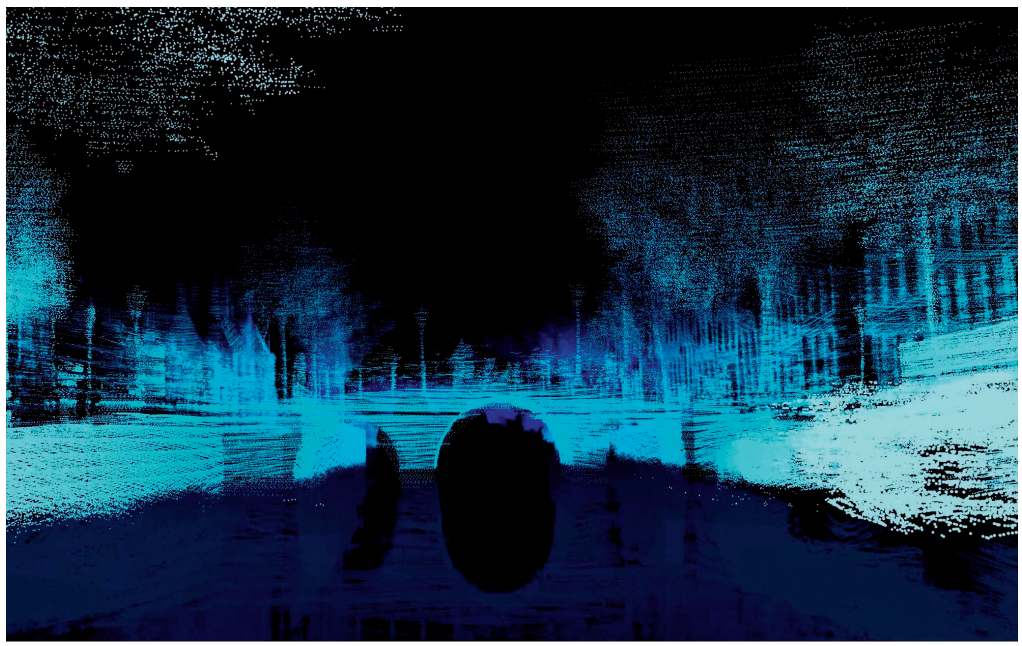


3-1

一系列可用作水上市集的城市公共空间。通过不断挖掘城市水网中的各种潜在资源，Roboat可使运河再次焕发活力。

在上述设想中，Roboat既是一个多功能船体，也可以成为不同使用场景的载体。为了将这些设想转变为现实，研发团队需对其进行专门的设计和定制。其中，设计垃圾收集模块的主要挑战在于如何使每个Roboat单元的垃圾容纳量最大化，同时将每个模块的重量和机械复杂度降至最低。确保该模块能够在各种河道条件下通行并能够灵活投递各种垃圾袋是研发成功的关键，也是计划推进的重点。Roboat基本单元需要能够在运河网络中的任意空间——即使是非常局促的空间——进行移动且避免与障碍物发生碰撞，同时还能够实现单元间或单元与外部结构的对接。与此同时，研发团队正在开发一款万向移动装置，其可以在任何时间、向任何方向实现轻松移动，并可以现场进行操作。在原型研发过程中，研发团队还对船体设计、推进装置、空间单元、系统模块化，以及可重构性等问题进行了考量[10]。

Roboat不仅是一个模块化搭载系统，通过将自动化技术和传感器相



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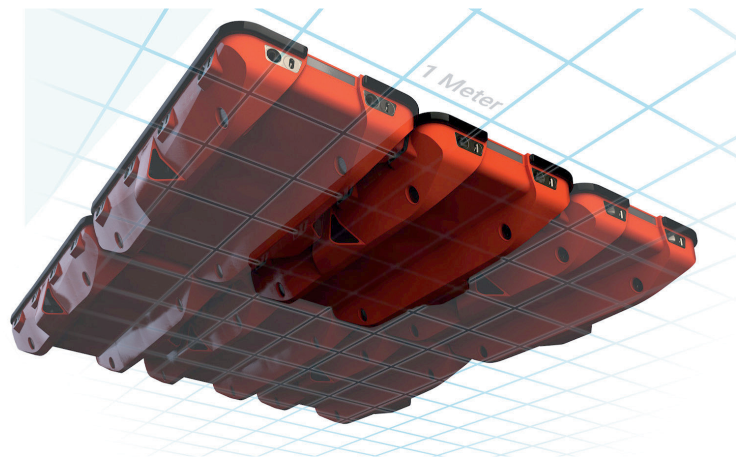

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4-2

结合，其还可以成为城市中的新型可移动传感平台。Roboat可以在各种环境条件下对水质、空气质量，以及气候条件等进行监测。与传统的静态监测点相比，可移动的Roboat能够以更高的空间分辨率收集环境数据。依据这些数据，当地政策制定者能够优化环境和公共卫生方面的决策。

Roboat是一个人工智能驱动的城市基础设施平台。通过不断研发相关技术，Roboat能够缓解人类与环境之间的冲突，并辅助人类运营越来越复杂的城市环境。

3 结语

人类与任何技术之间的关系都是一个复杂的交互模型。在道路交通系统中，这种关系是指人类驾驶员需要时刻关注交通路况，遵循社会共同制定的交通规则，并根据其他车辆和行人的情况及时做出响应。随着时间的推移，驾驶员在各种交互中逐渐积累驾驶经验。这些复杂的相互作用不仅存在于过去人类与马车、现在人类与机动车之间，随着自动驾驶车辆的普及以及其与城市中无数传感器逐步建立起密切的互动关系，人与技术之间的交互关系也将变得愈加复杂[11]。因此，人类与非人类事物（马车、机动车等）之间的关系是交通系统中的永恒议题，其中控制系统将发挥越来越重要的作用。

通过研发一套自动化系统，Roboat计划不仅解决了一系列技术挑战，并且重塑了人类、技术及城市之间的关系。通过介入阿姆斯特丹运河复杂而充满活力的水环境，Roboat实现了高科技与人类创造力的结合。**LAF**

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1 Research Background

The Senseable City Lab's Roboat investigates the potential of autonomous floating vessels to revolutionize urban services. Together with Massachusetts Institute of Technology (MIT)'s Computer Science and Artificial Intelligence Lab and Department Civil and Environmental Engineering, and researchers from Delft University of Technology (TU Delft) and Wageningen University, also of the Amsterdam Institute for Advanced Metropolitan Solutions, Roboat is a research project designed to push the limits of autonomy in urban aquatic environments.

There are several challenges in deploying an autonomous boat that navigates in the busy canals of Amsterdam, including perception, motion planning and obstacle avoidance, predictive trajectory planning, and multi-vessel coordination. Roboat is outfitted with several sensors [LiDAR, Inertial Measurement Unit (IMU), and RGB camera], WiFi router and adapter, battery, computer, microcontrollers, and its software operates using Robotics Operating System (ROS) middleware.

LiDAR and camera technologies are coupled to measure the distance to objects (Lidar) and label such objects (cameras with computer-vision algorithms). Perception technologies enable the boat to avoid other boats and obstacles while navigating. This information feeds the Roboat navigation system, which can plan its path to avoid collision with known obstacles by calculating the optimal obstacle-free path in real time based on a Non-linear Model Predictive Controller (NMPC). The NMPC considers the reference trajectory, dynamics, and thruster forces of the boat. Finally, since one of the goals of the project is to create temporary urban infrastructures with Roboat units, they are required to self-assemble, which requires communication, sensing, and networking technologies. Developing shape-shifting capabilities for boats is of particular interest, since there is no prior research in shapeshifting on water.

Historically, in cities with robust systems of canals and rivers, boats were used for the movement of freight and people. In recent decades, this transport has shifted to trucks, vans, and cars, compromising the environment and livability of these cities. In this chapter we explore how an emerging technology, autonomous vehicles, can foster the re-appropriation of an urban infrastructure — in this case, the deployment of a fleet of autonomous boats in the city of Amsterdam, the Netherlands, where hundreds of kilometers of canals are the formative structure of the city. With one of the most extensive canal networks in the world, Amsterdam

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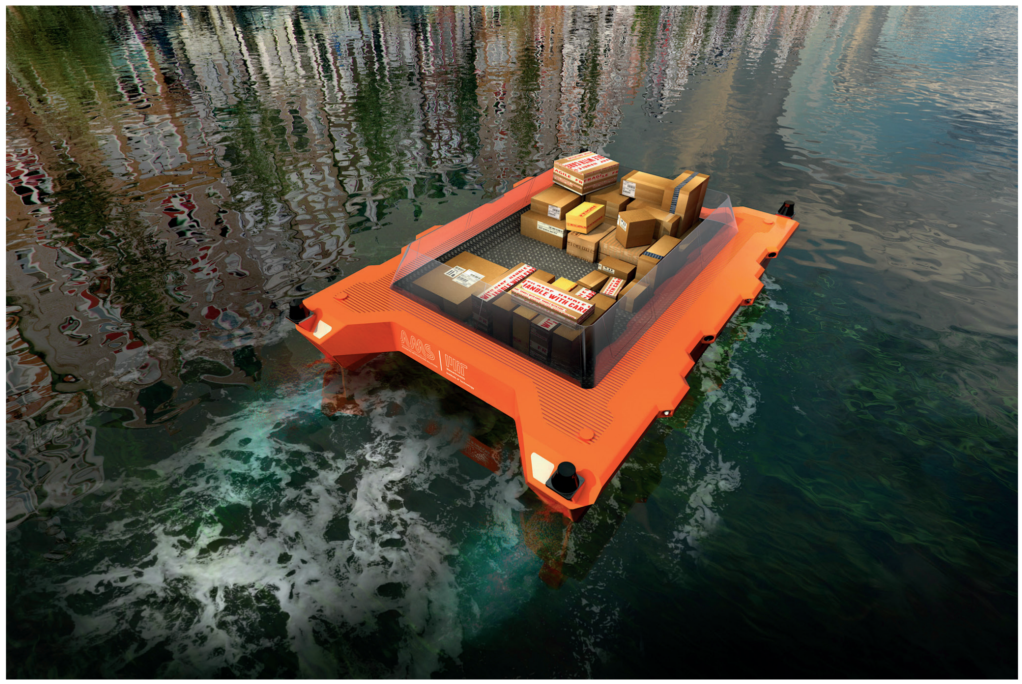

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4-1. Roboat单元模型
4-2. Roboat单元拼合
5. 由Roboat单元构成的桥梁
6. Roboat可用于货物运送

4-1. Roboat unit
4-2. Modular composition
5. Bridge made of Roboat units
6. Goods delivery

7 © MIT and AMS Institute

7. Roboat可用于小型运输
8. Roboat可用于公共运输或作为水上出租车
9. 由单一Roboat单元构成的小型水上集市

7. Roboat as small-group transport
8. Roboat as public transport / taxi
9. Floating markets in single Roboat units

has the unique opportunity to reclaim the canals for moving people and goods, rather than keep saturating its road system and ground transport.

Currently, the canals are mostly used by leisure and tourist boats. By 2025, canal cruise boats must produce zero emission, and in the next few years all boats must be electricity powered — which will contribute to the goal of having a reduction of 70% greenhouse-gas emissions compared to the boats powered by truck diesel engines. Since 2017, the city of Amsterdam enforces a maximum speed of 6 km/h in the canals, and the maximum size of boats in the central canals is 4.25 meters wide and 20 meters long. From 2018, the use of Radio-Frequency Identification (RFID) is mandatory for all boats entering the city, which allows a better monitoring of the boat traffic. These measures would help address the current exposure to pollutants to the significant population residing close to Amsterdam's canals[1].

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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 Amsterdamse Thermometer[2]), traffic and related emissions are still a concern. In addition to resident traffic for a total population of 850,000, the city receives 271,000 commuters daily[3] and an average of 45,000 tourists — all using underground and ground transport (including 2,300 taxis) to move around[2].

In addition, the transport of goods contributes 20,000 freight trips daily to 40,000 delivery and service points in Amsterdam's city center. Furthermore, 80% of the loading and unloading process happens on Amsterdam's narrow and sinuous streets, impeding the general flow of traffic[4].

Another pressure on urban freight is the accelerating phenomenon of online shopping and home delivery. In the Netherlands, more than 80% of goods can be delivered directly to homes[5]. From 1998 to 2011, the annual home market for Internet shopping in the Netherlands grew from 41 million euros to 9 billion euros, and went from a 2.8% market share in 2005 to 10% in 2011[6]. One could argue that home delivery does not have an impact on the general traffic because the increased number of freight vehicles on the roads is balanced by fewer individual trips to shops; however, increasing freight traffic in residential areas can aggravate local pollution.

This is a clear opportunity to utilize existing infrastructure: the canals. The Netherlands already has the highest waterborne freight transport rate in Europe, transporting 47% of the freight share — similar to the road transport[7]. 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[8]. In 2010, Mokum Mariteam started operating its first electric freight vessel in the city, using the waterways to deliver goods to shops[9]. J. H. R. van Duin et al.[4] have assessed the suitability of cargo boats to supply the demand of restaurants

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10. 由多个Roboat单元拼接而成的水上集市
11. 水上垃圾箱

10. Floating markets
11. Floating dumpster

and shops in 21 zones, which covered 2.5 km^2 in central Amsterdam. Their results 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 crafts.

We imagine the potential of a fleet of autonomous floating platforms not only to serve these purposes, but also to become a novel urban infrastructure. The ideas range from the micro scale (public dashboards for water quality data) to the macro (a network of autonomous platforms that collect fresh produce from farms and can be combined together to form floating farmer's markets). These ideas seek to engage the realities of everyday life in the city and propose Roboat as a platform to help citizens negotiate 21st century urban life.

2 Roboat as a City Navigator

We imagine that Roboat units can be autonomous water taxis or buses, adding to the experience of both tourists and locals. Individual units could be hired for specific trips, or routes could be developed along the canals to ease congestion. We posit that a system of autonomous taxis could help alleviate the concentration of tourists in Amsterdam by reducing the major barriers to travel outside of the central district interchanges on public transport. By establishing a platform that enables visitors to the city to both experience the canals from a first-person perspective and to reach less-visited museums and attractions. Leisure, however, is not an activity limited to tourists — by leveraging a Roboat as a tugboat, existing private boats can enjoy an on-demand transportation service. This system would allow individuals to moor their boats outside the city and request it on demand.

Platform Roboat units can join together to create temporary bridges, alleviating congestion on Amsterdam's centuries-old bridges and canal-side streets. As an autonomous system, Roboat can respond in real time to the ebb and flow of rush hour traffic. Individual units can also be tessellated to form floating stages and public squares on the canals, enhancing Amsterdam's strong tradition of water-based events with a 21st-century technology. We imagine that this technology, in the hands of citizens and visitors, can create new ways of public life in the city as the waterscape is reclaimed for use.

Roboat can be used to solve other fundamental urban issues such as trash collection. The central district of Amsterdam, where residents currently deposit trash on the curb for collection, is one potential site for this use case. To alleviate the many problems caused by large trash trucks on historic streets — congestion, pollution, noise, etc. — Roboat can serve as floating dumpsters that autonomously transfer waste, serving nearly 70% of the central district.

Looking more broadly to the area surrounding Amsterdam, we investigated the potential of Roboat units to form floating food markets or become pop-up stalls that appear on the canal's edge for citizens to collect crates of fresh produce. We imagine the use of autonomous boats could create new public spaces for floating food markets in Amsterdam. Roboat can activate the canals while tapping into the resources located on the pervasive regional network of waterways.

In order to accomplish these use cases, Roboat, both as a multifunctional vessel and a series of use-case specific shells, needs to be imagined, engineered, and manufactured. One of the main design concerns in designing the garbage module is the maximization of the volume of trash one unit could hold while minimizing the weight and mechanical complexity of each module. Ensuring the ability to negotiate varied edge conditions, as well as accommodating varying physical abilities to throw trash bags is key to the success of the use case and is vital in driving the project forward. The basic unit needs to be able to move independently within the entire canal network, even in very restricted spaces, to dock with each other or to external structures, and to avoid any obstacles. We are developing an omnidirectional vehicle, which is able to move at any time in any direction with ease while also performing operational maneuvers on site. In developing prototypes, the team considered the following themes: hull design, propulsion system, dimensional units, system modularity, and reconfigurability.[10]

Roboat is not merely a system of modular vessels, however, its autonomy and sensor package mean that it can become a new mobile sensing platform for the city. Roboat can collect mobile measurements on a variety of environmental conditions, including but not limited to water quality, air quality, and weather conditions. Roboat's mobility allows us to collect environmental conditions at a much finer spatial resolution compared to traditional stationary monitoring sites. The new information provided by Roboat will enable local policy makers to make better data-driven decisions on environmental and public health issues.

Roboat, as an AI-powered urban infrastructure and platform, continues the progress of technologies diminishing the friction between humans and non-humans in order to help humans navigate complex environments such as our cities.

3 Conclusion

The relationship between a human and any technology is a complex interactive model. On road-based transportation systems, this relationship requires that the human driver reads the surrounding traffic, follows socially-established road rules, and makes decisions to maneuver his way through traffic with other vehicles and pedestrians — over time, learning from each other's behavior and experiences. These complex interactions happen today with motorized vehicles, as well as previously with horse-based carriages, and will be even more complex with autonomous mobility and a high interdependency between the vehicles and the myriad sensors embedded in the city[11]. Thus, the relationships between humans and non-humans are a constant in mobility systems, in which control systems play an increasing important role.

Roboat addresses both the technological challenges (by developing an autonomous system) as well as the relations between humans, technology, and the city. By focusing on the complex and lively aquatic environment of Amsterdam's canals, Roboat leverages a combination of high technology and human creativity. **LAF**

PROJECT INFORMATION

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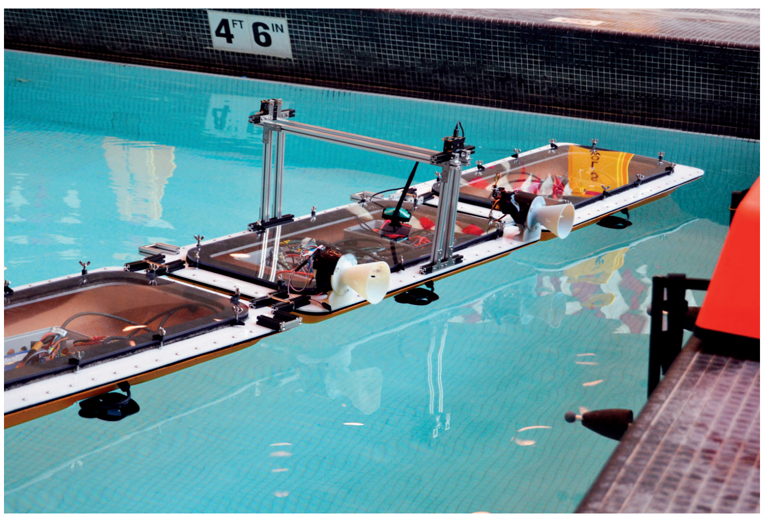

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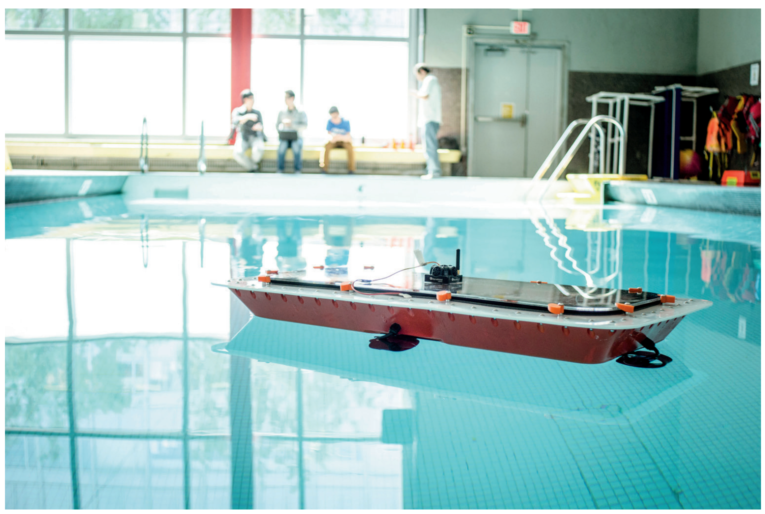

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13. 在2号游泳池内进行的室内测试
14. 在阿姆斯特丹进行的连锁Roboat单元户外测试
15. 在东京进行的单个Roboat单元户外测试
16. 研究人员在检测Roboat的运行效果

12. Test in the swimming pool 1
13. Test in the swimming pool 2
14. Test of latching Roboat units in Amsterdam
15. Test of single Roboat units in Tokyo
16. Researchers testing and reviewing Roboat's performance

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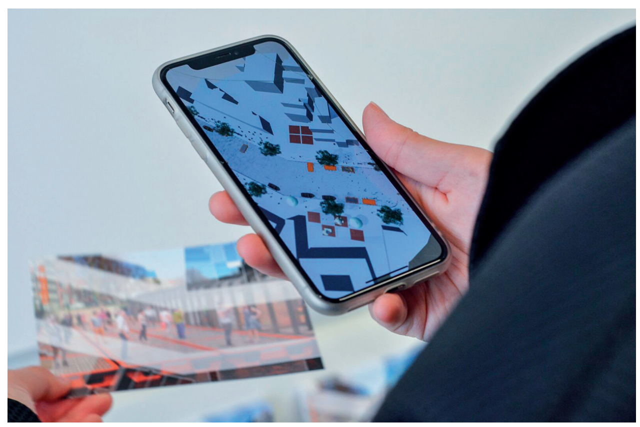

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