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Cooperative Autonomous Driving at the Intelligent Control Systems Laboratory

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Recently, Griffith University's Intelligent Control Systems Laboratory (www.gu.edu.au/centre/icsl), collaborating with INRIA's IMARA laboratory (www.inria.fr/recherche/equipes/imara.en.html), completed what we believe is the first on-road demonstration of autonomous passenger vehicles performing cooperative passing and traversal of *unsignalized* intersections. (Unsignalized intersections have no traffic lights, stop signs, or yield signs to control traffic flow.) This demonstration mated ICSL's communication and collaborative decision-making subsystems with IMARA's experimental vehicle platforms, creating autonomous vehicles capable of real-time cooperation in real-world applications (see Figure 1).

Design philosophy

To experiment with cooperation among autonomous vehicles without needing large-scale facilities, our early development work centered on creating small mobile platforms. The result was a family of Cooperative Autonomous Mobile Robots (CAMRs).[1] These small robots (approximately 30 cm in diameter—see Figure 2) have a differential drive system with optical encoders allowing precise control of velocity and heading. Their maximum speed is 0.1 meter per second.

The robots have three primary subsystems:

- Communication and sensing
- Collaborative decision making
- Motion execution

These subsystems are distributed, with individual functions having dedicated modules comprising a circuit board with a dedicated microcontroller. Modules communicate via an I^2C (Inter-Integrated Circuit) bus. Figure 3 illustrates the distributed architecture. This architecture makes implementing new functionality straightforward, eases maintenance, and avoids real-time-related difficulties that normally occur when a single microcontroller or microprocessor handles all control and decision-making functions.

Figure 4 summarizes the ICSL paradigm for cooperative autonomous driving. Here, *autonomous* refers to the ability to interact with the environment, cope with incomplete information, and adapt to unpredictable changes. *Cooperative* refers to the ability to work together to achieve global goals (for example, to avoid collisions) and to achieve individual goals (for example, traverse an intersection, stay on the road, and turn).

In Figure 4, the primary subsystems have interfaces (light blue) that correspond to the I^2C bus in the physical implementation; these subsystems' interaction leads to event-driven real-time cooperation. The system is event-driven because it uses messages, and it's real-time because it makes decisions immediately using the available messages. Cooperation results because a vehicle will consider other vehicles' needs before making any decisions.

Vehicle operation in an environment at any level requires some knowledge about that environment. Such knowledge could come from an a priori-created environmental map. However, our cooperative-autonomous-driving paradigm considers such a map as inappropriate for real-time on-road applications, where the environment is highly dynamic. Indeed, such a map is not required for the localized tasks of cooperative autonomous driving. We use an

Editor's Perspective

This installment describes a fundamental capability for future intelligent vehicles: cooperation. The possibility of cooperating and benefiting from one another's knowledge, and information in general, is crucial to achieving not only coordination—as described in the example at this article's end—but also high road efficiency and, consequently, global optimization. Intervehicle communication, and thus coordination, is also the key to improved safety, as Sadayuki Tsugawa described in this department in July–August 2000.

If you have any comment on this department, feel free to contact me. I also seek contributions on the current status of ITS projects worldwide as well as ideas on and trends in future transportation systems. Contact me at broggi@ce.unipr.it; www.ce.unipr.it/broggi.

—Alberto Broggi

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Figure 1. IMARA vehicles controlled by Intelligent Control Systems Laboratory hardware.

Figure 2. Cooperative Autonomous Mobile Robots.

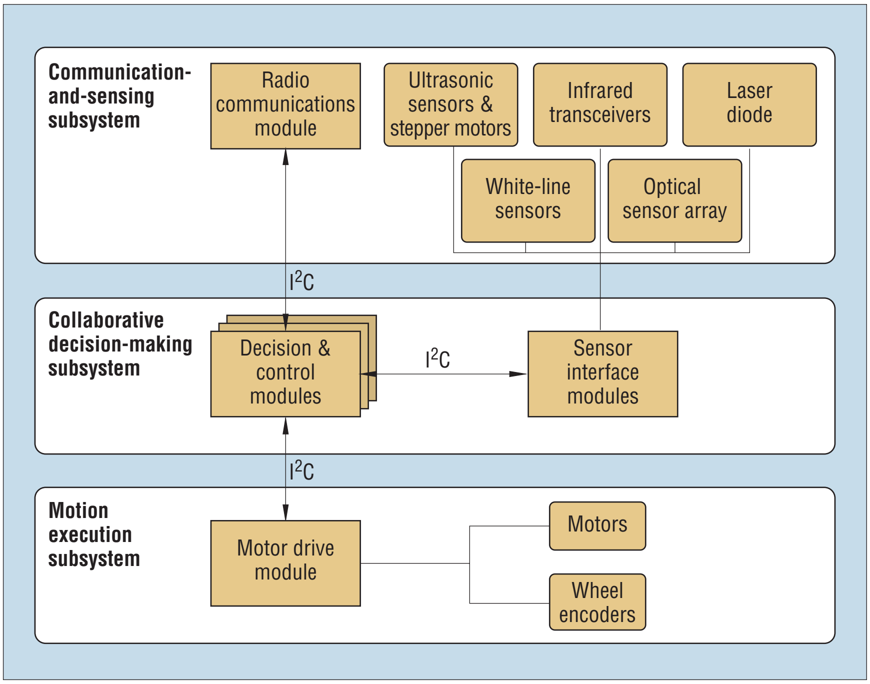

Figure 3. The CAMRs' system architecture.

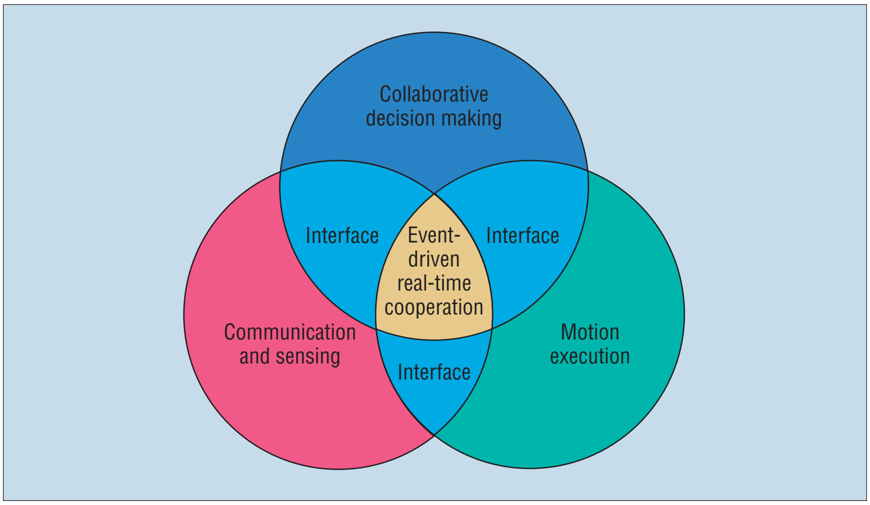

Figure 4. The cooperative-autonomous-driving paradigm.

event-based control and decision-making system where *messages* from the environment, other vehicles, or the vehicle itself trigger particular maneuvers and hence cooperation.

In general terms, messages can take one of three forms. *Implicit* messages refer to a common understanding of the correct maneuver under particular circumstances. For example, each vehicle should abide by the same road rules (CAMRs use Australian rules where necessary). *Passive* messages are inferred from an object's existence. For example, the white line on a road sends a message indicating the road boundary's location. Finally, *active* messages are explicitly sent by the originator and require an explicit communication channel. These messages provide information that the system could not otherwise infer via implicit or passive messages, such as a vehicle's (or driver's) intentions, and can subsume other message types.

Sensors and passive messaging

CAMRs use three forms of passive messaging. First, they can determine an object's presence and range through an array of 16 infrared transceiver pairs and two ultrasonic sensors. Second, they can detect lines on the road through an infrared white-line detector. Finally, they can determine their relative angle with respect to another vehicle through the optical-sensor array. These sensors fall into the communication-and-sensing subsystem. Because our experiments with the IMARA vehicles aimed primarily to demonstrate on-road cooperation, we retained the sensor technology developed for CAMRs rather than use more "robust" sensors such as ladar sensors.[2] To allow intelligent avoidance of dynamic obstacles, we are also developing a sensor that can segment the environment into coherently moving regions.[3]

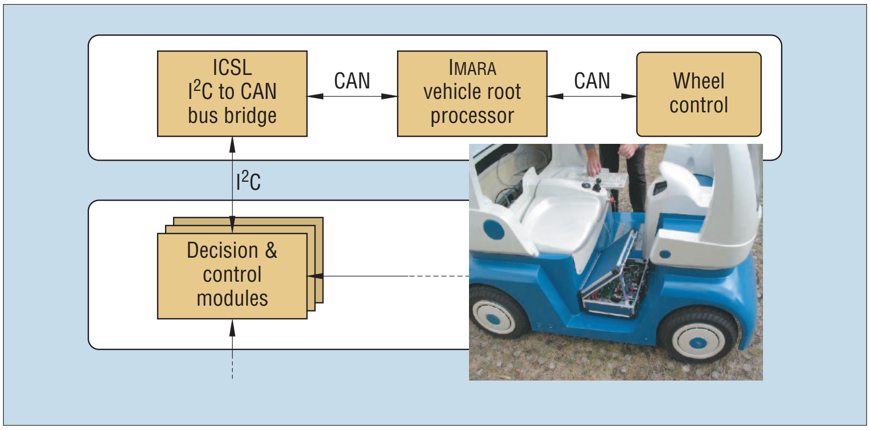

Figure 5. Mating ICSL hardware to the Imara platform.

Active messaging

CAMRs have two channels for external active messaging. The first is a general-purpose wireless link via a 433-MHz radio packet modem. This modem allows communication at 40 kbits per second over a range of up to 200 m. The second communication channel employs a combination of roadside beacons that transmit road information through a laser to a receiver on the vehicle. The radio modems remained unchanged for use on the Imara vehicles; however, we increased the roadside beacons' power and the receiver's size.

Driving maneuvers

A vehicle operating on a road must be capable of "survival maneuvers" such as road lane following and obstacle avoidance. Other important maneuvers for navigating through a road network include following another vehicle at a safe distance, passing another vehicle, and traversing an unsignalized intersection.

To implement road lane following and obstacle avoidance, CAMRs use the ultrasonic and infrared sensors. Rather than employing a visual cue to find the lane's center, we assume a "corridor" situation where walls mark the road boundaries. A CAMR then uses the ultrasonic sensors to find and maintain its position in the corridor's center, using the infrared sensors to detect and avoid obstacles.

To follow another CAMR at a safe distance,[4] a CAMR uses the ultrasonic sensor to determine the distance to the lead CAMR and uses the optical-sensor array to determine its own relative heading. A fuzzy controller in the following CAMR first matches the vehicles' speed and then aligns the following CAMR so that it follows directly in the lead CAMR's path.

Cooperative passing starts when a CAMR detects an obstacle ahead at some predefined distance.[5] When the CAMR detects such an object, it uses its optical-sensor array to determine whether the object is another CAMR. If the object is a CAMR, the first CAMR passes it according to Australian road rules (that is, pass on the right) under the assumption that the adjacent lane is a passing lane.

To traverse unsignalized intersections, CAMRs use messages from roadside beacons indicating the upcoming intersection's configuration, road markings indicating when the CAMR is about to enter the intersection (the stop line) and when it has exited the intersection (the clear line), and radio communication with other CAMRs to determine whether the intersection is clear. Cooperative intersection crossing operates on a first-come, first-served basis, with the intersection considered occupied when a CAMR crosses the stop line (in this situation, no other CAMRs can enter the intersection) and clear when a CAMR crosses the clear line. Experiments show that this approach works well, especially for low-traffic intersections.

From a hardware perspective, the decision-and-control modules (see Figure 3) make control decisions based on messages from the communication-and-sensing subsystem. The system then translates these control decisions into physical maneuvers via the motion execution subsystem. This separation of control logic and actuation makes the transition from the CAMR platform to the Imara platform straightforward because we need to replace only the motion execution subsystem. Figure 5 illustrates how we achieve this. Because the Imara platform uses a CAN (control area network) bus rather than I^2C, we have developed an I^2C-to-CAN bridge. We then program the Imara vehicle's root processor to correctly interpret messages from the master module so that the vehicle can perform appropriate maneuvers.

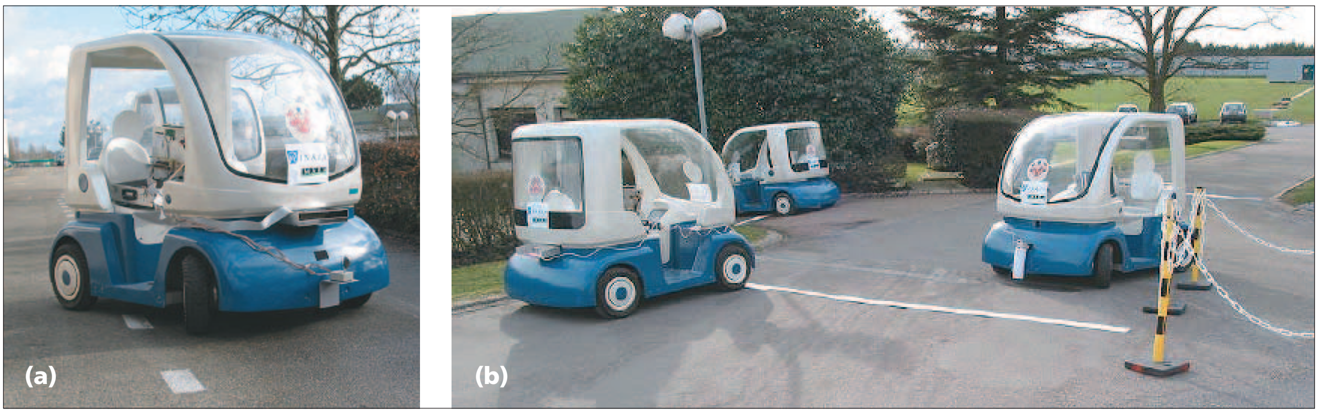

Figure 6. On road demonstrations of (a) cooperative passing and (b) unsignalized-intersection traversal.

On-road demonstration of real-time cooperation

Once we completed the interface from the ICSL hardware to the IMARA vehicle, we were able to perform successful experiments demonstrating all the available maneuvers. However, here we illustrate only cooperative passing and unsignalized-intersection traversal.

Figure 6a shows two IMARA vehicles performing cooperative passing. Here, the faster vehicle identifies the lead vehicle, pulls out of its lane, passes the slower vehicle, and returns to its original lane in front of the slower vehicle.

Figure 6b illustrates the success of our unsignalized-intersection traversal. In this demonstration, three vehicles approach an intersection. Following our algorithm and using the various messages described earlier, the three vehicles drive through the intersection without collision.

Our successful demonstration of real-time on-road cooperation among autonomous passenger vehicles shows how intelligent-vehicle technologies are coming of age. However, we still must resolve several aspects, including the appropriate choice of sensors for more robust messaging. Furthermore, because we tested each maneuver in isolation, we are now investigating the linking of maneuvers to ensure continual autonomy. We are also planning experiments with higher vehicle speeds (up to 30 kmh—the IMARA vehicles' maximum speed) and experiments incorporating our dynamic-obstacle-detection sensor system.

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Julian Kolodko is completing his PhD work by designing and implementing a sensor to detect and estimate motion for autonomous navigation. His research interests range from digital signal processing to autonomous-vehicle technologies and the principles of multirobot cooperation. He received his B.Eng. in microelectronic engineering and B.InfTech with first-class honors from Griffith University. Contact him at the Intelligent Control Systems Laboratory, School of Microelectronic Eng., Griffith Univ., Nathan Campus, 4111, Brisbane, Australia; j.kolodko@sct.gu.edu.au.

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