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Autonomous Grocery Delivery Service in Urban Areas

Mihai Kocsis
Heilbronn University
(Automotive Systems Engineering)
Universitatea TRANSILVANIA
(Faculty of Mechanical Engineering)
Heilbronn Germany
mihai.kocsis@hs-heilbronn.de

Johannes Buyer, Nico Sußmann
Heilbronn University
(Automotive Systems Engineering)

Heilbronn Germany
johannes.buyer@hs-heilbronn.de
nico.sussmann@hs –heilbronn.de

Raoul Zöllner
Heilbronn University
(Automotive Systems Engineering)

Heilbronn Germany
zoellner@hs-heilbronn.de

Gheorghe Mogan
Universitatea TRANSILVANIA
(Faculty of Mechanical Engineering)

Brasov Romania
mogan@unitbv.ro

***Abstract*—In big cities around the world air pollution is reaching harmful levels. One of the reasons for air contamination is the automotive emissions. Soft appeals by the authorities to the citizens did not change much of the situation. Many people use the car in everyday activities, e.g. going to work or every day food shopping in supermarkets. Recent studies showed that a replacement of the current vehicles through autonomous vehicles would help in reducing these emissions. A radical replacement is not possible. The actual infrastructure needs to be extended by technologies that facilitate autonomous driving. Therefor integration of knowhow from other domains like internet of things, big data analysis or transportation planning has to be considered. This paper presents a smart service where, based on the information provided by principals of industry 4.0 and internet of things, the planning of an autonomous grocery delivery fleet occurs. This service is implemented then at a smaller scale, as an autonomous ordering and delivery system for coffees, and realised at the Heilbronn University. Furthermore, the paper presents the benefits and the limitations of this kind of system.**

Keywords—autonomous electric vehicles, automotive emission reduction, sustainability

I. Introduction

Climate protection is a key challenge for building sustainable societies. Due to the economic upturn and higher incomes, the amount of vehicles used from the citizens for mobility purposes increased a lot during the past years. This led to an alarming increase of fine dust load. In big cities, air pollution is reaching harmful levels many days a year. A modality to decrease the amount of time people use their vehicles is to provide services that replace activities where, in order to complete them, a car is often required. An example of such a service is the delivery of groceries. In this way, a certain number of people that go individually for shopping using their personal car might be supplied by one vehicle in one course. For an optimal supply, a good route planning is needed. In order to make the delivery more flexible and cheaper the delivery vehicle could be an autonomous one.

In the last years many projects regarding the extension of the existing infrastructure towards autonomous driving, internet of things, industry 4.0 and cloud computing have emerged. Recently in the U.S., "the U.S. Department of Energy (DOE) on December 21 announced $15 million, subject to appropriations, to support community-based projects to accelerate the adoption of advanced and alternative fuel vehicles and demonstrate energy efficient mobility systems including connected and autonomous vehicles as well as new transportation system models"[29]. In the EU, other projects regarding connected automated driving are on role [30]. In Asia, the first summit for strategies and regulatory roadmaps for commercializing autonomous vehicles took place earlier this year [31]. There is no doubt that autonomous vehicles will play a key role on the market in the following years.

In order to transform cities into smart, sustainable cites the knowhow from many different domains has to come together. Some predictions go even further and introduce concepts like "internet of everything" or "internet of anything" [33]. In this prediction up to 50 billion objects will be connected to the internet.

In this paper, we present a service where these areas come together. Intelligent household appliances (e.g. a fridge) figure out the needs of certain products and then automatically order these products. The suppliers of these products (e.g. supermarkets) process the orders and plan the loading and routes for the autonomous vehicles used to deliver the products. In the route planning, time intervals, where the customer is available, would be considered. The work is preliminary to a research project, where, by the year 2019, several autonomous vehicles will perform tasks in a new build district in Heilbronn [47].

The outline of the paper is as follows: Section II presents a description regarding automotive emissions in big cities and a brief state of the art regarding autonomous cars in urban areas. In section III the concept and model for the automated delivery system is presented. Section IV describes the implementation of such a system at Heilbronn University where an autonomous golf cart is able to deliver coffees for the employees. This system is then tested and validated in Section V. Section VI depicts the results of a survey regarding the acceptance of autonomous delivery systems. We conclude and summarize in section VII.

II. Related Work

In the first part this chapter presents the problem of automotive emissions in big cities and follows with a short state of the

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art regarding the actual use of autonomous vehicles inside urban areas and an insight in the existing methods for vehicle routing and planning.

A. Automotive emissions in big "car cities"

Recent studies showed that outdoor air pollution kills more than 3.3 million people every year worldwide [23]. Coarse dust particles between 10 and 2.5 micrometres in diameter (PM10) recorded on sensors installed in big intersections, e.g. B14 in Stuttgart often hit around 200 micrograms per cubic meter while the European Union standards set the top limit of safe PM10 levels at 50 micrograms per cubic meter. According to Dr. Ulirch Vogt, head of Department of Air Quality Control, at Stuttgart University: "Combustion residues, mainly from diesel engines, as well as the abrasion of brakes and tyres, are the main reasons for these high PM10 values"[21]. The measurements taken by the authorities like truck transit bans in 2008 or introducing the concept of "fine particle matter alarm" in 2016, where residents are asked to stop using their personal cars and use the public transportation system, offering them tickets at half of the price, did not show much improvement [22]. Similar or even worse situations are in cities like Rome, Paris, Amsterdam, London, Calgary, New City, Los Angeles, New York, Bangkok, Beijing and many others. Harder measurements like a total diesel and gasoline car ban in the cities is also in discussion for the future [20], but it is hard to believe that these measurements will be actually introduced. Other sustainable solutions are required to solve these problems.

B. Autonomous vehicles in urban areas

Since 2007, starting with the DARPA challenge [4] a revolution regarding autonomous driving in urban areas has taken place. In less than ten years, autonomous cars have become part of the city life in places like Singapore [3] or California [2]. Following Google [12] and Apple, other big car manufacturers are working to release their first self-driving car [9], [10] and [11]. The field of autonomous driving has widened also in other areas, like public people transportation vehicles [8], [13], commercial vehicles [14] or service on demand [28].

Many benefits can be achieved using autonomous vehicles: reduce the number of traffic accidents, better integration of private and public transportation systems, various products distribution, help elderly live on their own much longer or reduce costs by using car sharing [17].

Recent studies [15], [16] reveal that electric autonomous vehicles can also help reduce pollution. Therefore, these vehicles have to be electric and an intelligent planning system is needed, in order to avoid congestions and reduce the travel distances for commercial vehicles.

Public authorities and governments already understood the significant benefits of autonomous vehicles. They offer financial support to industry and university stakeholders to develop the required technology, adapt the traffic legislation and improve infrastructure with technological components needed for the deployment of autonomous vehicles (e.g. [18] and [19]).

For the launch of autonomous vehicles, infrastructure components have to be extended with intelligent sensor systems, big amount of data from these sensors have to be stored and analysed and real time context-aware computation is necessary for planning and control. Communication systems between infrastructure and vehicle (Car2X) and vehicle-to-vehicle (V2V) have to be fast and secure. Communication with other components that are indirectly involved in the autonomous driving is also important. Therefore, appliance and further development of software engineering patterns for distributed systems is required. A possibility of sharing this information and perform integrated traffic management is presented in [32], where the concept of "internet of vehicles" is introduced. An architecture that incorporates the city infrastructure with humans, logistics, services, transportation system as well as utility and energy systems and the services provided through the computational systems that works with big data gathered by sensors systems, is strongly recommended. A reference architecture that combines all these elements is presented in [34]. In [35] an architecture based on orientated services is described by the same authors.

C. Vehicle planning methods

In order to have maximum efficiency in using autonomous vehicles to provide a certain service, an adequate planning method is required that depends on the number of used vehicles and the type of service that is provided. If there is only one vehicle involved, we speak about a typical travelling salesman problem. If more vehicles are involved, we will have a vehicle routing problem. In [36] some of the most common algorithms used for route planning in smart cities are described: Dijkstra [37], A* [38], tabu search [39], ANT based colony [40], genetic algorithms or hybrid genetic algorithms [41]. In choosing the adequate algorithm, the qantities travel time, travel distance and travel cost have to be considered. The algorithm gets as input the map, the vehicles characteristics, the current traffic conditions and the traffic predictions. The output of the algorithm is the calculated best route. During navigation, incidents on this route can change the path of the vehicles. To optimize the task processing and to reach the optimization objective Workload Resource Minimization (WRM), Smart Task Assignment (STA) or Task Mapping Algorithms might be used [46].

D. Conclusion

There are several architecture concepts for smart cities that are described in the literature (e.g. [35]). In order to make a city smart, a span between domains like utilities, communications, government, transport, emergency services and retail is needed. We propose a concrete service concept, which could be a part of the presented architecture. For the implementation of this service, communication between the different domains smart clients, supermarket servers, banking servers, autonomous vehicles and infrastructure is required.

III. Service Concept

The service concept we propose refers to an automated delivery system for grocery. A smart fridge figures out when grocery is running out and sends this information to the supermarket where the customer is buying these products. The supermarket server knows the address of the customers. Having more customers living near to each other, the server makes a plan for a delivery vehicle. In this plan, the date and times when the customer is reachable is also known. Users via a web-based application can also do the orders manually. Furthermore, the server has to take care of the secure money transfers.

Since a continuous delivery is in the majority of the cases not possible, waiting times will occur. The planning algorithm has not only to be time dependent, but also allow time windows. This means that the vehicle might have to wait for the customer. [43] describes an algorithm containing these quantities.

Another aspect that needs to be considered is the type of the products that are delivered. If the products have to be kept at low temperatures and the vehicle does not have a fridge, then these products have to be delivered as fast as possible.

fast and secure. It can download and cache specific HD maps, used for navigation, as well as react to navigation information from the server and interpret messages from other vehicles and from the infrastructure in order to react.

- A server that processes the orders and plans, the loading and path planning of the autonomous vehicles. The server is able to communicate with the vehicles during the delivery process and according to this information, to reconfigure the optimal navigation path. Furthermore, it informs the customers regarding the delivery time.

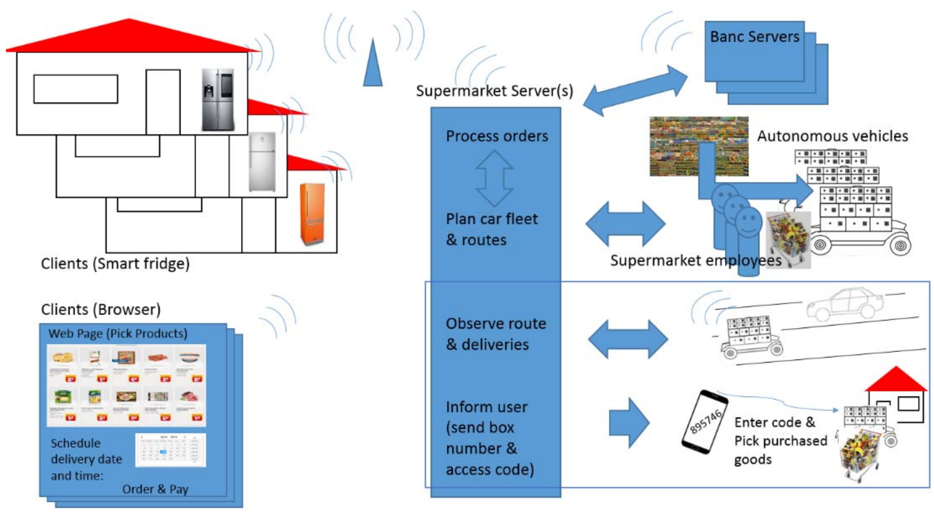

Figure 1: Service concept: Autonomous grocery delivery

The vehicles that deliver the products have to be electric and autonomous. In this way, emissions are reduced and the cost of a regular driver is spared. Consequently a longer, flexible and customer orientated delivery schedule is possible. The service would be available around the clock. The only part where people are involved is in loading the vehicles according to the plan calculated by the planning and routing algorithm. In [14], Google presented a concept of an autonomous delivery platform that contains securable compartments, which can be opened by the user, with a pin. For the paper at hand, the service for grocery delivery could use such compartments. This could be acclimatized if products like vegetables, fruits, meat or ice cream would be transported.

During the delivery, the vehicles are in contact with the server. Information about traffic conditions gathered by sensors or from the infrastructure systems are sent from the vehicle to the server. According to this information and the information coming from the customer, e.g. he is not reachable anymore at the scheduled delivery time, the server can change the route.

In order to implement such a concept, the following requirements have to be fulfilled:

- The existence of one or more autonomous electric delivery vehicles. The autonomous car has to be equipped with sensors and computational units that allow the recognition and localization in a specific environment. Communication with other external systems has to be

- Clients that place orders e.g. by smart fridge, smart phone, laptop, PC. These clients need then a specific software for ordering. Here the customers can define the products the service should deliver and specify the available delivery dates and times. They can also change these times informing the server that they will not be reachable.

Figure 1 depicts the presented concept.

IV. Implementation

A. Autonomous Vehicle and Connection

For a mock-up test, an electric golf cart was transformed into an autonomous car in a privious work [24]. ECUs that control the pedals, the steering wheel and the direction of the vehicle were built in and connected to the inbuilt vehicle controller. Sensors that collect information from the vehicle are for example, hall sensors on the wheels for speed measuring or angle measurement sensors on the steering column. The data from these sensors is then evaluated by other ECUs. All the ECUs are connected via CAN Bus to the main controller (Car-PC Adlink MX-E5401). The CarPC has an i7-4700EQ CPU, 12 GB RAM, 6 USB Ports, 4 Ethernet interfaces, 8 digital inputs and WIFI. It communicates directly with the sensors for environment recognition. For positioning, we use a FlexPak6™ Triple-Frequency + L Band GNSS Receiver with USB interface. Two laser scanners of type Hokuyo UTM30LX-EW, mounted in the corners of the vehicle, offer a 360° view together with a self-built stereo camera. The scanners and the stereo camera are connected to the CarPC via Ethernet. Another ECU is used as a watchdog for all existing ECUs. If messages from on ECU are not available on the CAN Bus at certain specified time rates or if the sent data is not in the required interval, the corresponding ECU is restarted. If the error persists, an error code is sent to the main controller. On the main controller the Robot Operating System (ROS) [25] is running. The CarPC is connected to the CAN Bus by a PCAN-USB adapter. The *SocketCAN* node uses the Linux socket CAN interface to access the PCAN-USB adapters and provides two topics (*can_to_ros* and *ros_to_can*) that are used to deliver the information from the CAN bus to the main system and from the main system to the CAN bus. Other nodes provide information from the sensors (inertial measurement unit, GPS, Hokuyo laser scanner). A 12-V and 120-Ah battery powers all the sensors and MCUs. If the voltage of the battery drops under 11 V, the actuating elements (steering motor) are disabled, the system's main controller is informed and the system asks for a recharge. Figure 2 shows the autonomous golf cart in action.

A server is able to communicate with the vehicle at any time through WLAN. A TCP based protocol is used therefore. If needed, for example if a customer cancels his order, the server can change the path of the vehicle.

The implementation follows the presented concept. A university employee can order coffee over an application. The order is sent to the server and from there, an employee in the cafeteria is informed. The cafeteria employee prepares the coffee and places the coffee labelled with a number on the vehicle. The label is provided by the server and transmitted to the customer. In the first instance, the user places the orders manually, not automatically by a smart system. Because the coffees have to be hot when arriving at destination, the use of a makespan algorithm instead of a travel time algorithm for the route planning is preferable. We use an existing optimized version of the Beam-ACO algorithm.

Figure 2: Autonomous vehicle during delivery process.

B. Map of the Heilbronn University Campus

Figure *3* shows the Heilbronn University campus that is used as test environment for the coffee delivery system. Marked with red are the stations where the vehicle delivers the coffee to the customer. The start point is the university cafeteria which is marked with a green ellipse.

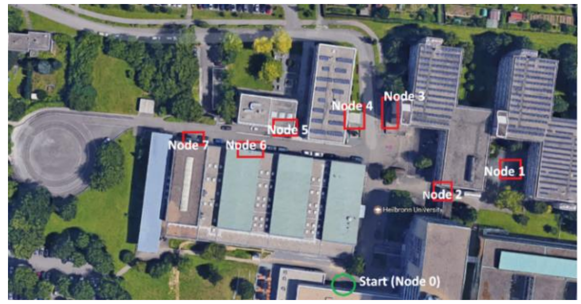

Figure 3: Bird's eye view over the university campus. Delivery points are marked with red rectangles and the start point with a green ellipse.

The map is represented similar to the problem description in [44] as a undirected complete graph $G = (N, A)$, where $N = \{0,1, \dots n\}$ representing the cafeteria (node 0) and n delivery stations where the employees can pick up their order. $A = N \times N$ represents the edges that connect the nodes. A travelling salesman problem with time windows solution is a sequence that visits each node from G exactly once starting and ending in node 0. A tour is defined as $P = (p_0 = 0, p_1, \dots, p_n, p_{n+1} = 0)$. The subsequence $(p_1, \dots, p_n)$ is a permutation of the nodes in $N/\{0\}$ with their position. p_0 and p_{n+1} represent the starting node. For each edge $a_{i,j} \in A$, i and j represent the nodes connected by the edge. Each edge has an associated cost $c(a_{i,j})$ that represents the travel time from i to j plus the waiting time in node i. Each node has a time window $[e_i, l_i]$. l_i means the arriving time in node i and e_i stands for the time the delivery can begin. For a particular tour P the departure time from node p_k is then calculated with the formula $D_{p_k} = \max(A_{p_k}, e_{p_k})$, where $A_{p_k} = D_{p_{k-1}} + c(a_{p_{k-1},p_k})$ represents the arrival time at node p_k. A tour P is feasible, if and only if $\Omega(P) = \sum_{k=0}^{n+1} \omega(p_k) = 0$, where $\omega(p_k) = 1$, if $A_{p_k} > l_{p_k}$, and 0 otherwise. A typical way to find an optimal path is to use the travel time minimization function: $f_{tt}(P) = \sum_{k=0}^{n} c(a_{p_k,p_{k+1}})$.

In our case, we want the car to return as fast as possible at node 0. Waiting times have to be minimum since the coffee might get cold. Therefore, the makespan minimization function f_m given in the tour P is $f_m(P) = A_{p_{n+1}}$.

C. Mapping

For the map creation, the Hokuyo laser scanners are used. A ROS node (*laser_tool*) fuses the data from all laser scanners. The fused result flows as input for the simultaneous localisation and mapping (SLAM) node. Here we use the GMapping algorithm.

Figure 4: Mapped area

The odometry of the vehicle is calculated from different sources. One hypothesis is calculated by using information like steering angle and speed according to the Ackermann model [26]. A second odometry hypothesis is provided by the RTK GPS. The two results and the data, provided by an inertial measurement unit (IMU), are fused through a Kalman filter [27]. This fusion leads to a more accurate odometry.

D. Planning

Based on the generated map and the defined locations (nodes), a path-planning algorithm calculates the path that has to be followed by the vehicle. The route planning is based on the Beam-ACO algorithm [1], which is a Travelling Salesman Problem with Time Window (TSPTW) algorithm. On this one, we apply a makespan optimization like described in [44].

During the navigation, the global route might change due to obstacles that appear on the route, which are detected by the laser scanners. In order to change the route we use the Timed Elastic Band (TEB) planner as a local planner [45].

V. TEST AND VALIDATION

After several successful simulation using Gazebo, we conducted a real test case. The service was set to a maximum simultaneous delivery possibility of six coffees. Ten orders with different numbers of coffees were placed one after another. The customer could also specify the delivery time. A user could not order more than six coffees. The first orders have the highest priority. The algorithm takes the next delivery time and places the orders that have the highest priority (max. 6). If the number of coffees ordered by one user does not fit in the transport vehicle, the system picks the next available order. If the delivery cannot be made on time, the user is informed and can choose to cancel the order or wait despite the delay.

User	No. of coffees	Order Time	Delivery Time	Node
1	2	12:00	12:00 - 12:15	5
2	3	12:00	12:00 - 12:15	1
3	4	12:00	12:30 - 12:45	6
4	6	12:00	12:00 - 12:15	2
5	1	12:00	12:00 - 12:15	4
6	2	12:05	12:05 - 12:20	1
7	5	12:06	12:06 - 12:21	5
8	3	12:06	12:06 - 12:21	2
9	2	12:10	13:00 - 13:15	3
10	2	12:10	12:10 - 12:25	7

Table 1: Order table with 10 customers (users), number of ordered coffees, exact order time, chosen delivery time and node as in Figure 3.

At time, t_0 the system has to choose between user 1, 2, 3, 4 and 5 and it will pick 1, 2 and 5. User 3 chose a later delivery time and user 4 ordered six coffees, but only one fits in the current delivery. The calculated route will be node 0 – node 1 – node 4 – node 5 – node 0. The vehicle leaves the depot at 12:04:14 after the coffee is prepared. The vehicle arrives at node 1 at 12:05:52. It departures node 1 at 12:06:03 to node 4 and 5 and arrives back at node 0 at 12:09:45. Since the next coffees are already prepared, the vehicle is loaded and delivers the coffees for user 4.

Table 2 shows the transport schedule with the corresponding delivery times for each customer (user).

T.	Start	U.	Delivery	Departure	End
1	12:04:14	2	12:05:52	12:06:03	12:09:45
		5	12:06:37	12:06:57	
		1	12:07:44	12:07:55	
2	12:10:03	4	12:11:20	12:11:25	12:12:39
3	12:12:48	8	12:13:57	12:14:30	12:17:09
		6	12:15:13	12:15:19	
4	12:17:15	7	12:18:47	12:18:53	12:20:28
5	12:20:36	10	12:22:58	12:23:09	12:25:37
6	12:28:04	3	12:30:04	12:30:15	12:32:04
7	12:58:50	9	13:00:01	13:00:08	13:01:23

Table 2: Delivery times for each customer (U.), transport number (T.), start and end time in node 0 and departure time from customers.

VI. SURVEY

In the recent past, there were suggestions for similar autonomous systems, which are technologically not realized. We were interested in whether they would find acceptance among the population at all. We presented the concept to 100 people at the entrance of a big supermarket in Heilbronn. The age average was 42,4. 92 % of the questioned were there by car and 56,52 % out of these cars were powered by diesel engines and the other 43,48% by gasoline engines. The customers buy grocery on average two to three times during one week.

Asked if they would use this system, only 58 % answered affirmative. The reasons for not using it are, that they want to see the products themselves before buying (88,09 %) or simply the shopping fun (11,91 %). The negative answers were from people older than 35 years. This might indicate also a difference between generations.

However, all the interviewed people answered affirmative at the last question if they consider the use of autonomous driving vehicles in areas like package delivery or landscape work in a park as useful.

VII. CONCLUSION AND FURTHER WORK

The paper presented a concept of a service in smart cities for delivering grocery using autonomous vehicles in urban areas. This starts with the (automated) ordering of the products, continuing with autonomous transportation using an electric vehicle up to the delivery point. During the transportation, rescheduling of the route depending on the availability of the customers and the traffic conditions is possible.

The concept was implemented in a smaller scale at the campus of Heilbronn University, as a service for coffee delivery. The simulation tests in gazebo showed the functionality of such a service. A real scenario test with the constraint of a maximum delivery capacity of six coffees per transport was conducted and presented. There are still problems when pedestrians or other obstacles block the path of the vehicle, causing a delay and the need of a rescheduling. Improvement of the system is therefore required. Also only one vehicle is available now. In the next steps, we will test the scalability of the system with more vehicles.

A performed survey showed that grocery shopping is a domain where the majority of people use their car. In most of the cases diesel or gasoline, engines power these cars. An open question is the acceptance of the proposed service, which seems to be generation dependent. Other areas to apply this kind of strategies are e.g. autonomous packet delivery, landscape work or garbage collection. Here the acceptance is much bigger.

We focused in this work especially on automated grocery delivery, this being one of the reasons people use their car most often. We consider that the proposed service is a solution for reducing emissions leading to a healthier environment. An intelligent route planning is mandatory, in order to serve more customers with one transport. Especially, the use of an autonomous transport platform is more flexible, cheaper and sustainable.

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