Research article

Towards a new mobility concept for cities: architecture and programming of semi-autonomous electric vehicles

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Abstract

Purpose – This paper aims to focus on cybernetic transportation systems (CTS) due to their effectiveness for solving mobility problems in cities. A new mobility concept is proposed which allows to attain the same flexibility of the private passenger car but with much less nuisances. It is based on small semi-autonomous electric vehicles, which may be used to complement mass public transportation, by providing passenger service for any location at any time.

Design/methodology/approach – A set of automatic guided vehicles for public transportation are described. Two different control paradigms of the fleet are compared: centralized vs distributed control.

Findings – The pros and cons of both control approaches are highlighted so as to support decisions about the configuration of a CTS for people transportation on public places.

Originality/value – The paper provides a new offer of transportation for people in short path cities downtown or public gardens, in order to move people based on sustainable and efficient public transportation systems.

Keywords Cybernetics, Passenger transport, Automation, Control

Paper type Research paper

1. Introduction

In many urban environments, the use of private automobile has led to severe problems with respect to congestion, energy (dependency on oil resources), pollution, noise, safety and general degradation of the quality of life. Therefore, the historical centers of many cities are facing severe problems since the traditional commerce is in decline and moving to the periphery of the cities, and the city centers become less attractive to tourists and citizens. Although public transportation systems have seen many recent improvements (mostly due to information technologies), in many cases the car still offers a much better service at the individual level. This leads to a constant increase in its use, hence to non-sustainable development of urban transportation.

A new approach for mobility, emerging as an alternative to the private passenger car, tries to offer the same flexibility and much less nuisances based on small automated electrical vehicles. These automatic guided vehicles (AGV's) may be a solution to public transportation systems in specific areas and may complement the mass transit and non-motorized transportation, providing passenger service for any location at any time. This new mobility transportation system is known by the acronym cybernetic transportation system (CTS).

1.1 Cybernetic transportation systems

Supported on this concept of CTS and framework, the CyberCars and CyberMove were two important projects belonging to this endeavour. CyberCars (CyberCars Project, 2006) aims at improving the technology necessary to implement and run such as CTS by generating a new class of vehicles named CyberCars. CyberMove (CyberMove Project, 2004) aimed at demonstrating the feasibility of CTS's using fleets of CyberCars in the urban environment and in historical cities. Cybernetic cars use technology which has the potential to contribute to the sustainable development of European cities with a new type of vehicle.

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These automated vehicles are designed specifically for public use in cities and have fully autonomous driving capabilities in order to provide an on-demand door-to-door service.

The CyberCars Project (2006) was an opportunity to test and exchange best practices for the development of a new platform for urban mobility. A major part of the work carried during the project has been the development and test of several key technologies for the enhancement of the existing systems. These technologies concern better guidance, collision avoidance, energy management and fleet management, and the development of simple and standard user interfaces. Cooperative work was developed in order to reach a consensus on the certification techniques of these systems which are now developed in a very imprecise regulatory framework.

The CyberMove Project (2004) attempted to demonstrate that CyberCars have enough potential to make an essential contribution to the sustainable development of the cities of tomorrow. Through the dissemination activity, results on the selected test sites are helping other cities to plan future targets on increased public domain capacity, energy saving, traffic congestion effect, potential safety improvement. CyberMove was a project to compare different new transportation systems based on CyberCars in several historical cities (Valejo *et al.*, 2004). Public demonstrations were carried out in these cities so as to prove that CyberCars offer a cleaner and safer transportation mode available to everyone, including people who cannot (or should not) drive, for a level of service better than with private cars (door to door, individual, on-demand transportation).

Projects like CyberMove aim at creating a new transportation option for city authorities to move towards sustainability and increase the attractiveness of city centers. The essential goal is to create a new offer of transportation to city authorities to move towards sustainability and demonstrate that the new mobility concept has the potential to make an essential contribution to the sustainable development of the cities of tomorrow. The advantages of a CTS include the reduction of congestion, better air quality, low noise, energy conservation, increased safety when compared with manual driving and no need for a driver's license. Moreover, cybernetic cars are easily moved from one location to another and, when not needed, they can drive themselves autonomously to a remote parking area. The concept and associated technologies may be even appropriate for delivery of goods and even garbage collection. The flexible design of a CTS makes possible to optimize the overall system performance.

1.2 Outline

This paper proposes CTS due to their effectiveness for solving mobility problems in cities. The CTS technology have already reached suitable levels of reliability, safety and user friendliness that they can be useful to solve some mobility problems in the cities (CyberMove Project, 2004). Two different approaches for the fleet control are compared in this paper: centralized control and distributed control. The former one was used to deploy a CTS inside a new re-qualified area of Coimbra's green park, with a loop configuration (Valejo *et al.*, 2004). The latter one is planned to be used on a CTS inside the engineering and technological campus of University of Coimbra, so as to serve a more complex transportation network. Section 2 describes the AVG's used in the case study. Section 3 presents the aforementioned control paradigms and compare their pros and cons. Section 4 concludes the paper.

2. The automatic guided vehicles

This section describes the electric vehicles that have been used in the cybernetic experiments carried out in Coimbra (Valejo *et al.*, 2004). Figure 1 shows photos of these AGV's. Each vehicle is an electric AGV for transporting up to four people. It is supplied by lead-acid batteries with an operation time of 52 min/h in full mode operation. It can move at a maximum speed of 10 km/h or more and an average speed of 8 km/h. Its range is 30 km. The vehicle was originally designed for transporting people within golf fields and further adapted to transport people in urban environments. It has built-in autonomous guide by wire.

The vehicle has been provided with important add-ins such as automatic passenger detection, a human-vehicle interface and laser-based collision avoidance (Figure 2). Concerning the vehicle's navigation capabilities, an innovative navigation system has been developed in the CyberCars Project (2006) which is based on the fusion of differential GPS (DGPS) and inertial sensors (Figure 3). The system takes advantage from the complementing characteristics of both sensor modalities: DGPS provides reliable positioning with a bounded error but with a poor precision (few meters); dead-reckoning based on inertial sensors may provide high precision short-term relative positioning (few centimeters) but suffers from the accumulation of integration errors. The navigation system uses filtering techniques (Kalman filters) to attain highly accurate positioning from inertial sensors, being their errors bounded with the absolute localization provided by DGPS (Alves *et al.*, 2003; Alves, 2005).

The complete infrastructure of the intelligent transportation system is shown in Figure 3. It includes fleet of cybernetic vehicles equipped with an on-board embedded computer and GPS receivers and wireless communication. The system also includes a GPS base station to support differential GPS, access points of a wireless computer network, stop stations with user interface, battery chargers and a central computer for the fleet management and supervision.

3. Fleet control

This section addresses the control of a fleet of cybernetic vehicles whose goal is to provide people with an on-demand transportation service in an urban environment. Two different case studies of a CTS are used herein to illustrate two alternative control paradigms for the fleet. One is a CTS controlled from a centralized computer, aiming at providing a transportation service with a loop configuration, having 12 stop stations located in the Coimbra's green park. The other CTS is based on a distributed control paradigm and aims at serving a more complex transportation network located within the engineering and technological campus of the University of Coimbra, having 37 stop stations distributed along several loops.

3.1 Centralized control in a single loop configuration

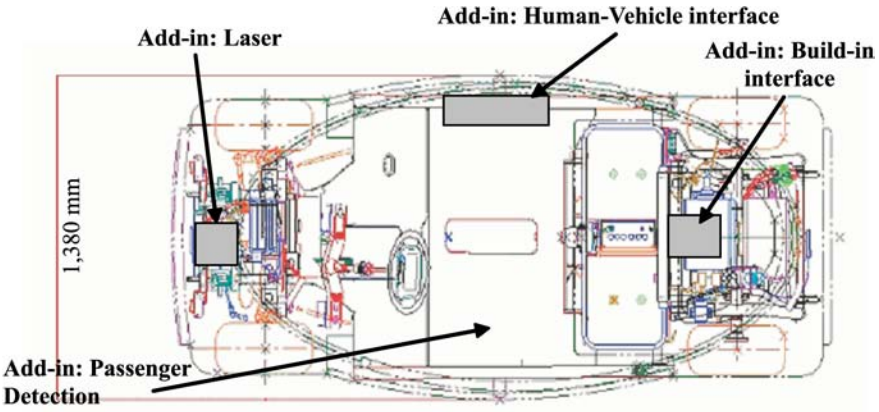
This section describes a CTS that is located inside a new re-qualified area financed by the Polis Program and supported by the Portuguese Government. This site has been profiting

Figure 1 The cybernetic vehicles

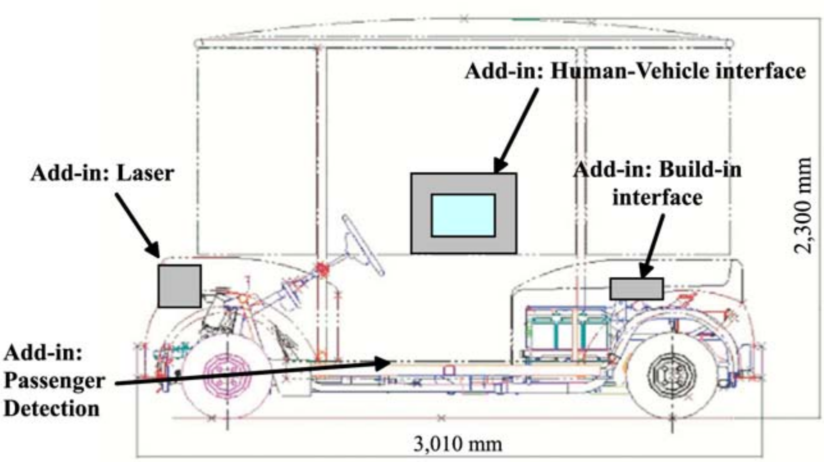
(a) Automatic guided vehicle from Yahama Motor Europe

(b) Two of the vehicles used in the Coimbra's CyberMove demonstration

Figure 2 Drawing of Yamaha's cybernetic vehicle

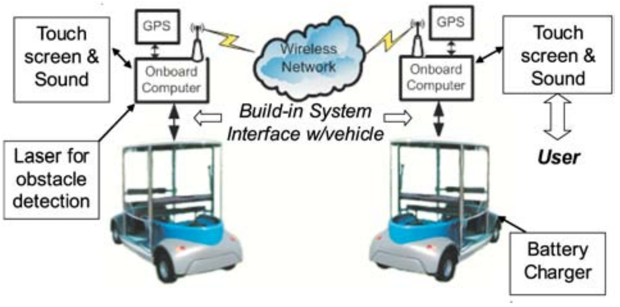


(a) Top view



(b) Lateral view

Figure 3 Diagram of the transportation system infrastructure



from this program that is intervening in an area of about 80 hectares, on both sides of the Mondego river, in Coimbra. The CTS supports activities within an area that is located between an old bridge named Santa Clara Bridge and a new bridge named Europa Bridge, covering a green park with several buildings. The mobility is mainly based on lanes for pedestrians or special mobility devices. The experimentation site is exactly located in the right margin of the river, between the old Santa Clara Bridge and the Portugal Pavilion (Figure 4).

The CTS aims at providing transportation for people that park the individual car in the car-parking and intend to go to the city center; for people that use the local train station and commute between it and the city center; and for green park users. Car-parking users have their jobs around the experimentation site area, mostly in downtown. The people from the train station come from south peripheral areas of Coimbra city and need to get to their jobs, mostly in downtown, or to get to the local commerce in downtown. The green park users mostly use the park for their amusement. Elderly and disabled people are in this class of users who use the CTS to go from one place to another.

A loop configuration was developed in the CyberMove Project to deploy the CTS (Valejo *et al.*, 2004). It is used herein to compare a centralized approach with the distributed transportation system described in the next section. The loop configuration was comprised of twelve stop stations but, because of its circuit's topology (Figure 5), we can consider that the system had only seven principal stops: two at each end of the circuit and five distributed along the way. The loop's length was about 1,900 m.

In this system, any user could access the CTS by walking towards the nearest stop station and requesting the transportation service through the user interface provided at those places. This kind of orders were sent to a centralized fleet's management system, which ran on a remote computer located in the supervising and maintenance building.

The block diagram of the fleet's centralized controller is shown in Figure 6. The connections listener received the incoming transportation requests from the Stop Station Unit which concentrated the requests coming received from every stop stations in the transportation circuit. The Fleet Management Client Handler managed the clients requests queue which were further dispatched in real-time by the dispatcher. The Cyber Car Unit interacted with every vehicles of the fleet. The DB Access Module accessed the fleet management database which registered every transactions and events occurring within the CTS.

This centrally controlled CTS was successfully demonstrated in public dissemination events organized within the CyberMove Project. The system comprised of three vehicles was able to transport 1,584 persons per day and a maximum of 88 persons per hour. The average waiting time was equal to 6 min.

This kind of centralized control is particularly suited for this kind of simple transportation systems with a loop configuration, since the vehicle's routing is obviously very simple. The routing complexity of a more complex transportation network would require a huge amount of computation power in the central computer and, thus, the centralized control is not easily scalable to a larger CTS. Moreover, the physical configuration restricts the fleet size to few vehicles and, thus, their control from a central computer becomes viable. With larger fleets distributed along wider areas, centralized control would be also almost impractical due to the exponential increase on the complexity of scheduling, routing and dispatching.

Figure 4 Cybernetic transportation system located in Coimbra's green park

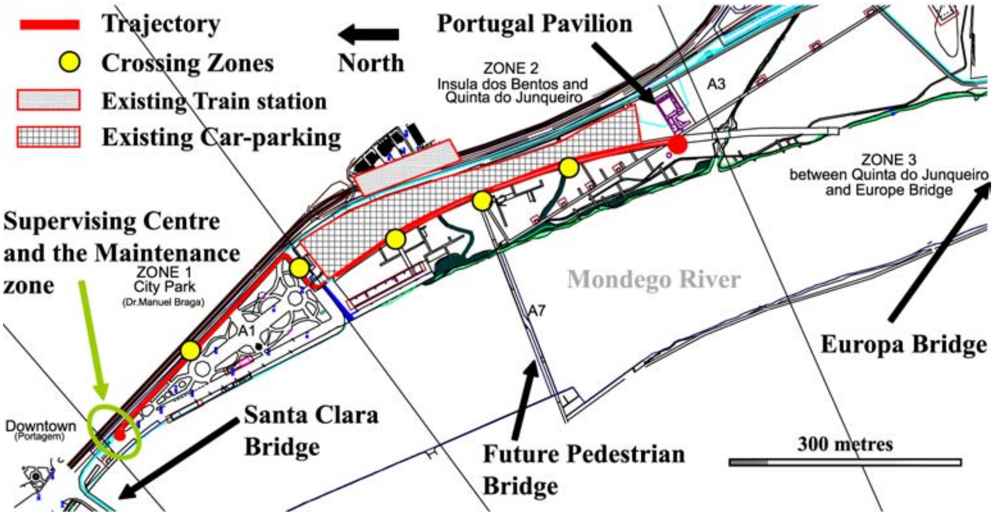


Figure 5 Loop configuration of the cybernetic transportation system located in Coimbra's green park

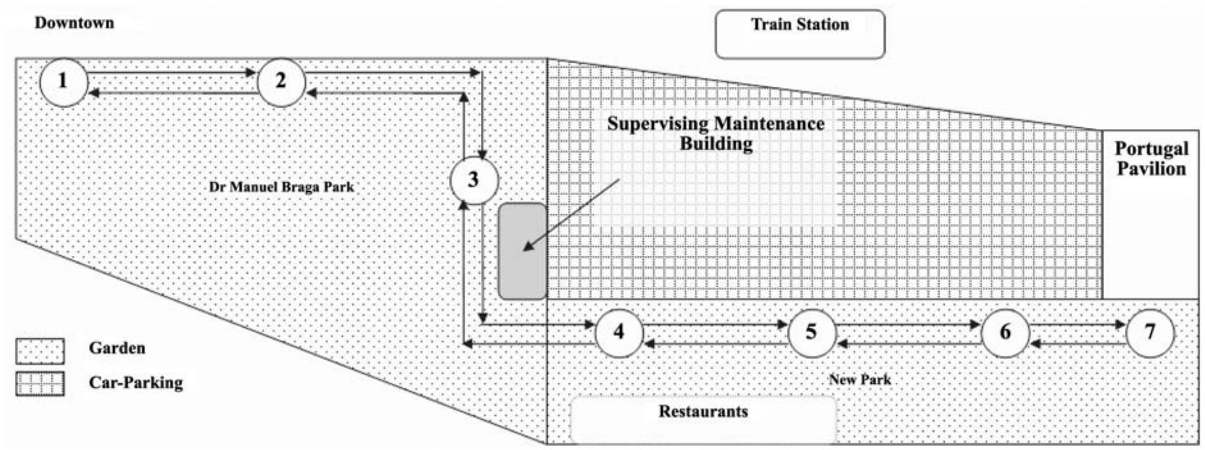
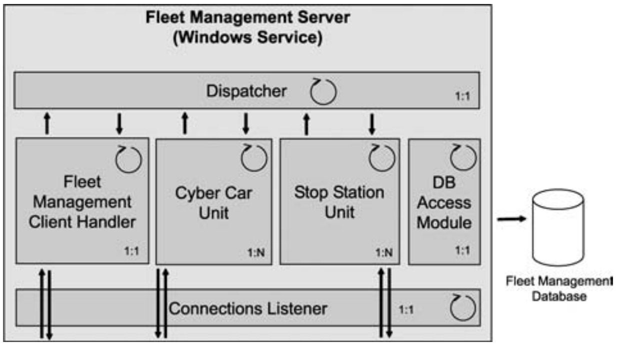


Figure 6 Centralized controller of the cybernetic transportation system



3.2 Distributed control in a complex network

This section addresses the distributed control of a larger fleet of AGV's, which are spread out over a larger area than in the loop configuration described in previous section. The CTS shown in Figure 7(a) is used as a case study.

The CTS is aimed at providing on-demand short distance transportation of people within the engineering and technological campus of University of Coimbra. The campus covers an area of 0.25 km^2 comprised of several buildings, namely the main building (FCTUC), different engineering departments (DEEC, DEC, DEQ and DEM) and social services (SASUC) such as cantinas and students' residences. Besides, connecting these buildings, the CTS connects them to the public transportation system, which has three stop stations inside the campus. As Figure 7(a) shows, the CTS is comprised of 37 stop stations spread out over the campus. An user or a small group of users (up to four people with current AGV's) can request the transportation service from any one of these locations to any other stop station belonging to the network. The CTS automatically sends a free vehicle to the station from where the request is issued that minimizes the waiting time.

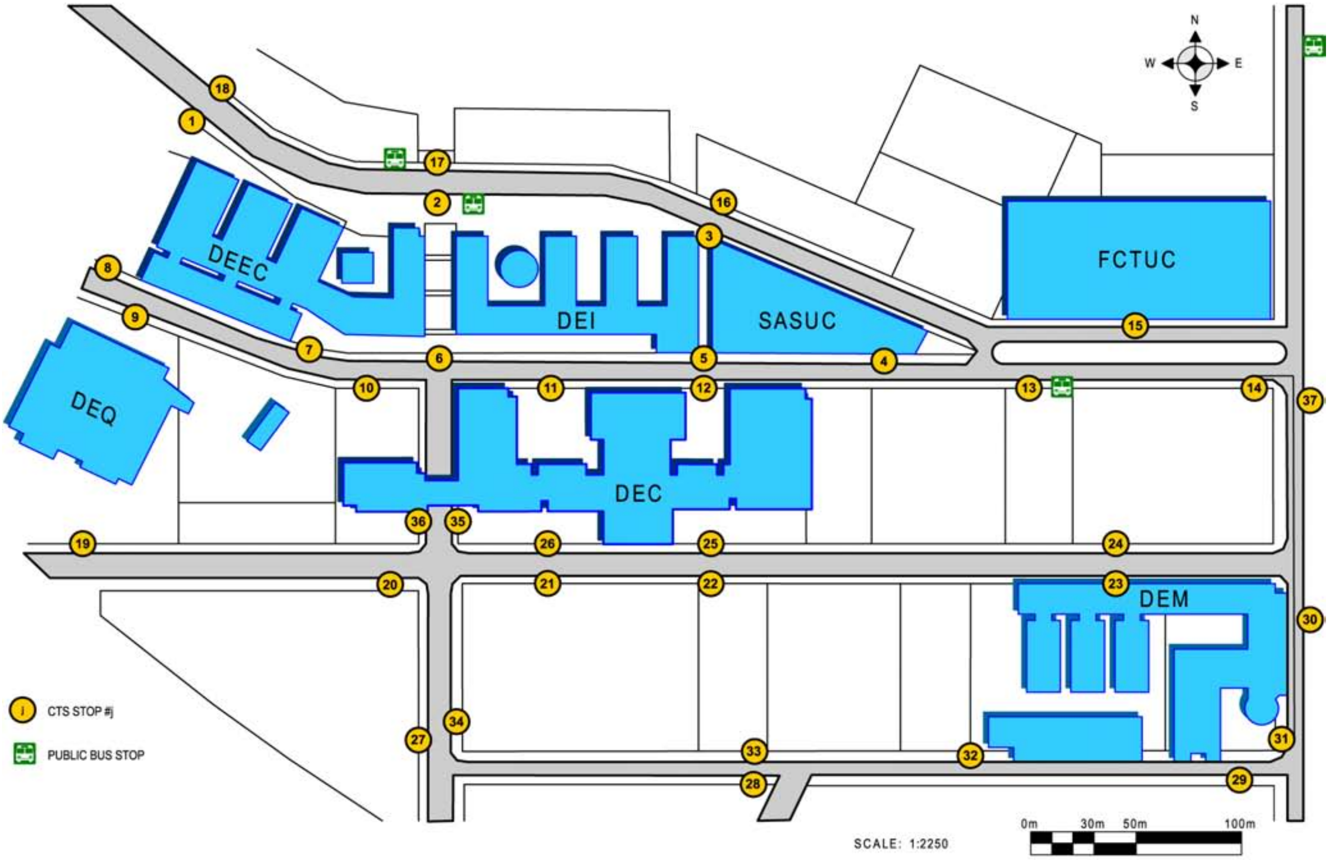
Figure 7(b) shows a connectivity graph of the CTS. Although its high connectivity makes the provided service very flexible, the routing complexity is huge when compared with a simple configuration such as the one shown in Figure 5. It is comprised of many loops and several alternatives to reach many nodes of the network. The problem becomes more severe with the increase of the fleet size, which is denoted hereafter as n. Using a centralized controller to manage and control such a CTS requires a huge amount of computation power on the central computer that controls the entire fleet, which increases exponentially with n. Moreover, the system is not sufficiently robust, because any failure occurring in the central computer implies the overall failure of the transportation fleet.

A much more intuitive and reasonable solution is to distribute the control tasks and the associated computation power over all the AGV's belonging to the network. This distributed control paradigm has been demonstrated to be useful in different application domains of mobile robotics, due to its intrinsic scalability with the team size, fault tolerance and graceful degradation and increased robustness. Its viability is further justified by the evolution that computers have known for the past decade. The technological opportunity of having nowadays high on-board computation power at low cost, have given a significant boost towards the increase of mobile robots' autonomy, including control competences.

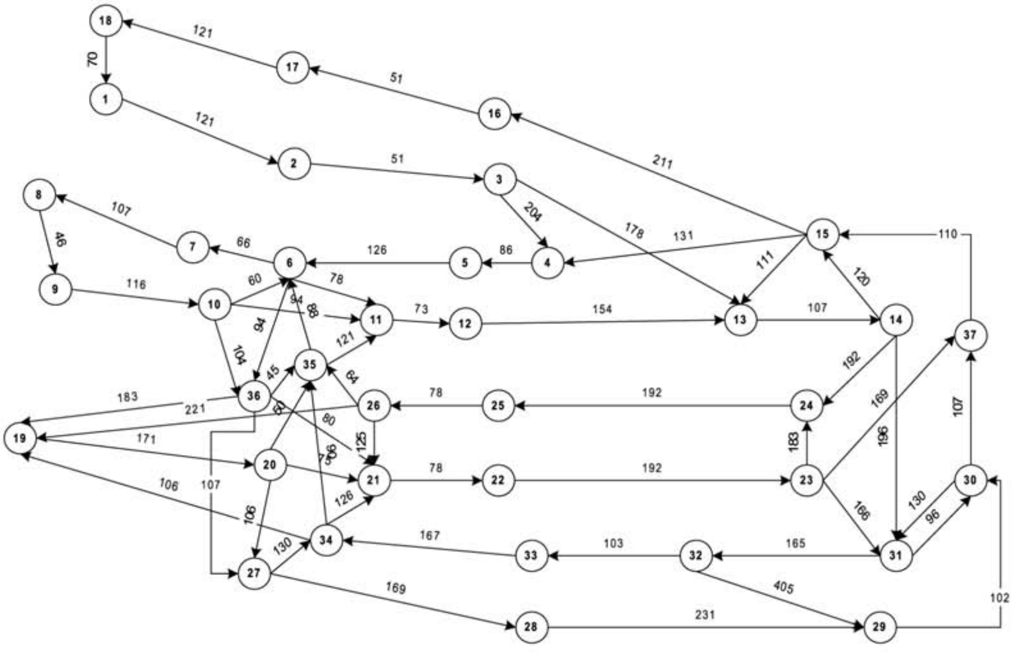
Instead of concentrating all the decision and computation power on a single computer – a classical approach denoted as centralized control – the adoption of decentralized or non hierarchical (distributed) systems has been proposed, wherein the computation burden is distributed and each mobile robot participates actively on the team's control decisions. Regarding the CTS, this means that each AGV cooperates with the other AGV's of the fleet to use efficiently the team's resources through participating actively on the distributed scheduling activity (task allocation). Moreover, other control activities, such as path computation (routing) and operational control of the AGV (navigation), which were usually centralized, may now be delegated to each AGV and coordinated with the rest of the team. The more challenging issue on deploying a CTS with distributed control is to coordinate properly the individual competences of each AGV, so as to attain a good overall performance for the team.

Figure 8 shows a diagram of such a distributed control architecture. Each AGV plays an active role on the team's scheduling, through its scheduling layer. On a lower level, it also takes care about other control activities that also need sometimes to be coordinated with the rest of the team. The routing layer computes the best path to move the AGV

Figure 7 Cybernetic transportation system located in the engineering and technological campus of University of Coimbra

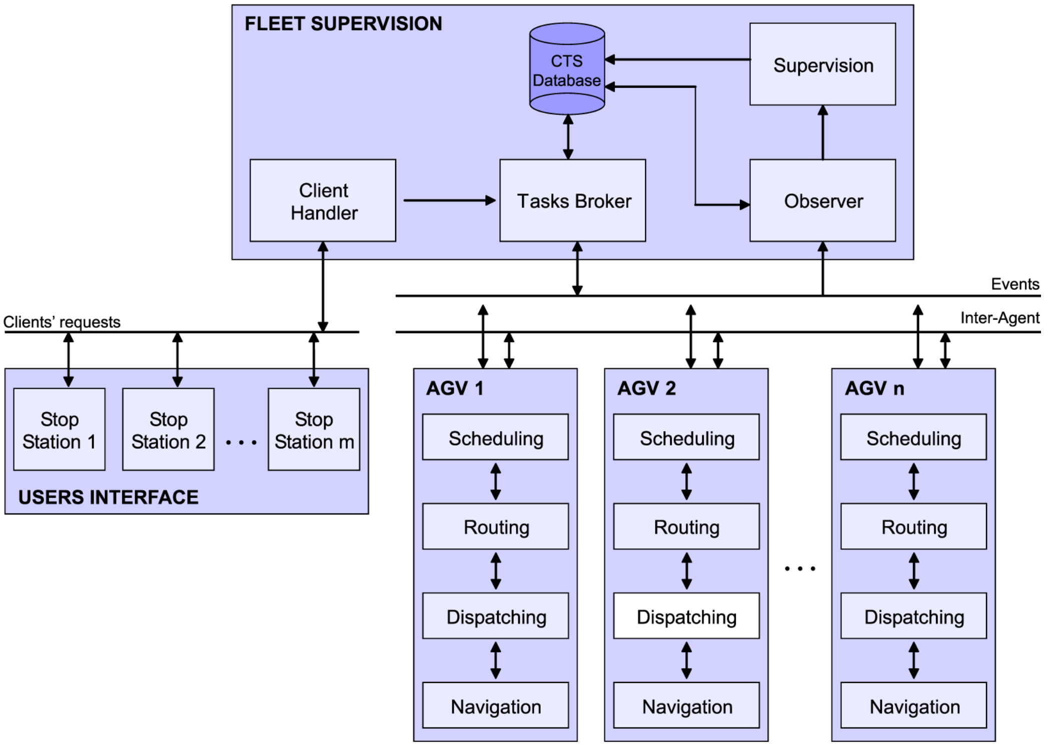


(a) Map showing the stop stations' location



(b) Connectivity map showing the distance in meters between the network's nodes

Figure 8 Distributed architecture of the cybernetic transportation system



between two nodes of the transportation network, while simultaneously optimizing the network occupancy by the AGV's. The dispatching layer partitions each task assigned to the AGV into elementary actions (e.g. moving between two nodes, boarding passengers, etc.) and controls the AGV's actions. Concerning the motion control, it also coordinates the AGV's motion with the rest of the team, so as to optimize the traffic over the network. The lower control layer is the navigation layer, which ensures that the AGV moves safely through the environment through accurate real-time localization and obstacle avoidance. The architecture includes inter-agent communication which vehicles use to support their coordination at different control layers. Moreover, each vehicle informs the fleet's supervision about all the relevant events occurring as a result of its autonomous operation.

The interface of the CTS with the users is distributed along the transportation network. Each node of the network may provide users with a user interface which communicates to the fleet supervision clients' requests. The requests issued to the system are concentrated on the fleet supervision's client handler layer, which runs on computer devoted to the CTS's supervision. Besides, receiving service requests, this computer moderates the allocation of transportation tasks to the individual AGV's – tasks broker layer – tracks the vehicles' activities and records all the relevant information on a database – observer layer – and allows the system's supervisor to tune the criteria ruling the distributed task allocation process – supervision layer.

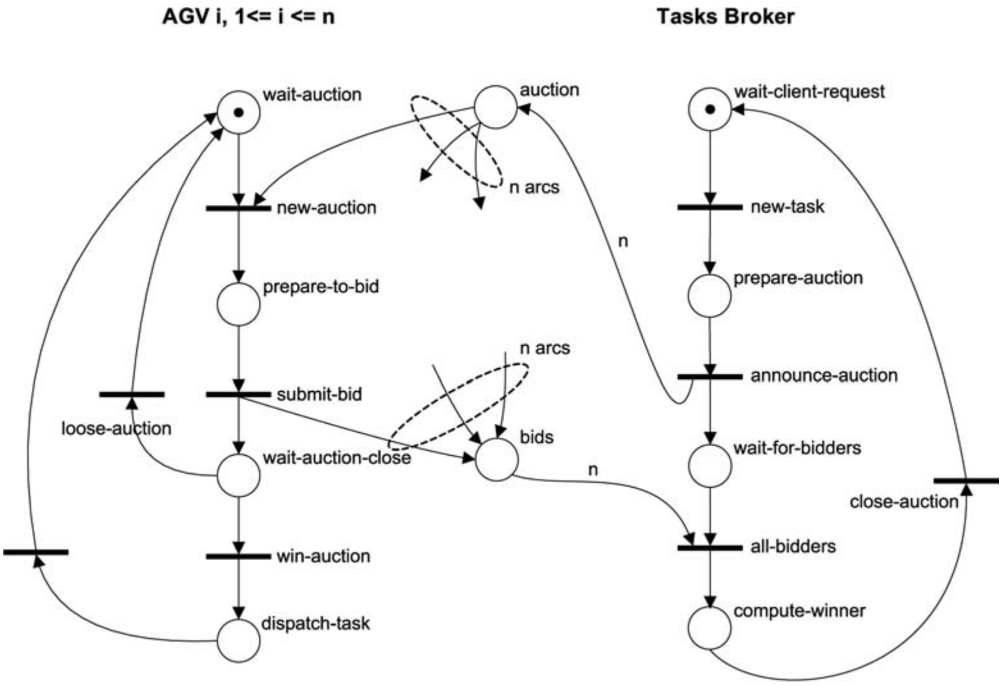
Figure 9 shows the interaction between the tasks broker and the scheduling layer of each AGV of the fleet. These entities implement a distributed task allocation mechanism following an auction-based paradigm (Gerkey and Matarić 2002). After receiving a new client request, the tasks broker moderates an auction in order to "sell" the task to the best offer received from the AGV's.

After the auction announcement, each AGV uses its current state to compute a performance function that measures its fitness for the task (e.g. the function may compute an estimate of the time needed by the AGV to accomplish the task). Then, each AGV bids for the task and waits until the auction is closed by the tasks broker. At this time, the auction's winner is given a time-limited contract to execute the task and the losers return to listening for new tasks. The auctioneer monitors the task execution and, if sufficient progress is being made, it renews the contract to the winning AGV. Otherwise, a new auction is announced so as to assign the task to a fitting AGV (more likely a different one). This kind of time-limited task allocation is essential to ensure the fault tolerance of this distributed scheduling mechanism.

4. Conclusion

This paper proposes a new mobility concept for cities, which uses a CTS to complement the public transportation system with an on-demand short distance passenger service. Its goal is to attain the same flexibility of the private passenger car with semiautonomous electric vehicles, but with much less nuisances. Two different control approaches for the fleet are compared along their pros and cons, so as to support decisions about the configuration of a CTS for people transportation on public places. On one hand, centralized control is suitable to a small size CTS (few AGV's) having a simple configuration (e.g. single loop configuration). On the other hand, distributed control makes possible to deploy a more complex CTS, comprised of a larger fleet operating in a

Figure 9 Auction-based distributed task allocation



Note: Petri net model showing the interaction between the AGV's scheduling layer and tasks broker

wider area and more complex network, while scaling well with the team size and being sufficiently robust and fault tolerant.

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