# Building a connected autonomous vehicle: design, construction and control

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**Abstract**

This paper describes recent work on the design and construction of a small fleet of connected autonomous vehicles intended to operate in closed or private spaces. These reduced size scenarios and the advanced capabilities of new generation communication networks open the door to innovative approaches in the design and management of these transport systems. Using the CORTEX cognitive robotics architecture, a two-level distributed scheme is proposed that assigns individual on-board controllers to vehicles at the edge of the network, while maintaining a central node for service planning and monitoring. Information flows in both directions, up and down, between the participants and the central node, resulting in a real-time distribution of events generated by the vehicles and by potential sensors placed in the environment to provide contextual information. The final system is analyzed after several experimental sessions, highlighting the robustness of the mechatronics, the coverage of the sensor system, the performance of the communication network, the transmission savings due to the two-level control architecture, the versatility of the monitoring station and the acceptance of the final user's mobile phone application interface. Several videos of the complete system are presented, both in simulation and in operation within our university campus.

**Keywords:** Connected Autonomous Vehicle, CORTEX, RoboComp

# 1 Introduction

There is currently a growing interest in integrating emerging technologies with the aim of harnessing the innovative capabilities that this combination of systems can offer. The idea of autonomous, safe, and efficient mobility has been in the spotlight for years, capturing the attention of users, governments, and companies [1]. Concurrently, the capabilities of next-generation networks in terms of throughput and latency open up a vast field of research and work, extending the capabilities of traditional vehicles and leading to the rise of Connected Autonomous Vehicles (CAV) [2].

CAVs represent the confluence of next-generation networks, autonomous systems, and the latest advancements in artificial intelligence systems [3]. However, their design, implementation, and validation require modern tools and methodologies, presenting complex challenges beyond the reach of traditional systems. It is at this juncture that the use of Digital Twins becomes imperative a real-time digital representation of the physical system that allows for the simulation and analysis of complex operations[4] [5].

This work, framed within the development of the 5G autonomous vehicle project in the city of Cáceres, addresses the basic needs of such a system, where vehicle control is shifted to the edge of the network. In this scenario, the virtues of next-generation networks become indispensable. Equally complex is the real-time maintenance of the digital twin, where data acquisition and updating are paramount to ensure informed and safe decision-making, especially considering the number of elements communicating simultaneously, all essential for the system's optimal operation.

Based on the RoboComp robotics framework developed at the University of Extremadura [6], a distributed system will be constructed to serve as the foundation for building the digital representation of the testing environment, the digital twin. This representation is shared by all system participants and is generated using the CORTEX technology developed in the same laboratory. Through an exhaustive analysis, the advantages and challenges encountered during the work will be presented, from sensor integration to communication and driving tests assessing the system's performance, laying the groundwork for subsequent developments.

Within the automotive industry and academia, the classification developed by the American Society of Automotive Engineers (SAE) [7] is widely standardized, which describes the levels of human intervention within driving as well as the capabilities of the autonomous system on a basic scale.

The SAE level classification provides a clear framework to which manufacturers and governments are adapting to develop their vehicles and the regulations around the everyday use of AVs. The development of the vehicles coincides with a high level of automation, where the route to be followed by the vehicle along the circuit is predefined.

# 2 Related work

The evolution of autonomous vehicles at a commercial level has seen significant progress in recent years, with several leading brands and projects largely setting the advances and trends in the market:

- Tesla: a pioneer in the development of electric and autonomous vehicles. Their driver assistance system, known as Autopilot, has been one of the most highlighted in the market. Using a combination of cameras, radars (currently being phased out), and sensors, Tesla vehicles can perform tasks like staying in the lane, automatically changing lanes, and parking autonomously. The Full Self-Driving (FSD) program is under development, aiming to achieve complete autonomy in their vehicles [8].
- Waymo (Alphabet Inc.): a subsidiary of Alphabet Inc. (Google's parent company), stands out as one of the leading companies in autonomous vehicle development. They have conducted extensive tests on public roads and accumulated millions of miles of autonomous driving. Waymo's vehicles are equipped with a wide range of sensors, including lidar, radars, and high-resolution cameras, to obtain a comprehensive view of the environment and make safe decisions.
- BRAVE (Bridging gaps for the adoption of Automated Vehicles): consortium in which the University of Alcalá is collaborating about conditioned automation, develops new paradigms of human-machine interface, systems of interaction between vehicle and environment and seeks to ensure the reliability of the system in any scenario. It develops predictive systems capable of identifying the presence of users on the road and predicting their behavior, carrying out tests on its DRIVERTIVE autonomous vehicle [9].
- AUTOPIA, connected and automated vehicle: research group belonging to the CSIC and dedicated to autonomous mobility, navigation, decision and control. It has a fleet of prepared vehicles and a circuit for autonomous navigation tests [10].

## 3 Mechatronics

The first objective in building our autonomous vehicle is to transform a commercial electric golf vehicle into a computer-controlled car. The manual procedures (turning the steering wheel, operating the brake and accelerator pedals) have to be replaced by a mixed system, merging manual operation with "drive by wire" technology that allows electronic control of the vehicle's main systems. Control is subsequently performed whether by a human remote operator, or the autonomous driving system.

The use of an electric vehicle greatly facilitates the adaptation process by dispensing with complex mechanical systems. The initial set of modifications made to the vehicles are:

- **Steering control:** Control of the vehicle's steering through an electromechanical system, relies on using a servomotor attached directly to the steering column of the vehicle.
- **Brake system:** The brake pedal is driven by a linear electric motor with a belt system acting on the pedal shaft installed as standard.
- **Engine and transmission assembly:** In automatic mode, both the gear and accelerator control are switched to the values provided by the control system installed in the vehicle, where the necessary signals are emulated from the data received in the vehicle's PLC through a network connection.
- **Monitoring and use of the battery system:** The vehicle itself must serve as the power supply system for all the vehicle's sensing and control elements. This

(a) Steering (b) Brake

**Fig. 1**: Main actuators installed on the vehicle

level necessarily implies a battery monitoring system that allows its remote reading and a whole power supply system capable of supplying energy to the remaining subsystems with the variety of supply voltages used.

The adaptation process is carried out by allowing manual operation of the vehicle and begins with the choice of an electric vehicle for golf courses, model MELEX 427 (Fig.2). This model has simple mechanical systems, easily adaptable without the need to make substantial modifications to the essential elements of the vehicle that could affect safety during operation.

# 4 Control Architecture

## 4.1 RoboComp

RoboComp is a development framework specialized in robotics and developed at the University of Extremadura. It provides the necessary tools to create and modify applications interconnected through interfaces defined in IDSL (Interface Definition Specification Language). This framework is based on the development of these software components, mainly in C++ and Python, and on their combined operation to execute tasks of varying complexity [6].

The ability to form a distributed system thanks to the modular approach allows the development of individual components with very specific tasks, from image processing to navigation tasks. Connecting these specific components allows for the simple operation of complex distributed systems.

RoboComp includes tools for automatic code generation, allowing us to focus on the specific logic of the component and overlook low-level communication processes, standardized by using previously defined communication interfaces [6].

**Fig. 2**: MELEX 427 vehicles as base units.

The processes of exchanging information between components are carried out through the ICE (Internet Communications Engine) communications middleware from ZeroC, offering an efficient, transparent, and optimized communication system between components, regardless of whether the processes run on the same machine or in a distributed system, even operating successfully over a public network.

## 4.2 CORTEX

CORTEX is a robotics cognitive architecture that combines several types of memories and processes or agents that create and maintain the flow of information within it. The core element in CORTEX is the working memory, implemented as a shared, distributed representation [11]. This memory is a hybrid mix of symbolic and numeric elements, such as sensor reading, and relations among these elements that can be geometrical, such as pose transformation matrices, or logical predicates. The joint action of multiple agents, working with a common representation of the robot and its environment, is expected to provide the appropriate dynamics for intelligent behaviour (Fig.3).

One of the main challenges in a complex architecture lies in avoiding the bottleneck imposed by maintaining a high number of agents working simultaneously. The current CORTEX implementation provides a solution based on two key technologies [11]:

- Use of RTPS, Real-Time Publish Subscribe Protocol. High-performance communication middleware configured to use reliable multicast transmissions over UDP. All shared information is transmitted at once to the rest of the agents, minimizing the necessary bandwidth compared to an unicast transmission (same information transmitted agent to agent).

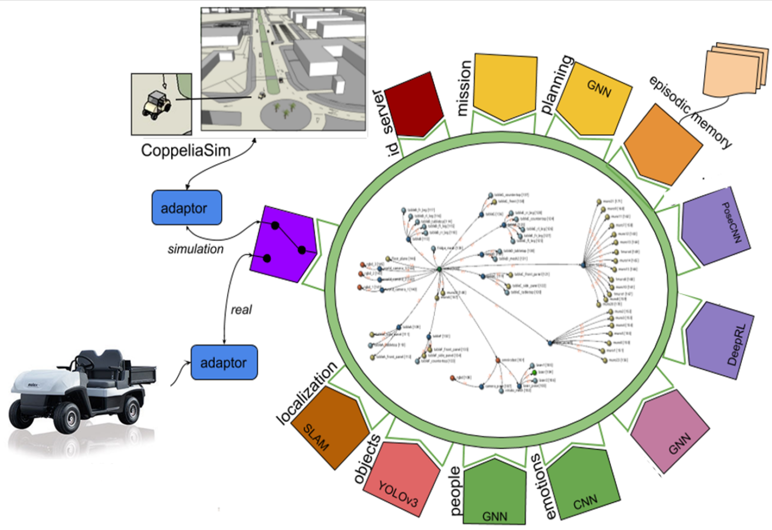


**Fig. 3**: Multiple agents acting on the shared working memory presented by the DSR.

- Use of special data types called Conflict-free Replicated Data Types (CRTD), that allow the asynchronous editing of data structures by a distributed set of processes without blocking states.

The combination of these two technologies allows any agent with a local copy of the graph to make changes to it, and have these changes sent over the network and update the remaining copies. The efficient use of network resources that avoids point-to-point connections, the use of an optimised middleware, eProsima Fast-DDS, and the theoretical properties of CRDTs entail that the multiple copies of the graph held by the agents can quickly converge to a common state [1] and act as a shared distributed memory[11].

The visual representation of the DSR image is given in the form of a graph (Fig.4), in which each node represents a concept, a device, a sensor or a person. Additionally, nodes contain a list of attributes that hold more information about their internal state.

The relationships between nodes given by the edges express a relationship of some kind. The most common is the relative spatial position given by the edge RT, which is represented by an $4x4$ affine matrix that allows fast transformations from one coordinate system to another. Other relations represented in the edges are logic functions between symbols [12].

[1]This property is known as eventual consistency


**Fig. 4**: Symbolic representation of the graph that constitutes the DSR.
Source: Robolab.

## 4.3 Two Levels

One of the innovations of this work is the introduction of a two-layer CORTEX-based control architecture. A global perspective of the system is shown in Fig.5.

The local control of each vehicle is performed by an instance of CORTEX running in the onboard computer (Fig.6), containing updated and real-time information from all sensors installed in the vehicle.

The complete system runs another instance of CORTEX at a global level (Fig.8) and on a server located at the edge of the network, this one containing reduced versions of the graph located in each vehicle, being the information updated on demand using communication bridges designed *ex profeso* to perform the reading and updating of both CORTEX instances.

### 4.3.1 CAV Level

This level, composed of the set of sensors, actuators and the CORTEX instance located in the CAV, is intended for both the acquisition of information from the environment and the direct control of the vehicle actuators, implementing low-level safety routines to avoid dangerous situations in case of loss of connection or obstacle detection. These requirements obey the needs of the project and of the physical environment in which the tests will be carried out. Among them, there is the choice of inexpensive hardware that still can acquire sufficient information from the environment to achieve the project objectives.

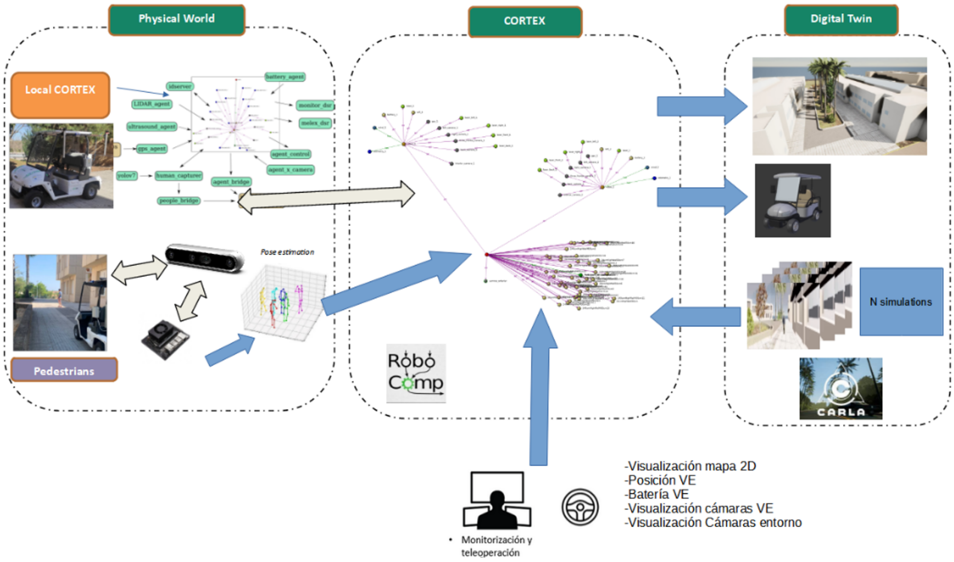


**Fig. 5**: Symbolic representation of the graph in CORTEX.
Source: Robolab.


**Fig. 6**: Symbolic representation of the graph in CORTEX.
Source: Robolab.

The option that has been followed to fulfil these requirements is the use of stereoscopic cameras instead of the more expensive Lidar systems. The accuracy and range of the implemented 3D camera system are sufficient for the tests carried out in the proposed scenarios.

Among the sensors or complete systems installed in the vehicle, we find: (Fig.7):

- **Vision system:** a set of cameras arranged around the perimeter of the vehicle to obtain image and depth information, both from the exterior and interior of vehicles.
- **Synthetic LiDAR system:** Emulation of a LiDAR system generated from visual information provided by the use of stereoscopic cameras.
- **GPS tracking system:** Use of precise location systems to obtain the real-time location of the vehicle.
- **Obstacle detection: LiDAR and ultrasound:** Use of proximity sensors for object detection in the near field of the vehicle. Different technologies have been used throughout the project, ranging from ultrasonic systems to single-point LiDAR and RADAR systems.

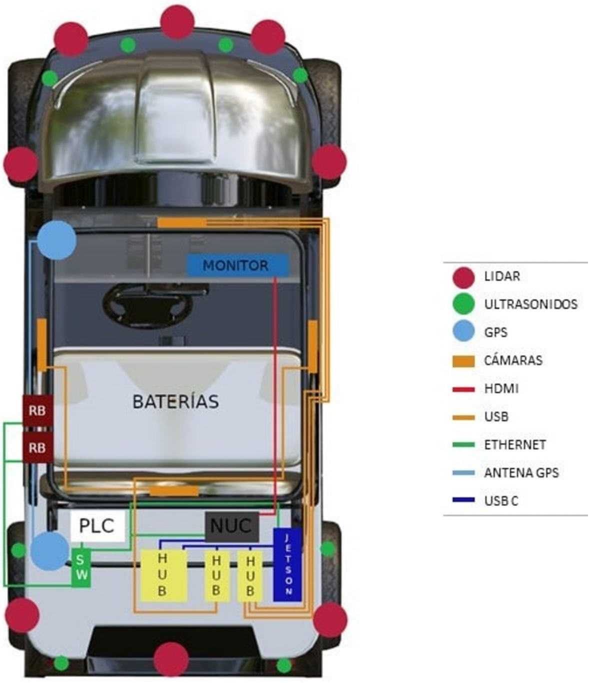


**Fig. 7**: Distribution of sensors in the CAV.

Each of the different sensors involves the development of an agent or component that transfers the corresponding information from the sensor to the DSR instance located in the CAV, this implies developing specific software for capturing information through the method of communication with the sensor (USB, Serial Connection, TCP/IP, etc) and its adaptation to the appropriate format and developed within the architecture to keep the control architecture updated in real-time and at an appropriate rate.

### 4.3.2 CAR Level

In real-time and from the remote autonomous control through the communication bridge, the necessary data are requested from the vehicles to keep the DSR representation updated (Fig.8), which contains the global image of the system. In this remote control centre, the necessary software for decision-making will be implemented. This CORTEX instance also represents all those CAVs that participate in the system, together with the operating environment data in which they work.

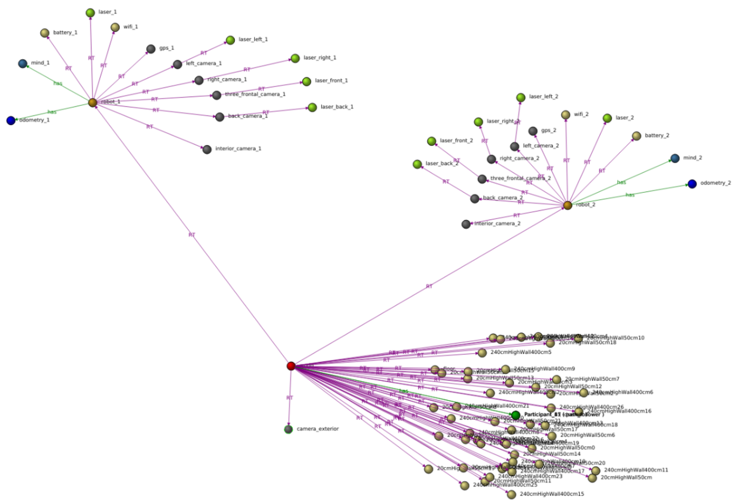


**Fig. 8**: Graph of the system with both vehicles and world elements

The main agents developed and implemented at this level form the vehicle control layer, which receives user requests and manages vehicle missions. Based on the origin and destination locations, the sequence of CAV control commands is generated and transmitted to the vehicle, taking into account both pedestrians and other vehicles.

## 5 Results

The remote driving tests are performed by a human operator located at the control station in the RoboLab laboratory. The created driving interface (Fig.9) shows the front view of the vehicle together with the vehicle's side cameras and the interior camera, displaying updated data on speed, battery status, vehicle position and orientation in real time. This interface runs independently of the driving mode, allowing a perspective from inside the vehicle at all times.

An example of remote driving is shown in Fig.10, where the operator controls the vehicle from the remote control centre. In the case of pedestrian detection, the vehicle slows down and eventually stops in the presence of a pedestrian.

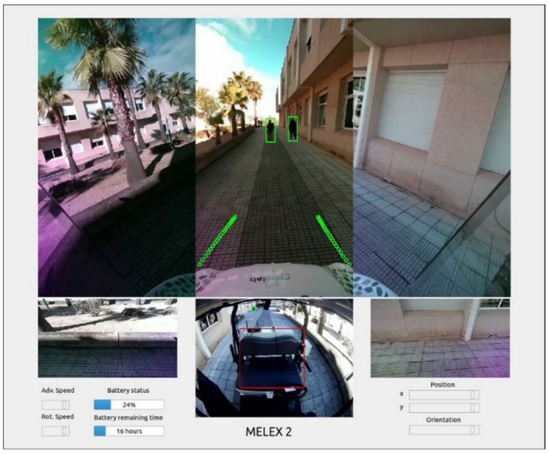


**Fig. 9**: Vehicle monitoring interface used in remote control integrating driving aids.

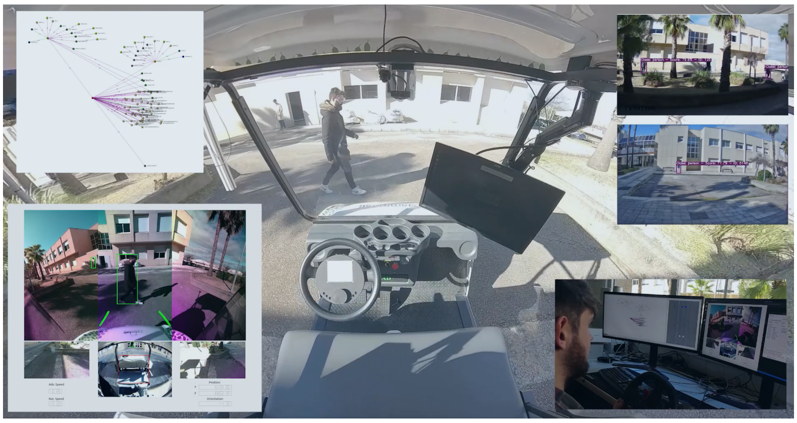

**Fig. 10**: Overview of the remote driving process and information visible to the driver, system graph, building CCTV cameras, vehicle interface with multiple cameras and driving aids (person and trajectory identification).

## 5.1 Autonomous driving

Autonomous driving tests are performed in a closed circuit where the vehicle remains in a loop waiting for a request. When a request enters the system (Fig.11) it is assigned to the first free vehicle that starts its way to the target. After arriving at the pick-up point and stopping, the vehicle waits for confirmation from the pedestrian via the application to start driving towards the target point.

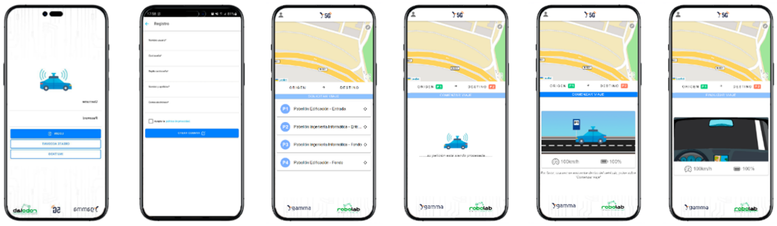

**Fig. 11**: Stages of the user application to request displacement.

Once the trip is resumed, the application presents updated information to the user until the destination is reached. After the user confirms the completion of the trip at the destination point, the vehicle resumes the trip, awaiting the next request.

# 6 Conclusion

Throughout this paper, we have detailed the adaptation process of a new autonomous vehicle controlled by a novel two-layer CORTEX-based architecture, where the control and management of the CAV fleet are performed at the edge of the network. The ability of the architecture to manage all the information flows has been successfully tested in both simulated and real scenarios, where the versatility in terms of operation allows a fast reconfiguration of the system, allowing it to move processes between the different devices. The advanced capabilities offered by the new generation networks allow a smooth and real-time exchange of the complex information flows required for CAV applications, where latency and bandwidth become critical.

**Acknowledgments.** This work is part of the project TED2021-131739-C22, supported by MCIN/AEI/10.13039/501100011033.

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