I-Cave : integrated cooperative and automated vehicles

i-CAVE Integrated Cooperative and Automated Vehicles

The future of moving forward

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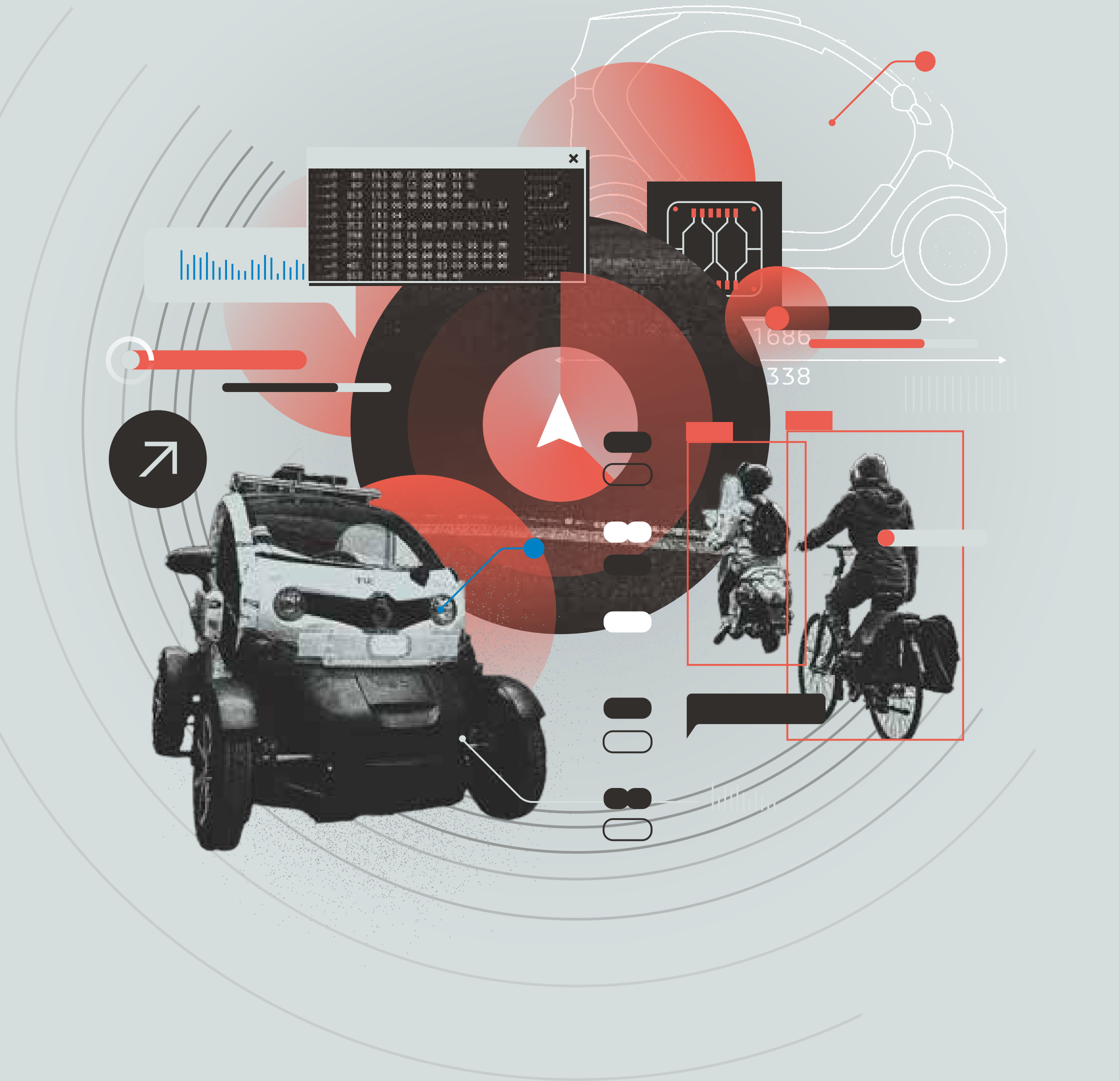
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The vehicle that 'does it all'

Ever since the first automobiles appeared on the road, the concept of the self-driving vehicle has captivated the minds of many. The 'auto' in automobile, not only stood for propulsion without the assistance of a horse, but also expressed the hope of a future in which humanity could benefit from a revolution in transportation. But as of yet, we're still waiting for that one magical vehicle that simply needs us to tell it where it should go, providing us with a smooth, safe and comfortable trip to our destination of choice, wherever that may be. And whilst in the meantime we have been capable of sending vehicles to Mars and beyond, getting to the grocery shop in a car still requires our own manual input behind the steering wheel. On the question of 'why is that?', there's only one possible answer: because it's just incredibly complicated.

That doesn't mean however, that the scientific community has given up on the subject. On the contrary; scientists, as well as the automotive industry, are developing new technologies at an incredible rate with new developments in driver aids are abundant and readily available in the vehicles of today. The invention of anti-lock brakes, electronic stability control, adaptive cruise control, different riding modes, automatic parking, emergency automatic braking, lane departure systems and many more, has already dramatically improved the safety and comfort of our journey from A to B, and each development has brought us at least closer to different forms of partial automation. Thanks to fundamental research, now is the time to rethink the area of mobility and push forward in developing new standards and innovating how we use technology to ultimately bring us closer to the realisation of the self-driving vehicle.

The I-Cave programme

And that's where the I-Cave programme comes in. Over the last five years, this research programme addressed many of the current transportation challenges regarding throughput and safety with an integrated approach to automated and cooperative driving. In I-Cave, a Cooperative Dual Mode Automated Transport (C-DMAT) system consisting of dual mode vehicles which can be driven automatically or cooperatively to allow maximum flexibility, was researched and designed.

The programme has integrated technological roadmaps for autonomous and cooperative driving, accelerating the development of novel transportation systems addressing today's and future mobility demands. In the case of autonomous driving, the vehicles, or more accurately the algorithms that control the vehicles, use information they collect themselves. If they partially or entirely obtain their information via other vehicles, then this is called cooperative driving. In that case, the information improves the collective behaviour, which, amongst other things, improves the traffic flow. However, this does require the vehicles to communicate with each other via a wireless connection. The research proposal was aimed at various aspects of autonomous and cooperative driving.

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Besides these enabling technologies, focus was put on fault tolerance and fail safety, wireless communications, human factors and others addressing transition of control between manual and automated driving and response of other road users. I-Cave has tackled much of the main challenges of automated driving, achieving high levels of safety and reliability through rigorous technological design, combined with seamless integration between automated and manual driving to obtain maximum flexibility and user acceptance. A living lab, consisting of a number of small electric vehicles, has been used for the integration and evaluation of accurate vision-based mapping and localisation techniques, distributed cooperative vehicle control algorithms and fleet management methods. This allowed for a close-to-market transport system, which can be commercialised by the transport industry, and specifically the leading automotive tiers in the Netherlands, by applying the results in their roadmaps.

The scientific challenges were abundant, to say the least, all stemming from the central research question of the I-Cave programme: How can the technological aspects of cooperative and automated driving be combined with the human factor aspects whilst guaranteeing efficient, safe and acceptable cooperative automated driving? The innovative character of I-Cave lies in the coherent and integrated setup of its projects, which shows an internationally unique multidisciplinary approach, solving the fundamental challenge of advancing and integrating different enabling technologies with human factors (HF) in a fundamental concept of mobility.

To provide answers to the central research question, a primary set of scientific challenges were identified and addressed.

How can we:

1. Design intrinsically safe and efficient Cooperative Dual Mode Automated Transport services for goods and people with a maximum level of comfort in urban type environments?

2. Design highly reliable, accurate, and scalable digital video-based sensing, mapping, and localisation technologies that support cooperative and automated driving?

3. Control individual cooperative vehicles taking into account vehicle dynamics, longitudinal and lateral string stability, and human behaviour, including how to obtain a sufficient level of fail safety and fault tolerance?

4. Manage (dispatch, route and reposition) a fleet of cooperative autonomous vehicles for passenger and cargo transport in an efficient and cooperative way, taking into account longitudinal and lateral string stability and cooperation between multiple strings of vehicles?

5. **Obtain an intrinsically fail-safe, fault tolerance system of Vehicle-to-Vehicle (V2V) communication to support cooperative driving?**

6. **Take human factor issues into account for drivers, as well as guarantee the safe interaction with other road users including vulnerable road users?**

7. **Design and evaluate the functional architecture and quality model of autonomous and cooperative vehicle software?**

To address all of these challenges, the I-Cave programme was divided into seven distinct, but intertwined projects, with each project group focussing on one of the mentioned scientific challenges. Below is a short description of the seven projects that collectively formed the basis for the programme:

1

Project 1 Sensing, mapping & localisation: focused on sensing-related challenges in automated driving. In this project, research and development focused on self-learning computer vision technologies (detectors and classifiers) that allow the vehicle to better perceive its surroundings, reducing its dependency on Highly Automated Driving (HAD) maps and real-time computer vision technologies for accurate localization in HAD maps under all weather conditions. Developing distributed computer vision technologies for crowd sourcing the information required the team to also (partially) create and update HAD maps as part of the project scope.

2

Project 2 Cooperative vehicle control: focused on designing an experimental evaluation of distributed controllers for cooperative and automated manoeuvring, global and local control algorithm concepts. Implementations that ensure longitudinal and lateral string stability of platoons of vehicles were researched and evaluated as part of this team's dispatch.

3

Project 3 Dynamic fleet management: focused on developing fleet management (FM) methods taking into account uncertainty in demands and dynamic situations. Their objective was to leverage fundamental research to develop practical approaches for scheduling, repositioning, and making use of parked vehicles to reduce the overall amount of vehicles and parking spaces needed. Extensive experience with FM strategies for fleets of port-based automated guided vehicles (AGVs) for cargo transport, and strategies for coordination of fleets for inter terminal transport and routing of airplanes formed the basis for addressing these challenges.

4

Project 4 Communication: focused on radar-based communication. This project aimed at exploiting existing radar front-ends as a means for (radio) communication and levering existing WiFi-P protocols for radar-based communication. Special focus was paid to tight integration of both communication modalities, with the aim to develop highly robust multi-modal communication technologies, protocols, and standards for vehicle to vehicle communication. These protocols and standards also involve high-level mechanisms for sharing crowd sourced data between vehicles (radar-based) and traffic management systems (WiFi-P based).

An integrated quality model was explored, for use at all stages

5

Project 5 Human factors: focus was on configuring a fail-safe human-vehicle symbiosis in which the driver knows exactly what the vehicle will do under what circumstances, and in which other road users interact with the vehicle in a natural and self-explaining manner. Questions that were explored included: How to safely design for dual-mode transitions? How to design an intuitive Human Machine Interface (HMI) for dual-mode vehicles? How should the Cooperative Dual Mode Automated Transport system (C- DMAT) 'behave' so the driver does not overrule the system, and how do drivers respond to (apparent) vehicle failures or limitations? How do other road users respond to and interact with (partially) automated vehicles?

6

Project 6 Architecture & functional safety: focus was on design and evaluation of the functional architecture and quality model of autonomous and cooperative vehicles software. An integrated quality model was explored, for use at all stages - from architectural design to implementation - by extending the Hazard Assessment by Risk Analysis. Evaluations were conducted by running scenarios from Architecture Tradeoff Analysis Method (ATAM) on the living-lab demonstrator system.

7

Project 7 Demonstrator platform: covered all key enabling technologies for sensing, system integration and communication architecture including dynamic fleet management, handling of human factors and functional safety for technology demonstration in a living-lab environment. Results and deliverables of projects Project 1 to Project 6 were combined and integrated in Project 7 into a demonstrator, consisting of several dual mode automated vehicles, operating in a concerted mobility system in which transport demands by end-users is matched with vehicle availability, human factors are fully integrated in the transport concept, with the aim ultimately, to create an intuitive and safe user experience and avoids accidents in the entire system.

Reflecting on research

Within this book, all of the projects above are featured with the responsible project leaders and staff members reflecting on the past five years of performing research. What were the goals they set out to achieve? Did they succeed in reaching them? What kind of obstacles or surprises were found along the way? These questions, and many more, came along when working on this book. Their personal stories bring years of research to life, summarising the great scientific progress that has been made by each of the individual project groups, and which have brought the future of mobility more than a few steps closer to the world of today. It's been a privilege to speak to each and every one of them.

— Jaap van der Sar, editor.

I-Cave: a driving force in further research

HENK NIJMEIJER

Henk Nijmeijer, leader of the I-Cave programme and a relentless pursuer of the science behind autonomous and cooperative driving, set out six years ago to push the boundaries in this futuristic field of the automotive world. Now I-Cave has come to a closure, he reflects on the past years and provides us with a peak into a future of 'new mobility'.

"Running a programme as large as I-Cave creates its own challenges. Not only did each of the separate projects have their own scientific challenges, which were often truly challenging in themselves, we also set a requirement that the 'users' be well connected to each of the projects- with the ultimate aim to reach beyond merely achieving a set of 6 distinct outcomes. In this way, Project 7, the demonstrator platform – became the melting point in which the outcomes from the other projects were fused to establish the development of dual mode vehicles.

Even though at the start, and even ahead of the start of the programme, we already had a clear idea that a Renault Twizy from a previous research project would be our baseline demonstrator vehicle, it needed to be adapted to become autonomous and/or cooperative. Bringing in additional tooling from the other projects was by no means a trivial undertaking, as any extra sensors needed to be fused in hardware and software from the baseline vehicle. And then, given that a Twizy isn't that big; we were faced with additional challenges of where to place the extras? Is the battery capacity sufficient? Do the various software platforms 'match' each other? And so on."

"Given that this was a programme with separate projects, once a year, a full day meeting was organised to enhance collaboration between the projects, and where possible, to also stimulate further interactions with the large number of industry stakeholders who provided sponsorship in various ways to the programme. The Automotive Technology lab at the TU/e was the home for the demonstrator project and in the course of the programme several of the researchers found their way to the lab further strengthening the mutual trust and the desire to join forces."

Challenges unforeseen

"And then early March 2020 as the Covid-19 pandemic gathered pace, everything collapsed: The universities closed, the AT lab closed, no direct interactions between researchers, students, supervisors, were possible and our world went fully online. Besides the fact that no one could have foreseen this, it also presented serious challenges the individual researchers who, now based at home, continued to work on their research areas, were sometimes worrying about the remaining time and how to cope with possible experimental testing of their specific solutions."

"As programme leader I had to face the largest question: how should we redefine I-Cave given the limitations due to Covid-19. The adaptability and resilience of the team members really shines through when you see how each project was able to reset its goals and overcome obstacles to achieve what we did - details of which are highlighted in this book."

"As a relatively small research team, at least in comparison to car manufacturers, we have been able to work on our dual mode vehicle and to obtain some very good illustrations of what is required for a cooperative/autonomous vehicle. I am extremely proud about what has been accomplished, especially given all unforeseen problems. Overall, the clear fact that as researchers we have been able to develop new tools, algorithms etc and demonstrate this either on our Twizys or in software demonstrations – these are the achievements that have been a real highlight for me."

The potential of digital twins

"One of the buzzwords of in today's tech community is 'digital twin' which are essentially fully developed software models of the real set-up. Looking from a distance at the I-Cave programme, we have seen that within in each of the individual projects we have built a digital twin, and the demonstrator platform acts as the integrator of all the digital twin components. I should confess, we aren't there yet, but it forms probably one of the most promising views I have gathered from this project."

"Did we achieve our goals? Of course not, research in itself always has some elements which are out-of-control, and there is never a moment that researchers will say 'it is finished'. Research also is a driver for further research and the I-Cave programme is no different. We may not have created THE perfect dual mode vehicle, but we have learned and demonstrated, how our way of integrating some of the separate project results may provide THE way to design a complex integrated technological platform. I kindly invite you to read the personal stories of the project leaders and staff members from all the different I-Cave projects, and get a glimpse into the future of mobility."

1

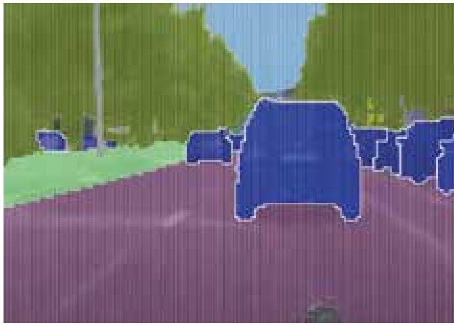
Building the brain

GIJS DUBBELMAN

Gijs Dubbelman, leader of Project 1 in the I-Cave programme, has been involved with the concept of self-driving vehicles for many years. In his mind however, the reality of present-day transportation capabilities, is far behind what the future of autonomous transportation could be, - a hassle-free, cheap, reliable, fast and especially- safe way of mobility. Whilst we're not there yet, his work on the sensing, mapping and localisation challenges of creating 'the car of the future', will no doubt steer our current reality closer towards his dream.

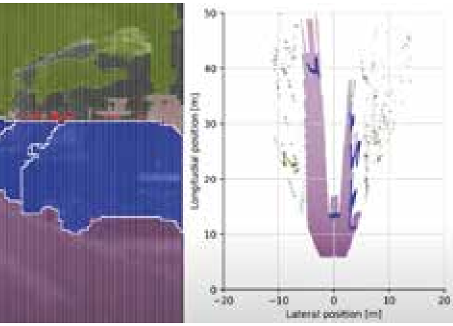
"In the years before the preparations for the I-Cave Project started in 2014, I was involved in researching the concept of the self-driving vehicles at Carnegie Melon University in the United States. So, it's safe to say that

In our field of research, we build the brains behind the eyes.



this subject had definitely already captured my interest. But while my former colleagues all left the scientific community to work at high tech companies in the US, I could not get enough of doing more fundamental research in this area. So, I returned to the Netherlands, to the Eindhoven University of Technology, where it turned out that there was not yet a lot of expertise in the field of mapping, localisation and perception, which are all key elements for a self-driving vehicle. After all- it needs to know where it is and it also needs to look at its surroundings and just as important, understand these surroundings. Fortunately, there was an ambition at the university to obtain this expertise, an expertise which I already had, so that's how I ended up as part of the Sensing, Mapping and Localisation project within the I-Cave programme."

"The self-driving vehicle is such a fascinating concept, in which a lot of different fields of expertise coalesce. And yet, the basic concept is actually quite simple: imagine yourself driving a vehicle with a blindfold on. It's impossible and you are guaranteed to crash in no-time. You need your eyes to operate a vehicle, and that is exactly what our artificial intelligence, or AI, is aiming to be. Now picture yourself looking out of the vehicle, you see a pedestrian on the side of the road. As humans we can translate this into all kinds of information, but for a computer it is just a collection of pixels. They don't have any meaning yet. We need to apply artificial intelligence to that picture, and to all the other sensory data as



well, so that the system can add meaning to this data. Then the computer starts to understand the environment. In our field of research, we build the brains behind the eyes."

Leveraging developments in Artificial Intelligence

"This all may sound relatively easy, but it's difficult enough to figure out how our own brains work, let alone to create an artificial brain from scratch. What helps us with that, is the enormous leap in the development of artificial intelligence, caused by the phenomenon called Deep Learning. This is a methodology in AI where you make use of deep neural networks that you train through data. These neural networks are inspired by the way human brains work and make it possible to teach the computer how to interpret the data coming from the 'eyes' of the vehicle. It's fascinating technology that has revolutionised artificial intelligence and allowed us to make powerful brains for vehicles."

"We started our project with defining the tasks we needed to work on. To go back to the 'problem' of the pedestrian I referred to earlier, one of these tasks we identified that needed to be solved was how to detect whether or not a person is going to cross the street. We needed a form of AI capable of predicting that. This is in fact a deep learning task, which therefore requires the initial collection of the right data which then needs to be annotated. Annotating data simply means that a human must look at all this data and say: 'Yes, this pedestrian in this picture is going to cross the street, this one isn't, this one is, etcetera.'. By doing this, we help the system to actually learn from all this data which allows us to create a model that not only recognises what a pedestrian is, but can also predict whether a pedestrian is crossing the road or not when new data is coming in."

"As you can see, human involvement in annotating the data is necessary. The system cannot learn by itself yet, so it uses the model that's been created by humans. Most systems however, stop learning as soon as humans stop annotating this data, so in order to keep learning, a lot of human input is needed. The more data is collected and annotated, the more accurate a system will be able to perform tasks and make the right decisions.
So how do you collect all this data? That's where the power of a whole fleet of vehicles comes in. Tesla was one of the first brands to actually make use of all data collected by each individual vehicle. How does that work? They send a message to all of their vehicles, for instance, 'give me all the video feeds where you saw a pedestrian cross the street by a traffic light'. All of this data is stored at Tesla, the data is then annotated by humans, the model is trained and the new model is ready to be uploaded to all Tesla's via remote software update. In this way, you create a continuous loop of improvement, which is incredibly powerful. Indeed, the more data that becomes available, the better you could say."

Sharing data

"The safety aspect of our artificial intelligence is also an important factor. If the architecture of our artificial neural networks would be standardised, in a way that all the manufacturers would use the same systems, that would be very helpful. But that's only half of the story. The other half is the training data. Standardised open data, for everybody to use, would also be helpful. Much more data would be available meaning the systems could improve and become safer more quickly as well. If those factors

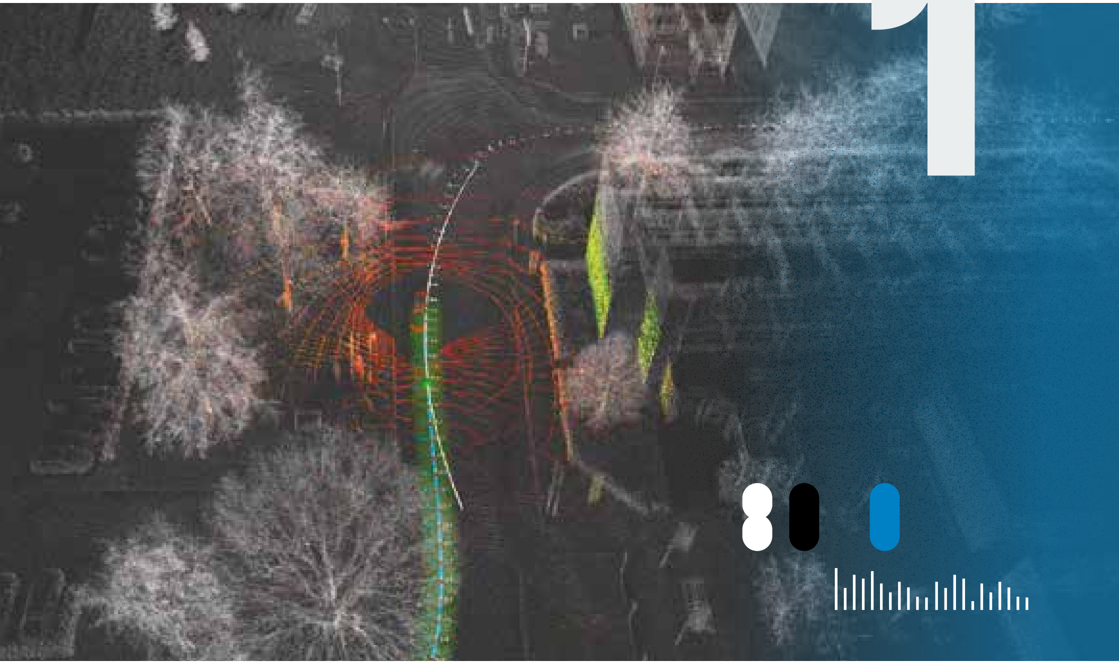
were realised, the development of usable artificial intelligence could get a real boost. But as things are right now, the manufacturers want to keep their data to themselves, because the data is where the money is."

"Will we ever drive a fully autonomous vehicle? In all honesty, things could go either way- 'yes' and 'no' are both credible options. At the moment, we can distinguish two lines of technological development. The first line continues in pace with technological progress in the automotive industry. Step by step, more sophisticated driving aids are added to vehicles and with each step, more autonomy is added as well. That might be enough to work in certain areas, such as highways or industrial areas, but despite these developments, I have my doubts whether fully autonomous driving in every condition will be feasible within the next couple of decades. Urban areas are simply too complex, especially since cyclists, non-autonomous vehicles and pedestrians don't always follow the traffic rules, creating unpredictable and chaotic situations.

Will we ever drive a fully autonomous vehicle? In all honesty, things could go either way- ‘yes’ and ‘no’ are both credible options.

There is however, another line of research on the concept of the ‘robot taxi’, in which the domain where the vehicle can drive is restricted. Since a fully autonomously driving vehicle in all conditions might be out of reach, it is important to also research how to switch between autonomous driving and manual driving. We call this dual-mode driving. These dual-mode concepts require a lot of considerations regarding user experience and therefore are researched in Project 5 by the team of Marieke Martens.

In this scenario of the robot taxi, we can make autonomy possible only on certain routes, for instance from the airport to the train station or from the harbour to the underground. It includes only a limited number of destinations, always driving on the same track and, on this track, we can incorporate special traffic rules. For example, traffic lights always responding in favour of self-driving vehicles, that would be safe and



fun at the same time! Even more interesting is technology that allows vehicles to communicate with each other such that they can jointly plan safe and efficient actions. We call this cooperative driving and it is an important aspect in many of the I-Cave Projects. If all road users could communicate with each other, safe self-driving would be considerably easier to realize. If we can shape the environment within a limited domain to align with technological developments, then autonomous driving would absolutely be possible in the near future.”

Bottlenecks

“If you follow the line of the ‘robot taxi, two big bottlenecks occur. For a self-driving vehicle to work, they have to depend on extremely detailed maps, far more accurate than the maps we currently use for navigation, almost digital copies of the environment. Creating maps like this,

especially if you want to make them for a whole country, is extremely labour intensive and therefore, not economically viable for development. Part of our research challenge therefore, was to investigate whether it would be possible to develop better automation techniques to create these maps in a less time-consuming way.
The second bottleneck was essentially the other side of the coin: How can we make vehicles less dependent on these maps? Can we use artificial intelligence in such a way that these vehicles don't need these detailed maps? Making the map more efficient was a more 'applied' research goal whilst the implementation of artificial intelligence was a more fundamental research goal. We then started working on those problems, two PhD students for each bottleneck, with the 'Mapping' part working very close with our partners TomTom and Navinfo Europe."

"To put the technology that we developed to the test, we were eager to develop a research vehicle, that could house all the research technology so we could use that as a testbed. Of course, this also included using the Renault Twizy's from Project 7, but next to that we decided to create our own test vehicle, a Toyota Prius. On top of this vehicle we installed a series of sensors for the Prius to perceive its environment."

Reaching our goals

"During the research we set ourselves one tangible goal: by the end of I-Cave we want to end up with a vehicle that can create its own map from our artificial intelligence and have the capability to function autonomously. It is nice to know that we actually achieved this; the Prius is a very functional testbed, on which the 'mapping' part of our research could be extensively tested. It works, has the same kind of capabilities as these robot taxis do and has proven that it can drive autonomously in a restricted area. So yes, we have made a lot of progress, thanks to our PhD student and partners.
If you also look at the scientific goals that we have achieved, then you see that we have also made key achievements in the development of

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If you look at the scientific goals that we have achieved, then you also see that we have made key achievements in the development of artificial intelligence.

artificial intelligence. One of our PhD students, Chenyang Lu, developed a so-called auto encoder, a mathematical technique, with which the human effort in annotating data can be greatly reduced. This will save thousands of hours of human input in the future and will bring artificial intelligence a big step further. This is a real innovation which we are very proud of. And yet, it also demonstrates the gap between real fundamental research and applied science, because bringing this technology to life in a self-driving vehicle, will take still a lot more research, man-power and not to forget: extra funding. That's not possible in an academic setting, we can only hope that this will be picked up by the industry, so that it can get the chance to grow."

"If you look at the whole I-Cave Project, a lot of people, universities and companies have been greatly involved with research and developments on all of these very important fields that exist in the world of autonomous mobility. Yet, if you compare the I-Cave Project to all the research that is still being done by the industry and other countries worldwide, literally billions are spent, and I-Cave is just a small player on an enormous field. The thing we Dutch are really good at however, is picking out some small parts of this giant field of research, and excel in thinking of real innovative solutions that can have a big impact. Therefore, we can be extra proud, because what we did achieve in the development of the self-driving vehicle, is really helpful to bring mobility some steps closer to the future. And we have to consider as well that the progress is not only dictated by technological developments alone. It depends on so many societal factors as well."

"For me personally, the end of the I-Cave programme is a starting point for doing even more research and seeing if it's possible to bring our achievements in the field of artificial intelligence to date- a step further. Our research has also shown me where the role of the university ends; you can only do so much and then the continuation of the project has to be brought outside of the university, because other research projects deserve their own time and space as well. We can never solve the whole puzzle of the self-driving vehicle, it's just too much work, and the role of a university is there to provide a safe haven for all kinds of research, not only the autonomous vehicle of course. Therefore, we've created a start-up called AI In Motion, which is meant to close the gap between fundamental research and applied science and accelerate the application of artificial intelligence to continue the work that has already been done during I-Cave. So, the story lives on, thanks to the I-Cave programme, taking more steps into a whole new world of autonomous mobility."

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Improving Artificial Intelligence

CHENYANG LU

For artificial intelligence to actually be any good, a lot of bright minds have put their own intelligence to work. One of these minds belongs to former PhD Chenyang Lu, an expert in artificial intelligence. He combined his creativity with in-depth and innovative thinking in order to bring artificial intelligence to a new level, and in the process made critical steps forward in the long road towards the self-driving vehicle.

“During the writing of my proposals at the outset of the I-Cave programme, the main question that I really wanted to dig into was: how can we teach computers to think? How do we get them to mimic the human brain?

These are grand questions of course, but essential if you really want to make progress in the field of the self-driving vehicle. For a vehicle to be able to understand the real world, it needs to ascertain what to do with all kinds of sensory input from cameras, radar systems and other devices. Whilst there are already multiple options that exist to perform these tasks, using artificial intelligence or not, these options are not efficient enough and depend on a huge amount of human interference before they can be put to good use. Putting my proposal together, it became quite clear to me that there was still room for improvement by using artificial intelligence to create new possibilities which can ultimately deliver more than the traditional capabilities of computers. This proved to be my starting point for my research."

Teaching computers

"To build the foundations of my research I established what current artificial intelligence is capable of. What can it actually do? I can assure you that artificial intelligence as we use it now, is still a far cry away from

I can assure you that artificial intelligence as we use it now, is still a far cry away from the artificial intelligence that we see in the movies.

the artificial intelligence that we see in the movies. The programmes and algorithms for AI that exist now require a large amount of manual input in order to teach artificial intelligent algorithms how to operate. This is a typical paradigm. As humans, we subconsciously process millions of thoughts informed by our experiences and knowledge before we take a decisive action. For example, when we see a vehicle ahead of us on the road, we process multiple possible situations and predicted scenarios before we decide: 'ok, I'm going to stop here, or otherwise we'll crash'. This is of course, the logical decision anticipated upon seeing a vehicle brake in front of you. If you want artificial intelligence to act in the same way, and for it to take the best possible action in a given situation, you'll have to teach the computer all these millions of possible scenarios as well, which is extremely expensive and maybe even impossible."

"From all these different scenarios however, which is the most important? For 99 percent of the scenarios, we only need one percent of data, or possible examples, to be available. That's because there are traffic rules and certain ways we behave in traffic and the number of possible situations is actually limited. It's the 1% of extreme scenarios however, that happen rarely and go against the system, that require the use of the other 99 percent of data or extra efforts. Currently, this is a major challenge for an artificial algorithm. To my knowledge, no academic research, vehicle manufacturer or big supplier has solved this problem yet. From my point of view this is therefore the critical challenge to be overcome; if you can succeed in teaching artificial intelligence every possible scenario that exists, then you've cracked the problem and the objective of the autonomous vehicle will have been achieved. At present, we can actually foresee a future including vehicles with limited autonomous characteristics, as long as we create an environment that requires a limited number of scenarios. If pedestrians have no access to the road for instance, you won't have to teach the system possible dangerous situations involving pedestrians."

A new approach

"Numerous problems still need to be solved if we're ever going to drive autonomously. So, can we accelerate progress by limiting the amount of teaching you have to put into artificial intelligence systems? Or, is it possible to automatically feed endless amounts of scenarios to the system, without humans having to provide the corresponding expected ground truth to the computer for learning? As a result of my primary focus on solving these questions, I've come up with a different approach. If you make use of as many cameras as possible from all kinds of vehicles, millions of images are available to use. Then, one could feed these images without expensive manual annotations into the AI algorithms that can learn to understand scenes, or even to make correct further decisions, by themselves. This will save us from doing endless, intensive and especially boring manual labour, that nobody wants to do. Whilst I still need a lot of data to further develop this new approach, coming up with this concept, and figuring out for the most part how to implement it, is probably my biggest contribution to our project. But before it's ready to implement, we've still got a long way to go."

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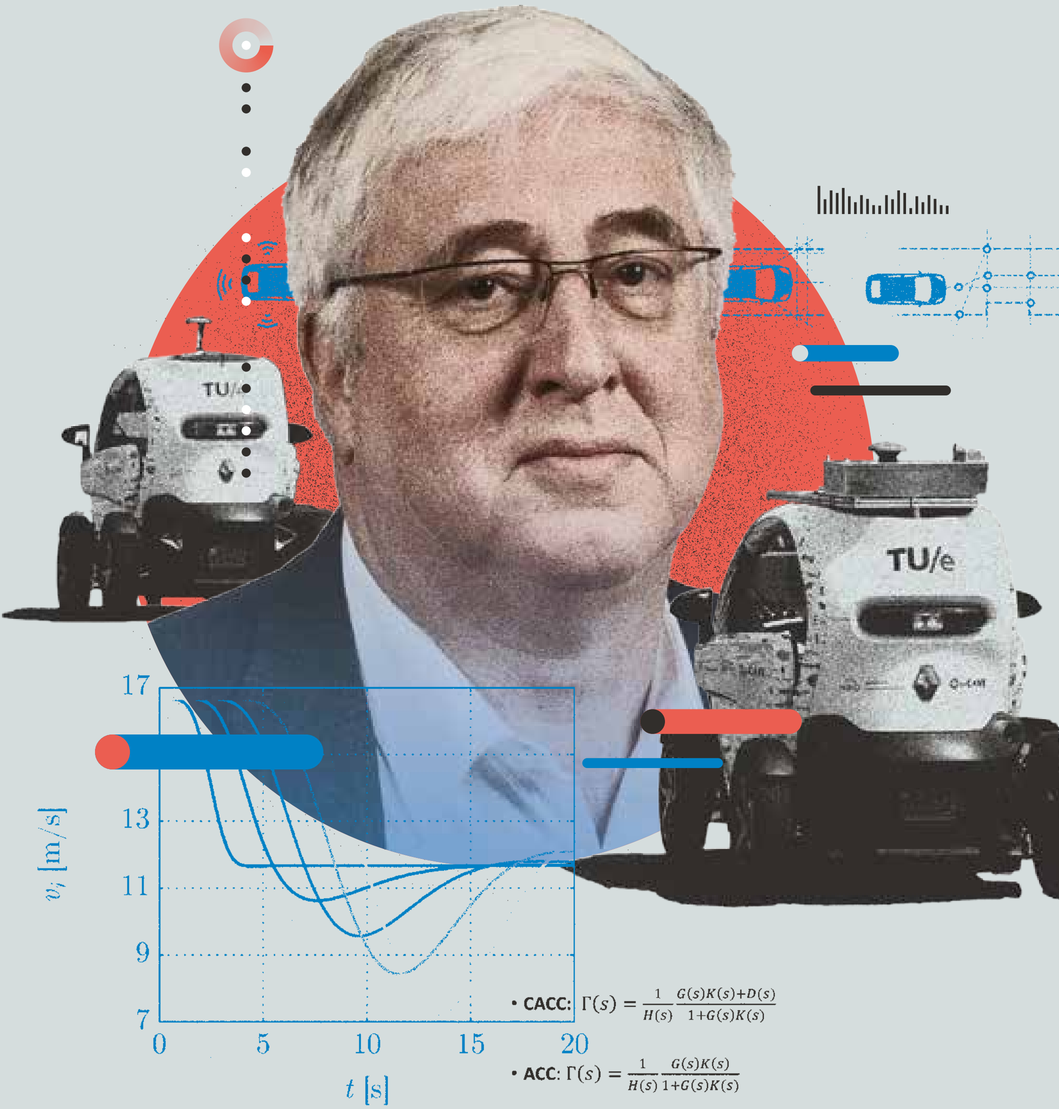
If you can succeed in teaching artificial intelligence every possible scenario that exists, then you've cracked the problem.

“On a personal level the biggest highlight for me has been the ability to bring my creative side into the fold and to contribute to the development of fundamentally important research in this field of artificial intelligence. Combining my thinking with the other project groups within the I-Cave programme was really what made this experience so special. You learn from each other, get inspired and come up with new ideas and possibilities that may not have happened by working in isolation. Despite our limited resources and budget, we were able to make some truly innovative steps towards the future. For me, the work on this concept is going to continue, and who knows, maybe someday it will contribute to a vehicle that brings me to work and back, while I'm trying to solve yet another challenging problem.”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The challenge of control

HENK NIJMEIJER

Getting a vehicle to move from A to Be on its own could be extremely simple, if it weren't for an environment full of endless uncertainties. The more you dive in to this, the less possible it seems to tackle every uncertainty that a vehicle and driver can encounter when travelling from the front door to the final destination. Henk Nijmeijer took the lead in the research project of cooperative and autonomous vehicle control and gives us insight into a world in which each answer seems to lead to an entirely new set of questions.

"The word 'control' is the essential ingredient in this part of the I-Cave Project. The project as a whole of course, is centred around the theme of the dual mode vehicle. A vehicle that can navigate its own way in a restricted area, completely autonomously, whilst also being able to function cooperatively as part of a platoon of vehicles. The fundamental question that immediately presents itself: is it possible to develop one control technology, a software package, that is able to carry out these two different tasks? Or, do we need to develop two distinct pieces of software architecture, each capable of doing one of these tasks? In wanting to combine autonomous and cooperative, we're faced with two completely different ways of thinking in driver assistance. Cooperative driving depends on communication with one or more vehicles in a chain, with a vehicle in the lead to 'set the pace'. That's an important condition for cooperative driving. Of course, a cooperative vehicle can have its own sensors, cameras or other technology, but the main thing is that it utilises the information provided by the vehicle driving in front of it. What is its current speed, how fast does it accelerate, when does it brake? With a continuous flow of information, a cooperative vehicle makes use of that information to drive from A to B as efficiently as possible."

A head start

"When we look at the autonomous vehicle, we soon come to the conclusion that this is a completely different concept all together. An autonomous vehicle does not have the need to communicate with other cars, or make use of information coming from cars in front of it. Indeed, instead of being helpful, other cars merely act as moving obstacles that have to be watched and taken into consideration. For this part of the I-Cave programme however, we focused purely on the concept of the cooperative driving vehicle and how to use existing, or future technologies, to make this kind of vehicle feasible. We did not need to start from scratch luckily, as the Eindhoven University of Technology was already a world leader in this field of research at the beginning of this programme. Prior to I-Cave, we had been undertaking projects together with TNO Helmond to develop technology for creating platoons, that is cars driving cooperatively within certain areas. We had already made

When we look at the autonomous vehicle, we soon come to the conclusion that this is a completely different concept all together.

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progress as far as accelerating, keeping distance and braking was concerned. In cooperative driving however, the aspect of steering has proven to be a whole different playing field and until now we still need a human driver to operate that facet of driving.”

“The precursor to the concept of cooperative driving is already common in the car industry, in the form of adaptive cruise-control (ACC). The main difference with cooperative adaptive cruise control, or CACC as we call it, lies in the area of communication with the vehicle in front. ACC uses only the car’s own sensors, radar and camera. As there is no data from other cars feeding in, it has a much slower response time, and therefore, functions best when roads are not too busy. When you add ‘cooperative’ to the equation, you can make use of a wireless connection between cars and the response time is reduced to just a fraction of what ACC is capable of at present. The most important thing however, is that this has also shown us where the difficulties are. The challenges in the development of software architecture particularly come to mind here; How can you develop control technology within one basic architecture that can be used in all vehicles? Do we develop a standard control, that sets boundaries and conditions on how to respond to the actions of the lead vehicle- no matter what type of vehicle it is?"

Leading Cars and Platoons

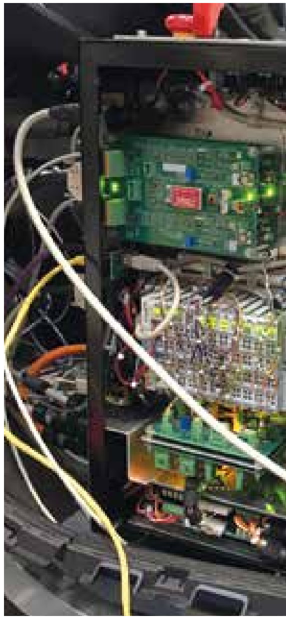
"One of our PhD students, Robbin van Hoek, went to work on this issue and developed an algorithm that can function as a generator for a leading car. In a cooperative environment, a vehicle like that 'sets the tone' for the rest, but it needs to possess autonomous characteristics as well. There is no other car to tell a lead vehicle where to go, so it sets the course for the rest of the platoon. Therefore, some autonomy has to be developed for the lead car, or alternatively, you can use a human driver. If you do that, you can have designated vehicles that only need to follow, and do not have to find the way by themselves. I'm convinced that in the near future we will increasingly see platooning on our roads, especially in commercial transport, as trucks are very suitable for it. Only the driver in front needs to drive as normal, the rest can take a rest, read a paper or do some work. If the lead chauffeur is tired, he can drop to the back of the platoon and a fully rested chauffeur takes the lead. A system like this has incredible value. It reduces the potential for accidents, shortens distances between trucks, saves fuel, and makes use of the roads far more efficiently."

"But what happens when a deer suddenly crosses the highway? What are the implications for the chain of vehicles? Questions such as these also need to be fully explored. What we do know already though, is that due to the accumulation of specific data collected by the leading truck, the following trucks are better equipped to take immediate action. Their response to actions happening ahead of them is enhanced, because data about speed and braking is being shared in fractions of a second. And then there is such a thing as string stability. What you often see on the road, are traffic jams created by what we call a 'accordion effect'. Someone brakes,

the car behind is late in reacting, has to brake even harder and before long, traffic comes to a standstill behind the car that was responsible for the initial action. This is far less likely to happen in a platoon, because response times are so much faster. It takes about a second for a human to respond, CACC only needs one-tenth of a second. That is huge progress."

Mimicking human characteristics in software programming

"Another question that one of our PhD-students, Wouter Scholte, took under his wing proved likewise as a challenge: What happens when a vehicle wants to join a platoon? What is needed when a car wants to merge in this system and find a place in the chain of vehicles? The amount of decisions that have to be made and tasks that have to be executed is substantial. Merging on the motorway can be considered as an intricate arrangement, one that asks a lot from the vehicle looking for a space in which to merge, but also requires a sense of courtesy from other vehicles,



A big question of course in I-Cave is: is it possible to merge cooperative and autonomous driving together in one piece of software architecture?

a degree of social consciousness, in order to willingly create a safe place for someone else. How can this be replicated this in software? That's almost asking for human behaviour from a computer system. An interesting fact to consider here is that a platoon of cooperative vehicles works together in the most optimal way possible. So, when another vehicle wants to merge, you are in effect asking the system to override this optimised setting, the opposite of what it's supposed to do. 'Hello vehicle 4 and 5, you're working in complete harmony, now let's throw in vehicle number 4.5 and let's see what happens'. It's fascinating to figure this out. Specifically for this part of the research, Wouter managed to come up with an algorithm that is now being tested at the DAF trucks testing ground in St. Oedenrode."

"A big question of course in I-Cave is: is it possible to merge cooperative and autonomous driving together in one piece of software architecture? Even when you break I-Cave into different projects, as we have done from

the beginning, you still have to find PhD-students, bright minds, and ask them to start tackling a couple of sub-questions which will consume four years of their time. It became apparent pretty quickly that the number of issues that we can solve is really limited, even with the project already broken into seven pieces. For this reason, identifying essential research components in the different areas was vital. For Cooperative Vehicle Control, the need to create an algorithm for the lead vehicle in a platoon and merging vehicles was critical. Another issue which presented itself within the context of vehicle-to-vehicle (V2V) communication: how can a leading vehicle improve his position on the road with information from the vehicles following it? In an ideal world, the lead vehicle would use a thoroughly accurate map of its surroundings, with every tree and pothole considered, combined with real-time information from its sensors to tackle variables such as weather or the exact position of other road users. We're not yet living in automotive Utopia however, so there will always be information lacking. Why not also add the information coming from the following vehicles to create a complete picture? Then you could end up with a situation where all vehicles in the platoon are helping each other, combining their 'thinking power' to determine their positions extremely accurately."

"Another, very important question, is still being worked on. What happens when you take the task of steering the vehicle into account? Unfortunately, we could only scratch the surface of this question. While the act of steering seems very easy, it actually instigates a complex set of problems. When a following vehicle mimics the steering action of the lead vehicle, things start to go wrong; the action of steering will be set into motion at the wrong moment. While the lead vehicle rounds a perfect corner, vehicle number 2 or 3 is likely to end up in a ditch. Something you want to avoid of course. So as you can imagine, timing is essential. There's still a lot of work to be done on that part. An autonomous vehicle on the other hand, can avoid this problem as it will always map out its own path, without depending on information from a lead vehicle. So that's where the I-Cave thought kicks in again: can we combine technologies to address these issues? One of the solutions for example could be a 'smart road', where the platooning vehicles also receive information from the road itself, so it can actually be the road that tells you how much steering action and what speed is required."

"It's nice to know that in a project like this, we could easily tap into the expertise of the other research projects as well. Frans Willems, who oversees Project 4, 'Communication' was able to provide us with the latest findings in radar technology, because they were occupied with the question of how you can extract the maximum information from newly developed radar technology- an experimental, and very promising technology. Our objective at Cooperative Vehicle Control however, was never to actually develop new technology, but rather,

In a project like this, we could easily tap into the expertise of the other research projects as well.

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to make the best use of existing technology to use the information gathered as efficiently as possible. Nevertheless, it gave us great insights into new possibilities still to be realised.”

What the future holds

“What are the odds of at least seeing cooperative vehicles functioning in a platoon in the near future? If you forget the totally autonomous part for a minute, platooning is certainly feasible and likely to become a reality in the very near future. We resolved many issues and managed to solve enough questions to make tangible progress. The main thing still needed is to develop a complete algorithm that enables vehicles to participate safely in a platoon. We need to agree on a system of communication, figure out the delay in communication, take that into account and then it’s possible to determine a safe distance between vehicles and a protocol for speed, acceleration and braking. A ‘dressed down’ variant of CACC, we call ‘degraded’ CACC, is basically ready for use in cases where the communication -temporarily- isn’t working. But the scenarios are still limited. The further we come in our research, the more we are realising that it is impossible to predict if it will ever be possible to create autonomous vehicles that can bring you from A to B in a 100 percent safe way, because the uncertainties in traffic and

Next-level technology is on its way, thanks to projects like I-Cave.

conditions are literally endless. Although it will take some time before every car on the road is equipped with it, next-level technology is on its way, thanks to projects like I-Cave."

"Cooperative driving, however, even in the simplest of variants, needs a lot of participating vehicles to work at all. We've already proven its benefits, but there is still a lot to be done. Very simply, you need to include additional communication hardware in the car (which costs money) and everybody has to use the same standards of course. The question of implementation however, lies not with the car manufacturers, but with big suppliers of electronic/software driving aids, like Bosch and Valeo for example. Every manufacturer makes use of the products of a limited group of suppliers, so if they start to move, the industry will follow. But let's look back at full autonomy: The closer we get, the more challenges we encounter. There's still a lot of work to be done!" And yes, that is fun, particularly as in this project we were collaborating with the other 'I-Cavers' and not to forget the interaction with some of our main users like Segula (now TBRM Engineering Solution), TNO, Ford and 2getthere.

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Mastering the bends

WOUTER SCHOLTE

Combining autonomous and cooperative driving might be easily put together in this sentence; to actually get it to work, lots of investigation and experimenting has to be done. What happens when you bring some form of cooperative driving into a platoon of autonomous vehicles, designed to function purely based on data from a leading vehicle? That's where Wouter Scholte comes in. He addressed the question: 'what does it take to merge a vehicle into a moving platoon of vehicles?' With lots of variables to consider, he looked for the best, most efficient way of blending these two together.

“I was looking for a challenge, and I surely was given one in the I-Cave Project. And while the human task seems so simple, finding a spot and merging in with the other traffic on the highway, There’s a lot of intuitive behaviour involved, and that’s not something that’s easily copied in programming code. It proved to be quite a challenge to actually come up with a concept, that merges an autonomously driving vehicle into an existing platoon of cooperative driving vehicles. During my research, I found out that most to of the existing literature on this subject was focussed on on-ramp environments. A logical place, since a lot of problems involving driving autonomously and cooperatively come together in this small area. There’s the short time available and the limited distance available to execute such a manoeuvre, combined with the difference in speed that has to be matched.”

Classifying possible problems

“It took about a year to make an inventory of the problems you encounter in this situation and to make a classification of which problems you want to tackle. As the investigation progressed however, I did deviate from that classification because some problems were not as problematic as we thought, and other problems occurred during the investigation. For instance: if you want to merge in with a cooperative driving string of vehicles, how do you decide which vehicles are going to have to clear some space? That proved to be more difficult than we had anticipated, while on the other hand a problem involving the curvature of the road and the extra distance a vehicle needs to travel to actually make a lane change, proved to be far less complicated because the extra distance travelled to cross over to the other lane is only a few centimeters. This distance is well within the margins we have to incorporate anyway, and negligible compared to the 139 meters of length you need with to make lane change. That’s what investigation is for, finding answers during the process.”

“One thing was obvious enough: for a vehicle to enter the highway, a gap has to be created. So there you go, now comes the difficult part. Cooperative driving is based on the idea of creating an efficient string of moving vehicles, and to create space for another vehicle goes against being as efficient as possible, within safe boundaries of course. We discovered that because the merging event happens for a short period of time, we need another analysis tool than that for steady state driving.“

“Withing our project group, we came to the conclusion that it is possible for a platoon to reduce the known ‘accordion effect’ in road traffic. If a vehicle in front of the pack has to brake, the effect created in a platoon means that vehicles further in the back do not have to brake as hard. The software and communication between vehicles will choose for efficient and safe braking, where people on the other hand have a longer response time and have to brake harder to compensate, amplifying the accordion effect and creating traffic jams or accidents as a result. We were able to figure out that due to the better response of the cooperative platoon, disturbances caused by gap opening are mitigated." That brings us back to the problem of deciding which vehicles on the highway are actually going to create a gap? We came to the conclusion that we would have develop a strategy for that, because the initial difference in speed means that the starting point of the vehicle that wants to enter the highway, compared with the platoon going much faster, is in a different spot than when the speed is matched after acceleration."

"If the autonomous vehicle is communicating with the string, it can come to an agreement on which platoon vehicles will create space to accommodate the new vehicle. Positions and velocities are factors that should be included in the equation, we still have to do research to find the best solution. These factors can differ as well, take acceleration for instance, we have to be able to predict how fast each vehicle can accelerate safely and take velocity at the beginning of the insertion lane into account. This involves quite some serious computing power!"

Getting closer to autonomy

"For me personally, the highlights of my work are to be found in the combination of creating a system to merge autonomous and cooperative driving and then being able to put it to the test, using the demonstrators from Project 7. A lot of testing is done in simulations of course, but if you do some actual, real testing on vehicles, you'll get a much better picture of how a vehicle actually responds to the objectives put to it. Take acceleration for instance, we made use of theoretical models for that, but in practice it proved to be different because the vehicle needs some time to process the information as well. You can only find this stuff out by seeing and feeling it happen in real life.

In my opinion, autonomous driving in the near future, without the help of any external data from other vehicles or sensory systems incorporated in the infrastructure, is not a realistic scenario. What we will see however,

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We were able to figure out that due to the better response of the cooperative platoon, disturbances caused by gap opening are mitigated.

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is the continuous development of detailed maps, sensory systems and driver aids, that can give us some form of autonomy if the circumstances allow it, which in effect means, in secluded areas, such as harbours, business parks, freeways, places where there’s less disturbance by other traffic participants.

But technology is only part of the equation. The regulatory environment also has to evolve to enable further autonomy to develop. We’re still a long way from total autonomy, but thanks to the I-Cave Project and similar projects around the world, we’re getting closer every day. And that’s something to look forward to, creating safer, cleaner and more efficient ways to address mobility in the future.”


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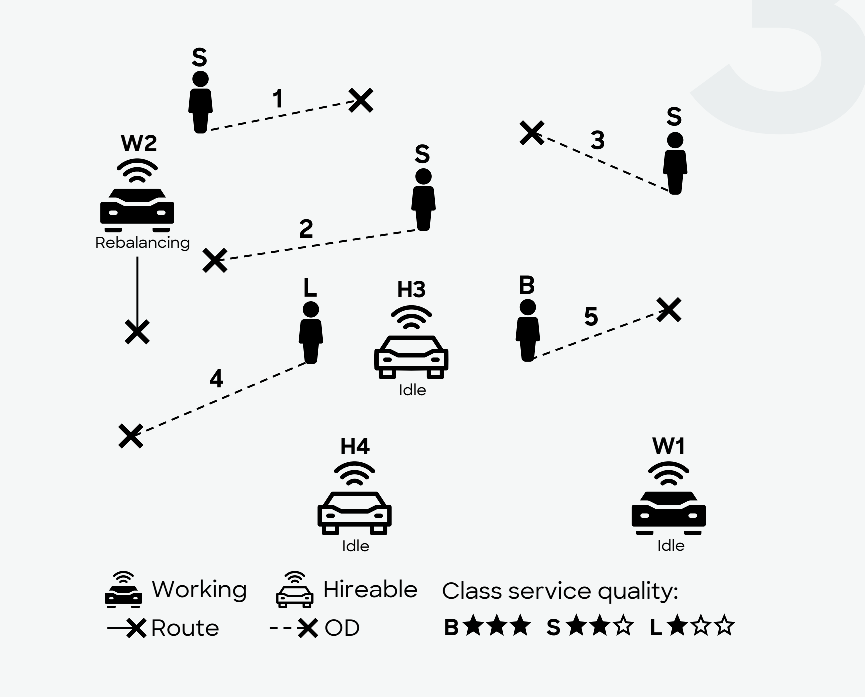
Improving the concept of mobility

RUDY NEGENBORN & FREDERIK SCHULTE

Autonomous and cooperative operating vehicles are inevitably going to affect how our daily commute looks like. But while 'reading a newspaper' or having a meeting for work while you're traveling are among the first thoughts that pop into mind, the characteristics and possibilities of such vehicles could also open up new ways of making use of our vehicles and infrastructure. That's exactly what Rudy Negenborn and Frederik Schulte have found during their work in I-Cave Project 3: Dynamic Fleet Management. They developed three concepts that propel mobility into an exciting new future.

Rudy: “Within the I-Cave Project, the key focus was to develop a dual mode vehicle; autonomous in restricted areas and cooperative in a highway platoon, assuming connectivity with the other platoon vehicles. Within our project group in the Department of Maritime & Transport Technology at the Delft University of Technology, whilst we focused on the same advanced vehicles as the other groups, we approached this concept from a different angle. Our job was not to make them feasible from a technical perspective, but rather, assuming that vehicles like this will develop on a broad scale: in what ways can they operate in new, safe and more efficient ways? What will the implications on mobility be? And how will mobility differ as compared to the way we approach mobility now?”

“Take for instance a drivers’ license. As it stands in today’s world, we need to learn how to operate a technical device, in order to get from A to B in the safest way possible. But as vehicles gain more autonomy, what will such a driving license look like in the future? Is it even still a necessity? So, we started with defining regions, beginning with areas in which vehicles can drive around fully autonomously. We know already now and certainly in the near future, that the technology will be capable of being able to operate in confined areas such as ports, industrial areas or campuses. In areas like that, a driver might not actually be needed at all. In between those areas, zones can be created in which autonomous or cooperative driving is possible, as long as a driver is available in the case that something goes wrong. Outside of that zone there would be the ‘non-autonomous’ driving zone, where a driver is fully in control and responsible again for the vehicle. As part of our thought process we took different levels of autonomy into account. We considered that vehicles capable of driving in all three of those zones may be needed, referring back to the dual mode vehicle, and we also had to take into consideration that there will be vehicles not yet equipped with such technology which would therefore be unable to operate in places suitable only for autonomous or cooperative vehicles.”



Extending the possibilities

Frederik: "And so, we needed to think in a series of steps about the future. You cannot simply say: 'today we're in charge of the steering wheel but tomorrow these vehicles will steer themselves'. We do have a baseline from which to start from. We know for instance, that autonomous driving platforms in ports and docks work very well, we've been doing that for some years now and have seen the benefits and experienced that it's safe to implement with the technologies available. The platoons are not yet connected to one leading vehicle, but, by taking small steps, and implementing new technologies such as those we've come up with in the I-Cave Project, we can gradually extend the possibilities. We are currently looking at an area in Rotterdam to do just that. A place where we can

With AVs we will be able to create advanced and equitable mobility services that replace the concept of vehicle ownership and drastically reduce the number of cars in cities.

test our concepts as an extension of existing terrain where autonomous transportation vehicles are welcome. We have a very good overview of what is going on in this area and there's room for experiment, developing working concepts for the field of dynamic fleet management."

Rudy: "To begin with, we divided our research into three concepts. One focusing on mobility - moving people in the future with autonomous and cooperative vehicles. The second concept is focused on freight - how do we move our goods in the future. And the third concept is focused on connecting different geographic areas using platoons of vehicles, from a port to the city outskirts for example, or from the factory to the consumer. Testing these concepts, we've been developing is key, for which we had to look beyond the Renault Twizies, available in Project 7. As a platform they're too small and more importantly, they are all the same, so we had to make use of simulation-based experiments

to put our concepts to the test. For this purpose, we developed a test for the dynamic fleet management concepts in the form of two computer games that gives the users of future self-driving vehicles, a realistic insight into why these vehicles could be useful and beneficial for them."

Frederik: "These games are very important tools for knowledge transfer. Because we've been developing concepts that sometimes are hard to imagine, these games help us and all the different stakeholders that are involved in our solutions, to experience how these concepts could practically work in future situations. In doing so we were able to actually experience how different decisions and solutions have impact on the management of a fleet of vehicles, for all our three research lines. It's great to see these concepts, that are basically theoretical and sometimes almost futuristic and philosophical, being put to work in a game."

Platform-based collaborative transportation

Rudy: “There has already been a lot of research on transport services and many people have reached the same conclusion: even with autonomous vehicles, the way we transport goods and people will remain the same for the most part, the main difference being a fit driver and safer roads. That’s a waste of technological progress in my mind. The further we got in our research, the more we concluded that lots of things are going to be very different. Transportation in the future will be much more efficient and safer, thanks to the specific characteristics of self-driving vehicles. Even current technologies available are going to have an inevitable effect on dynamic fleet management. That makes our concepts meaningful.”

Frederik: “To give you an example: in our concepts we were actually able to make use of parked vehicles. For this we used real life data, like New York Taxi data and datasets from the city of Rotterdam. Think of parked a vehicle that somebody left to spend a day in the office. Now you want to use that vehicle to let somebody else travel to a meeting in the next neighbourhood. An AV could come once the request is sent from your phone. A driver-based service would have to find a driver, who then would have to find the car and start picking up the user. This would take way too long and would be way too expensive to do. That’s basically the reason why we don’t see such a service at the moment. So that’s a clear example of an AV feature that lets us design new mobility and freight services. Shared autonomous vehicles will be smart, available, affordable, easy to use and reliable, so there’s no reason to still own your own vehicle. We guarantee that autonomous vehicles developed using our approaches and leveraging the growing prevalence of smartphones, will result in a much improved and efficient use of the mobility domain. This also goes for transportation of freight of course. You can do so much with local intelligence and sharing of information. There’s a phenomenon called ‘coopetition’, which means that competitors can actually work together for mutual benefit, and still remain competitive because the

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Transportation in the future will be much more efficient and safer, thanks to the specific characteristics of self-driving vehicles.

information being shared is safe, without revealing secret company information. In this way, two companies can be part of the same platoon without knowing their cargo, destination or clients for instance. At the moment, there is still a lot suspicion between companies because they are afraid of losing customers, but technology, efficient architecture and safe communication will eventually win them over."

Rudy: "This programme has been all about perspective, with a lot of PhD students and candidates contributing to this work. The great thing about this is that you really get to make discoveries, being surprised and being able to look into the future with the flashlight of research. You'll only find new insights when you take a creative look at the possibilities and developments that pop up during the programme. The questions that have to be considered: will there be fully autonomous vehicles around in the near future? Or do we shift our thinking to different zones in which access permission depends on 'how autonomous' a vehicle actually is, how this affects the level of education of the drivers, broadening the playing field and creating tailor-made solutions in the process. In the beginning of I-Cave I wouldn't have thought that we could stretch our concepts this far. Another example of that is combining freight and person transportation. Once we dove into that, all kinds of very feasible solutions came to the surface. Using shared autonomous vehicles with compartments, having the capability of changing from a 'person pod' during the day to a freight container at night, depending on the demand, transferring the container terminal to the city, also came up during the project and for sure isn't something we initially thought about. It's futuristic though, and might not yet be executable, but proposing these kinds of concepts opens a new door to explore and creates room for new solutions for city-councils and companies as well."

No more parked cars

Rudy: "Lots of questions remain of course, and as we progressed, even more than we started with. A nice one I can't resist to mention goes back to the issue of the driver's license: 'Do vehicles, instead of human drivers, need to obtain a kind of drivers license as well? Another form of the technical inspection, like the APK, that vehicles need to have nowadays? Can they still speak the same language as the other vehicles around? Is its computer-system still able to make use of updates? Can vehicles cope with new protocols? Are humans without a license capable of traveling fully autonomously, and how about children? Questions we don't have an answer for just yet, but they are going to have to be answered in the future. We did manage to lay out three very feasible concepts. Our project is based on looking forward and assuming that the other I-Cave Projects are successful, but on the other end it is really down-to-earth, because we're also trying to find out what autonomous driving actually means for the end-users once this technology is available. These end-users do not want to live in a big parking area, these concepts provide city-planners

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Our ‘angle of attack’ so to speak, was turning around the obvious way of thinking.

with new possibilities as well. With less vehicles taking up space, more space can be put to good use by building houses or planting trees. The concepts that we have been investigating can all be realised if people, companies and organisations want it. From the technological side of it, a lot already has been developed. If this technology moves forward just a bit further, vehicles can just park themselves out of sight in a designated area away from residential areas. Once recharged, they are ready to come to your door only at the time that you require their service.”

Frederik: “Our ‘angle of attack’ so to speak, was turning around the obvious way of thinking. Instead of developing technologies and then thinking of how it can be used in transportation, we’ve been developing solutions for people and freight in the future. Three concepts, ready to use. Now the industry has to figure out ways of making them a reality. With these concepts, we are able to steer the industry in a certain direction, which might accelerate the process of developing the right technological solutions.”

Rudy: “With that in mind. I do think that there will be fully autonomous vehicles in the next couple of decades, but maybe not everywhere, depending on the level of autonomy that these vehicles can provide. We still continue to learn and evolve these concepts, benefiting from the creation of new algorithms to help us. In this project of dynamic fleet

Not solving the industry's problems of tomorrow, but creating a roadmap that gives the industry something to look forward to.

management, we were able to put new ideas to the test. Not solving the industry's problems of tomorrow, but creating a roadmap that gives the industry something to look forward to. We are exploring the 'What ifs'? And asking 'how could we benefit?' A nice detail I would like to conclude with: at this moment we are investigating if the methods and possible applications of the concepts that we investigated for fleet management of autonomous road-going vehicles, are also relevant for waterborne mobility solutions. At the moment we're situated at the maritime and transport technology department, where we also investigate autonomous ships. For cities like Amsterdam, Utrecht or Delft, it's very interesting to think about what kind of logistic services you can provide over water once you have autonomous boats? And how can you combine that with road-going vehicles? It's a great spin-off of the I-Cave Project. As such, I-Cave's Dynamic Fleet Management project has provided new opportunities for cross-over projects into the waterborne domain, which we have already started to develop further in the research lab Autonomous Shipping. I am sure that this potential is also there for the other I-Cave Projects. So, I can honestly say: it's been a great ride."

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Re-thinking society

BRENO A. BEIRIGO

Creating new concepts for mobility and in the meantime recreating society: the field of optimisation is what Breno A. Beirigo brought into the bigger picture of the autonomous vehicle. With a series of mathematical models, he created the optimal strategies for autonomous vehicles to really excel.

“At the time that I applied for a PhD position within the project of Dynamic Fleet Management for the I-Cave programme, I was working as a Computer Science teacher in my home country of Brazil. Upon first hearing about the I-Cave Project, I was immediately captivated by the concept of cooperative autonomous driving and intrigued by the futuristic element of this field of research. At that time, this was a hot topic, and for me to be able to contribute my expertise in operations research, and more specifically in the field of combinatorial optimisation, was a unique opportunity. Prior to I-Cave, I had already worked significantly on mathematical optimisation models; it's essentially like solving complicated puzzles! I'm always looking for the best way to achieve a goal, whether that means trying to find the most efficient route through the supermarket, the quickest way to my holiday destination, or the optimal route to view all the sights in a city. Optimisation is what I love doing, and it was clear to me that through this concept of autonomous vehicles, our whole view on mobility in the future could radically change. Having the opportunity to investigate and create new scenarios to optimise usage of these vehicles was something that I really looked forward to."

Complicated puzzle

"When you start working in the field of Fleet Management, a number of questions immediately come to mind. Which vehicle types are needed? What is the optimal fleet size? How to best direct vehicles to ensure that people or goods arrive at their destination at the desired time?

Even when only small parts of these concepts are rolled out, the effect on the environment and liveability will be tremendous.

Those represent just a couple of uncertainties that you have to take into consideration. Fundamentally, this is a mathematical challenge: you have to create a method for the operations of the whole fleet to occur in an optimal way. From the very start, the main difference of our research compared to the other research fields within the I-Cave programme was that we could already imagine that vehicles – with different levels of autonomous capabilities – were already at our disposal. Instead of developing new technologies, we could focus purely on exploring how to make the best use of these vehicles when they were actually around. That gave us a lot of freedom to come up with new, daring concepts that could change the way we deploy and make use of vehicles and transport in the future. We set out to find scenarios in which the deployment of cooperative automated vehicles would become necessary and investigate under what circumstances they could provide a better service than what we have today. What would happen if autonomous vehicles became widespread in our communities?”

Freeing up space

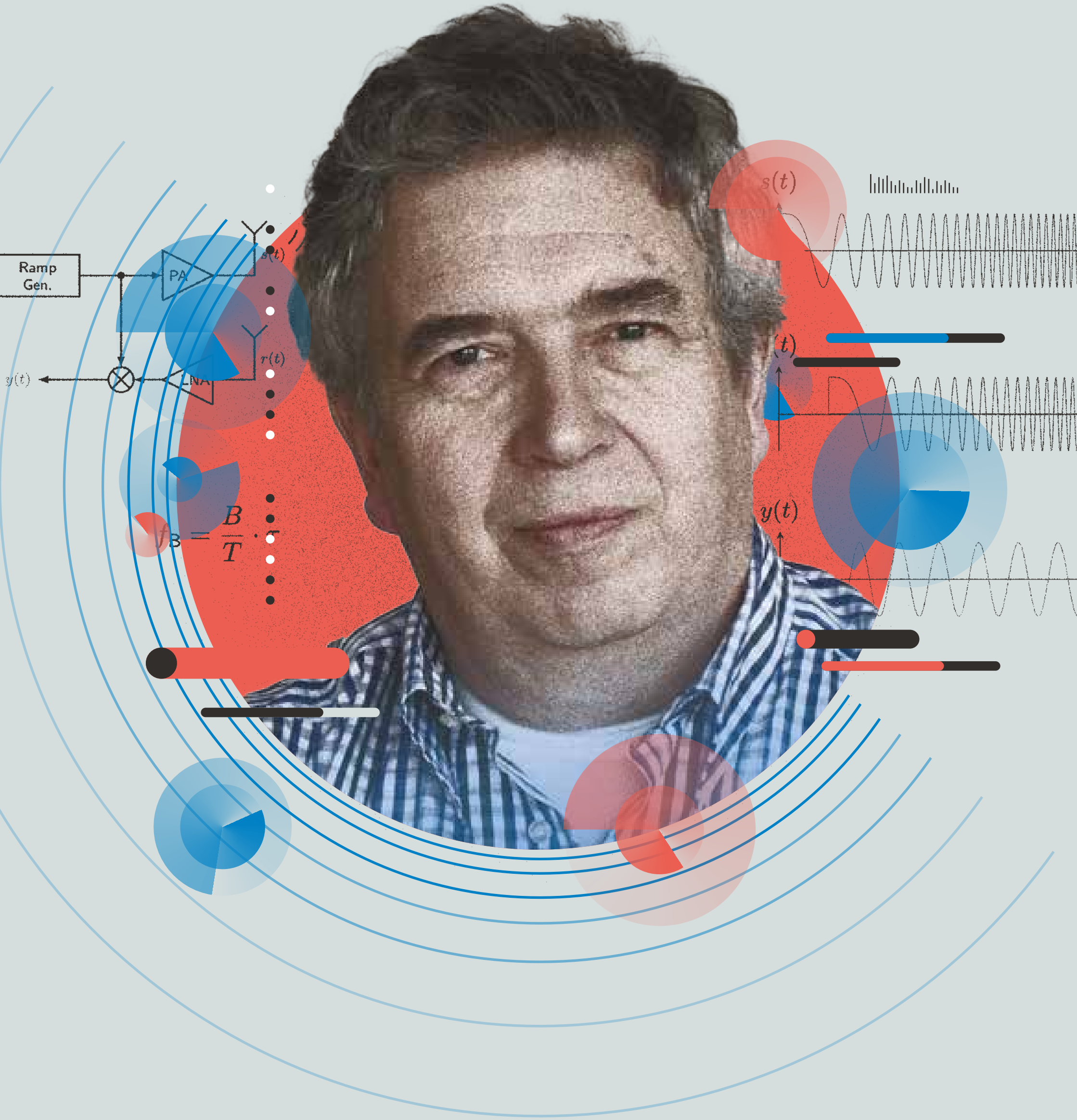
“We found that the impact of vehicle automation on vehicle owners, cities, the environment, and the general public would be profound. My main focus was to dive into the concept of sharing. In the future, it will make a lot more sense to share goods and means of transport instead of owning. From an optimisation standpoint, it's extremely inefficient to own a vehicle but only drive it for a minor percentage of your daily life. The alternative to car ownership is ridesharing: you buy the service only when you need it. An autonomous vehicle would be able to drive to your house, pick you up and deliver you to your destination and could afterwards park in a designated area so that it doesn't use space in a residential area. On the other hand, if you are a private autonomous vehicle owner wanting to have some extra source of income, you could share your vehicle with others at idle times. Then it doesn't make sense anymore to actually have your own car parked in the street for days on end. The outcome would be the need for far fewer vehicles, which, in turn, could induce enhancements in the standard of living – especially in urban areas – due to, for example, less congestion, noise, and air pollution. "But how do you make sure that people can still make use of a vehicle at the exact time that they require it? To convince people to share, you have to convince riders that the service will be on par with owning their own car, and we saw this as a significant challenge to focus on. We set out to identify scenarios where it would make sense to share and where the service quality could actually surpass that of owning a car whilst, at the same time, improving our living conditions. One of the concepts that we worked on was to combine people and goods transportation, making use of the same autonomous platform. In our model, a 'passenger pod' could be mounted during the day and changed into a container for goods during the night. You could, of course, also combine these modules, creating room for passengers and goods simultaneously. That's optimisation in its purest form, combining logistics and mobility, ruling out the need for single-purpose vehicles. If you combine that with a system that automatically finds the most efficient routes, you'll need far fewer vehicles as well."

3

On the verge of an autonomous ridesharing revolution, how do you make sure that people can still make use of a car at the time that they require it?

Incentive

“Some of the concepts we’ve created can be used as an incentive to the industry, governments, and city councils to continue developing technologies, as well as legislation, to benefit communities. Even if only a portion of these concepts are rolled out, the effect on the environment and liveability will be tremendous. And it’s not as if the advantages aren’t clear: ask anyone whether they prefer a city full of vehicles or a city where there is room to actually move around with much fewer vehicles blocking the way, and the answer will undoubtedly be negative. I’m optimistic about the future because most of our contributions can already be rolled out with existing technology, slowly creating a new way of thinking in living and mobility.”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4

The information challenge

FRANS WILLEMS

The challenge of getting messages from one place to another is as old as humanity. And with each development, communication has brought us closer together. But communication between vehicles presents us with a whole set of new challenges. What are the best and most efficient ways for vehicles to share information? And how can we make advances in this important field of research? Frans Willems, TU/e, leader of the Communication project group set out to explore ways of bringing radar and communication technology together.

“As the I-Cave programme was being developed, it became clear that there was a need to involve Information Theory, and more specifically, to investigate new ways of transferring information between vehicles.

The amounts of data being transferred between vehicles, from all types of sensors will increase enormously as we proceed in the development of self-driving vehicles. In order for this data to travel safely and reliably, we need to take a new look at the existing methods and explore new ways to optimise the exchange of such information. One of these new methods we wanted to take a serious look at, is radar technology. Of course, there's WIFI, Bluetooth and even 5G available and used within the automotive industry as well, but the use of radar technology in vehicles is becoming increasingly common, although it's not yet being deployed as a carrier of information. Why not use it for that as well, to create a more efficient way of communication? That possibility had never been extensively explored, so our job was clear."

Fundamental Limits

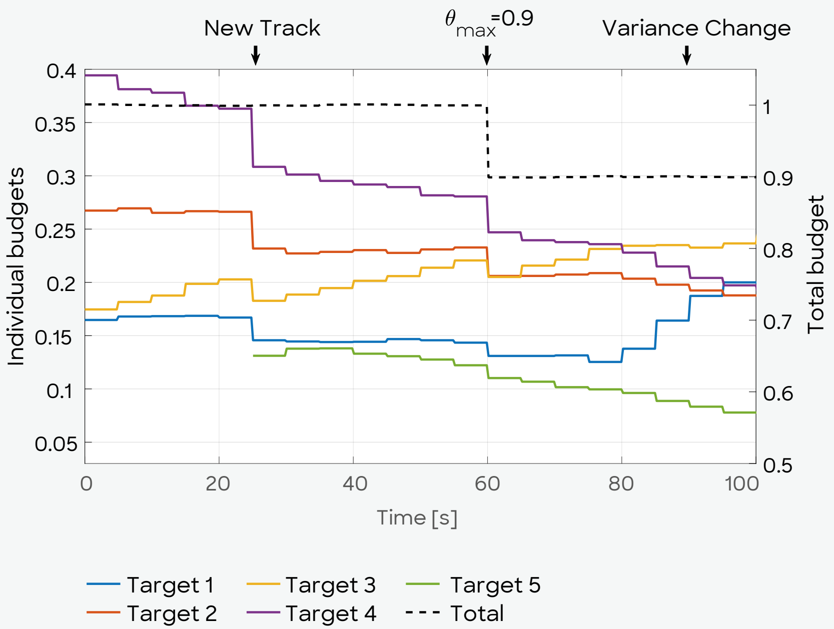
"That's where Information Theory comes in with a fundamental set of questions informing this research: how can we compress data into manageable amounts? In what ways should information be enciphered and deciphered? What methods of wireless communications do we have at our disposal and what are the restrictions and possibilities when it comes to speed and amounts of data being transferred? How far can we go in creating a reliable transmission with a specified channel? In our field of research, we call these 'fundamental limits'. To give you an example: Each specific communication channel has its own limits when it comes to the speed and capacity of data transferred, a set number of maximum megabits per second. Once you know the maximum amount of data that you can transfer without distortion within a certain amount of time, you still have to figure out how to reach that maximum. That's where coding comes in, which must then be developed and implemented in a good way. These are the basics of Information Theory; It becomes a lot more complicated as the number of transmitters and receivers grows or when different forms of communication systems need to understand each other, which creates an enormous growth in scenarios."

4

How far can we go in creating a reliable transmission with a specified channel?

“Within our project, the question then focused on radar technology, whether it would be possible to use radar signals for communication purposes as well, embedding extra information in radar systems so we can use radar not only for localisation purposes, but also as a way for vehicles to send messages to each other. That proved to be a challenge, because radar signal as it is being used now, was originally designed for detecting, rather than for absorbing information. When sent out, it doesn’t ‘talk’ to the receiving target, it is merely used to acquire positional information to the sending party in the current situation. Now we want the radar system to send out two signals or one signal with two purposes: one for communication and one for localisation. The main problem that occurs when trying to make this happen, is the influence this ‘extra feature’ has on the radar signal.”

“In this scenario, we needed to establish the limits of the amount of data we could send with this radar system, without severely limiting its performance. For this research, we were helped by our partner NXP, a company specialised in communication technology and all kinds of radar systems, including radar for the automotive industry. We also worked closely together with our I-Cave partners at the Delft University of Technology, where lots of experts in radar technology are located, so we could easily combine our efforts from the research group of Information Technology at Eindhoven University of Technology with the ‘radar wizards’ of Delft so to say. The starting point was clear however: the existing automotive radar systems all make use of Frequency Modulated Continuous Wave technology, or FMWC. Although other, newer technology in the meantime is being developed, it’s still very much in its infancy. The decision to focus our research and abstract analysis on this existing FMCW technology was made because it’s a well-known proven technology, and there is a lot of experience around which we could benefit from for our research. That narrowed down our focus, because the hardware was readily available from NXP and we were able to test our findings immediately in practice.”



That was quite a breakthrough so early in the programme.

”

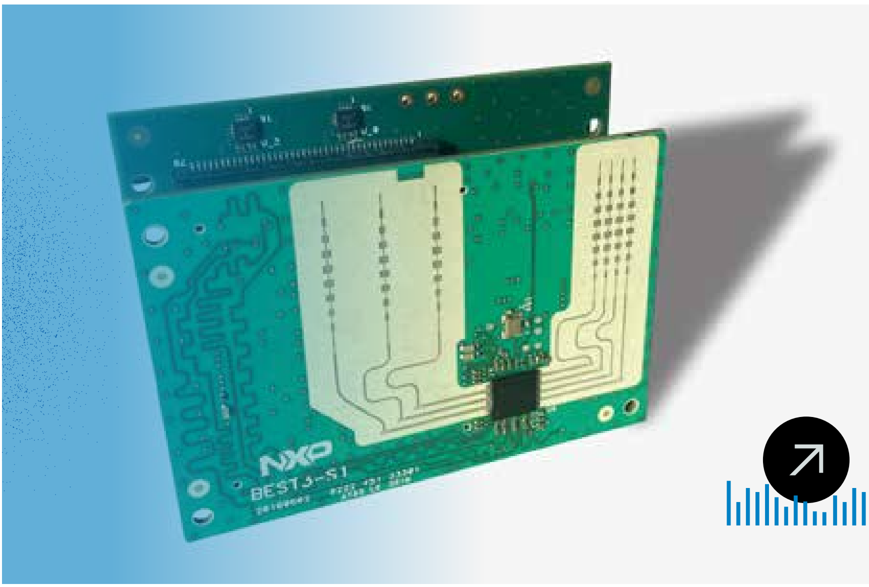
An early breakthrough

“With the radar technology as our ‘base material’ being clear, we started developing a scenario that could merge communication into the FMCW-signal. This signal is passive by nature, its only task is to be picked up by the target and bounced back to the sender – the output of the signal is only identified afterwards. After just three months into this project, one of our PhD students, Franz Lampel, had already devised a method that would make it possible for this signal to carry information as well. He achieved this by applying a way to reduce the disruptive impact of the additional information being fed into the signal. You can compare it with the noise reduction filter on modern headphones: this device is able to separate music from noise in the surrounding environment. The method created by Franz is able to separate the radar signal from the data and make use of both, almost without influence on the radar performance. That was quite a breakthrough so early in the programme.”

“In the meantime, however, I would like to point out that our colleagues at Delft University had discovered an almost identical way to achieve this goal, albeit from a different angle. They were also part of another project, working on the issue of using radar to identify different vehicles. It’s a bit of a detour from our project, but some information needs to be embedded in the signal if you want to achieve this as well. This then resulted in some nice publications, from our part as well as from Delft.

Since Delft University had significant expertise on the existing radar systems provided by NXP, it also created the possibility of collaborating more closely to put our algorithms into practice in a relatively short time. Simply put; we developed the theory, Delft University created a demonstrator, NXP filed a patent application and this way we were able to prove that our theory was both functional as well as operational."

'The next logical step would be to connect with Project 7 of the I-Cave Programme, in order to put our demonstrator to the test on the Renault Twizy demonstrator vehicles. Unfortunately, we weren't able to achieve that, because we couldn't yet ensure that this system would be 100 percent safe to use, which is essential when testing at close intervehicle distances. Nonetheless, our theoretical research, combined with the hardware and the demonstrator in Delft, has proven that it can be done. The next question of course is whether



OTFS should in theory make it possible to use only one ‘does it all’ signal.

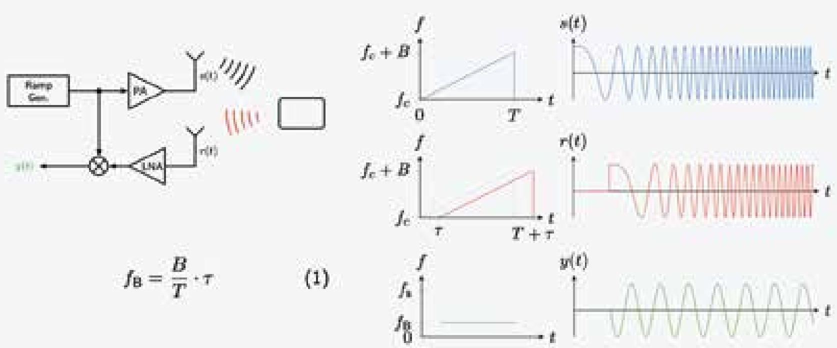
applications of this technology are actually realistic in the future? We’ve been able to make this work, but we also found some downsides of using FMCW-radar as a tool for communication. A big drawback is the amount of data we can merge into this signal, since the bit-rate is very low which as a consequence significantly restricts further possible development. With the large data streams needed for the autonomous and cooperative driving vehicles we have in mind for the future, you should consider that another system such as WIFI, capable of moving a lot of data, would still be needed. That was a bit disappointing, because we had hoped that we could end up with a reasonable capacity for data. Yet you cannot exclude the possibility that a suitable application for this system will be found in the future. Take for instance the possibility of knowing what vehicle is actually sending or receiving the radar signal. This identification is certainly valuable and doesn’t necessarily require a huge amount of data. Even small amounts of information can be relevant, when used under the right circumstances. And of course, you can make more efficient use of the hardware as well, using the signal for data or radar only, depending on what’s necessary at a certain moment. In Delft they are still working on exploring that part of the equation.”

An ongoing research challenge

“Our research however, did not end with the work that we’ve done on the FMCW-radar. New radar systems are already being developed including one of the most promising which uses OTFS, which stands for Orthogonal Time Frequency Space. This system is actually being developed from scratch, with radar and communication features embedded from the beginning. This is a completely different approach of course, from trying to add a feature to a system that was never intended to be used in that way. In the future, OTFS should in theory make it possible to use only one ‘does it all’ signal and combine it with just one piece of hardware, and therefore one computer processor, capable of executing numerous different tasks. This system is still in its infancy and a lot of research questions still remain open, but it looks very promising nonetheless. A system that can do anything, it sounds a bit like the holy grail, but that’s what you’re always looking for in scientific research of course.”

“There is also still a lot to be gained by solving how to use radar and communication hardware in a vehicle, in a more efficient way, sharing your resources across different tasks. Why expend energy to establish the position of a vehicle several hundreds of meters in front of you, demanding the most of your radar system, when you could simply ask a vehicle that is closer to the vehicle for this information? In Delft

FMCW Radar



$$f_B = \frac{B}{T} \cdot \tau \qquad (1)$$

OTFS should in theory make it possible to use only one 'does it all' signal.

they are working on questions like these as we speak, and that will eventually make all vehicles a lot smarter, when they start sharing data in an efficient way. If it comes to identifying the type of data needed however, other projects within the I-Cave project take over the reins. Ours only relates to the question of how this communication and radar technology can be merged in the best possible way. Which, by the way is an enough of challenge in itself. It all comes back to establishing the fundamental limits of sensing and communicating at the same time. With the FMCW-systems, you could say we already made a leap forward from this fundamental question, because we started out with an already developed system. Nonetheless. we've made real progress in that field, discovering new possibilities while keeping the fundamental question close at hand."

"Looking back on the I-Cave programme and our contribution in particular, I'm incredibly proud of the progress we managed to make with the FMCW-radar which culminated in a working concept. As for our work in the OTFS-system, that remains a work in progress and will be the focus of research efforts worldwide in the years to come. We've already found a way to simplify this concept and make it more manageable, so that keeps us and other groups busy for a while. Together with NXP and the other partners Technolution and AutomotiveNL, radar and communication research will continue to play a part in fundamental research of information technology. But

Never say never; science is inherently continuously moving forward.

as I reflect now on the progress made to date, and contemplate the possibility of autonomous and cooperative driving in the future, I have to say that in terms of Information Theory, a lot will be possible in the years to come, especially when it comes to sharing data and information, two key elements of course in making automated driving possible. Real autonomy is a different story however, considering the sheer number of uncertainties in traffic situations. But never say never; science is inherently continuing to move forward."

4

Innovation in sensing and communication

FRANZ LAMPEL

Discovering something new and actually proving that it works in real life; it's not always a given when you're conducting fundamental research. Franz Lampel from the Delft University of Technology, together with his colleagues however, developed a new concept that propels existing radar technology into a new future.

"When I entered the Communication project of the I-Cave Programme, I had just finished my Masters degree, which also had a lot to do with localisation and communication, but in a completely different context: groceries in supermarkets. For this research, we tried to incorporate

localisation functionality into communication signals of electronic shelves, so that we could not only update the electronic labels on the shelves, but also know exactly where the products would be located. My work in the Communication project of I-Cave then turned out to be just the other way around, when it became clear that our objective was to find a way to incorporate communication into a radar signal, to enhance communication between cars, while keeping the radar functioning as well. Combining two different technologies and research fields is an interdisciplinary challenge and as such, does not usually mix very well, but would be a great challenge and just my cup of tea!
I already had some experience with this concept and I soon found out that it would suit my love for optimisation. I'm always looking for the best way of achieving a goal, even when it's trying to find the most efficient route through the supermarket or the quickest way to my holiday destination."

Optimisation

"I was really happy to get this position, because combining two technologies into one system, is of course optimisation in optima forma. Combining communication and radar is considered a key component of autonomously driving cars. For example, autonomously driving vehicles must acquire information about their environment and share it with other vehicles. However, currently deployed communication technologies are considered a bottleneck for autonomously driving vehicles. Therefore, we needed to look into the alternative concept of creating a way to incorporate communication in radar systems as well. One thing was a known fact to begin with; we had to work with existing radar systems that are already commonly being used in the automotive industry, using Frequency Modulated Continuous Wave (FMCW) technology. This technology was never designed to carry data as well, it was only developed as a signal to detect other objects. So, there's your immediate problem: embedding something extra to a

signal that is in fact similar to a sound wave, will have a negative impact on the purity of the signal, adding noise to it, and resulting in a radar system that does not perform like it used to or should do."

Publications and patents

"To be able to solve this problem, I had to find a way to embed information in the signal when it is being sent out, and extract this information again when it is received. So, we went back to the drawing board, to figure out the theory first of merging these signals and separate them. Together with colleagues from Project 4 at the Delft University of Technology, who are specialists in radar hardware, we managed to develop a filter that enables the radar signal to carry information as well, without interfering too much with the radar signal. Eventually we were able to put our research into practice, creating a working radar system that can cope with two kinds of signals combined as one. Whatever it may be used for in the future, it was great to actually make this work, especially from a scientific point of view. With this working concept, we created something that wasn't possible when we started our research and ended up with several publications and two patents as a result, which is great."

"As always of course, this technology has its limits as well. We might have hoped that it would be capable of carrying significant amounts of data, but in practice the capacity is limited. We proved it works, but it also gave us the insight that we might need a more fundamental revolution in radar and communication technology to achieve optimal performance. We've gotten the most out if this FMCW-signal in terms of adding features to it, for the future we simply need a different solution."

Still moving forward

"In the last year of I-Cave therefore, we explored these combined features within a different setting, with the newly created Orthogonal Time Frequency and Space (OTFS) technology. This signal has its origins in a far more holistic approach, designing a signal that's capable of sensing, localisation and data transfer at the same time within one framework. If you start with this question from the beginning, the possibilities are far greater than trying to adapt an existing system to your needs. But it's going to take some time before we actually see it being used on cars, because the progress in deploying new technologies in cars is relatively slow. On the one hand, academic research is bursting with ideas for new technologies. On the other hand, the automotive industry is more restrictive. The common attitude in the automotive industry is evolution rather than revolution of technologies. But as long as we keep on exploring and creating new concepts, it will inevitably be used in the future."

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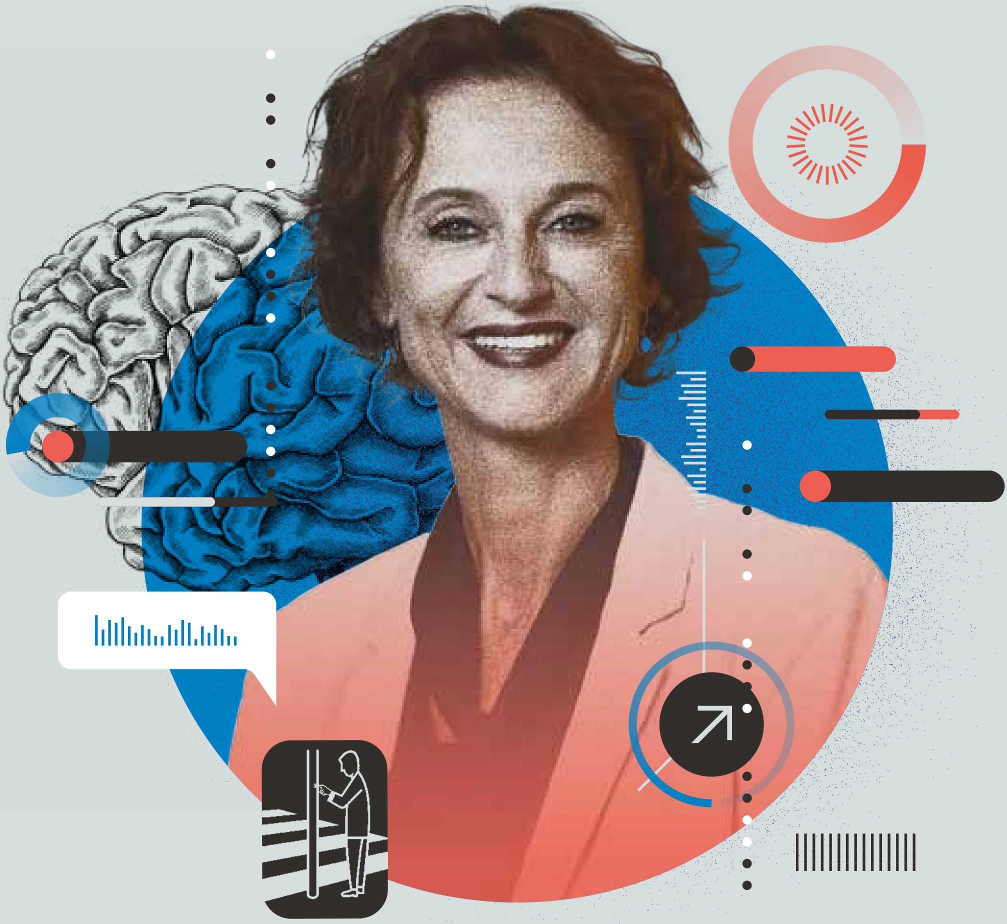
The common attitude in the automotive industry is evolution rather than revolution of technologies.

“If we look back now on the whole I-Cave programme, I really have to do my best to zoom out to the broader picture, to create some kind of image of the automatically driving car of the future, mainly because for the last few years I’ve been so focused on the granular level of radar technology. But putting my mind to work, I have definitely learned things about autonomous driving vehicles that I never thought about before. For example, the question of how a pedestrian perceives a car if there is no driver present. Or, how does an autonomously driving vehicle share its intentions with its environment? So, I learned that the idea of autonomously driving vehicles is much broader than expected.”



5

Back to Basics

MARIEKE MARTENS

The concept of the self-driving vehicle is often approached from a technological angle. But humans still play a crucial role in such a vehicle, whether it's as a passenger or 'part time' driver, or simply by being another traffic participant as well. Human behaviour plays a crucial role In accepting and understanding this new concept in mobility. Project leader Marieke Martens explains why.

"At the outset of our research, we made the decision to begin with the basics of human behaviour in traffic; To begin our research with the needs of automated vehicles already in our minds, ran the risk of missing vital information and therefore important insights. 'Known certainties' are not so certain at all. What happens when the human factor is taken out of the equation? How do we understand each other, or rather, how can vehicles understand their surroundings? To answer these questions, we needed to research communication in real life traffic; how do participants actually communicate with each other? PhD student, Debargha Dey, was tasked with observing traffic in Eindhoven. What happens when people want to cross the road for instance? How do they interact with drivers? How long does it take to make the decision to cross the road? Can we draw conclusions from that?”

“Surprisingly, he found out that eye-contact and gestures play only a minor role in communication in traffic. If fact, eye contact only plays a significant role in a very small and specific setting, with close encounters so to speak. In the majority of situations, eye-contact or gestures simply aren’t possible. The speed differences are too great, the weather prevents us from looking at a driver in the vehicle, the angle of sight is different, people wear sunglasses, the situation is more complicated than one-on-one, to name just a few of the variables impacting on our ability to communicate through eye-contact. This was certainly a revelation. Something we had considered as relevant, turned out to be not so important at all. So, there you are, a new starting point, simply by really going ‘back to basics’. ”

Reading the movement of vehicles

“In fact, through our research, we found out that for the most part we act, and react, on the basis of the behaviour of the vehicle. As humans we’re somehow capable of reading and predicting the movement of vehicles, rather than the person sitting behind the steering wheel. Instead of ‘organics’ communicating, we seem to be used to communicating with machines. And there’s your link with our project within I-Cave: human factors. You cannot simply say: ‘let’s make a technological device, in this case a vehicle, which acts unconventionally and in such a way that we have to educate people on how to use it. And when it’s not so clear how to use it, we’ll just add more warnings and guidelines’. That’s not the way to go. There are enough examples, of early autonomous vehicles and the surroundings completely covered with big signs screaming ‘watch out, autonomous vehicles driving around, keep your distance!’“

As humans we're somehow capable of reading and predicting the movement of vehicles.

"That's actually quite the opposite of what you want to achieve. A self-driving vehicle needs to be considerate of the way people are used to behaving in traffic situations. Only once this is factored in, can you provide context and guidelines for very specific situations. How the vehicle behaves in traffic must be programmed in and has to correspond with people's expectations of vehicles. You can create a vehicle that will objectively behave in a really safe way, however, as long as it is not perceived as safe by the people around it, it doesn't do the job. We all have to perceive a vehicle like this as natural and intuitive, for people in - as well as outside - of the vehicle. Otherwise it will inherently be unsafe.

Only when it 'feels right', are we willing to accept new technology.

If a vehicle is capable of a lot more than what we are used to, like driving at high speed while being just centimetres away from a vehicle in front of you for instance, or braking really hard, it does not feel safe for the occupants because it deviates too much from what we are used to. Therefore, human factors have to be on top of the list when developing new technology. Only when it 'feels right', are we willing to accept new technology."

"With existing former research in mind, we started working from the situation as it is at this moment. How far are we with existing technologies already implemented in vehicles and traffic? In what circumstances does it evoke questions? And are there cultural differences that need to be considered? One part of our project group worked specifically on that subject. For example; eye contact between a pedestrian wanting to cross the street usually means that the vehicle will stop to give the pedestrian the

opportunity to cross. But that's in the Netherlands. In some Asian countries it's the other way around, eye-contact means that the driver is okay to go. Therefore, creating a 'roadmap' was also very important, helping us to establish a baseline and move forward in our research from that point, allowing us to investigate how we can incorporate human factors for various forms of automated driving in the future."

Global agreement

"Within I-Cave, we always wanted to maintain close links with the technological projects of the programme. For Debargha's research in the behaviour of pedestrians in traffic for example, we took EHMI, (External Human Machine Interaction) into consideration. Interestingly, the developments in I-Cave were also developing in other parts of the industry. The International Organisation for Standardisation (ISO) and a couple of car manufacturers signalled that they were also investigating the same questions we were. What happens when we want to send messages from the vehicle to the outside? How do we make our intentions clear? What messages are we going to send out? Do you want the people on the outside to somehow know that they are dealing with an automated driving vehicle, or do you not want to send out that message? And if so, what actions do you want to communicate? Starting to drive, coming to a full stop, cruising? And whilst many questions still remain open, the knowledge we obtained in our research could be shared immediately with relevant partners. That's the beauty of it; our research revealed a complex set of questions for everybody involved in the automotive society. Moving forward, there has to be a global agreement on these themes; vehicles from different brands have to send out the exact same messages. We all need to agree on a lot of factors before new technology can safely be implemented."

The carseat suit

"To see how people on the outside react to an autonomous driving vehicle, we were also able to make use of a Renault Twizy, a small electric car that was also used by the other I-Cave research groups to test technological novelties. Because it was of course not yet fully functioning as a self-driving vehicle, we came up with some unconventional ideas, one of which was the 'carseat suit'. The driver could wear this suit when driving the vehicle, and for bystanders it looked as if nobody was actually driving the car. Whilst this was an effective way to simulate an automated vehicle for bystanders and other participants in traffic, it was no doubt just as "exciting" for the person in the vehicle, whose visibility and range of movement is severely limited by the suit! But this was also an opportunity to find out what actually makes the biggest impact on bystanders. Is it the fact that nobody is behind the wheel of the vehicle? Or is it the way the vehicle actually behaves that catches the attention of the people on the

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Our research revealed a complex set of questions for everybody involved in the automotive society.

outside? Developing a suit like that is a bit unorthodox, but it was a great way to find out if a driver in the seat or not, actually makes a difference."

"The fully autonomous vehicle was not the only purpose of the I-Cave programme. The project also included the concept of the cooperative vehicle as well: vehicles that can communicate with other vehicles and the roadside. The focus of this concept is not about getting into your vehicle at home and being dropped off at your holiday destination whilst the only thing you need to do is read a book, but rather, on technology that helps the driver and his surroundings in difficult or dangerous situations. For this part of the research, we made use of the campus of Eindhoven University of Technology. Many issues that we were going to research were to be found in so-called last mile transport, an urban or city-like context. The TU/e-campus proved to be the perfect testing ground, as it provided us with a closed-off terrain and yet a semi urban traffic environment, with cars, buses, bikes and pedestrians. A good representative for a real city setting."

The human inside

"Interaction with the vehicle and the outside world is of course a crucial issue, but our research focus was also on the humans inside the vehicle. The central theme here is drivers' trust in the automated driving of passenger vehicles, and the way this affects the interaction between drivers and vehicles. That is why two PhD-students, Francesco Walker and Anika Boelhouwer went out to explore this interaction. What are the implications of removing driving tasks from the driver? Is this possible under all circumstances or just a few? Again, we started with observations. Beginning with the basics: what are the expectations of drivers when they are operating a vehicle? We started out by making video-observations from within the vehicle at the campus of Twente University. These videos were presented to people in a driven simulator, making the subjects really feel like 'being driven' in a self-driving vehicle. What do people expect when they step in these 'self-driving vehicles'? And in what way are their expectations influenced by the information we give them in advance? What information should be offered to inform the driver that his input is needed? How do you present that? And what is the appropriate time to send this information?"

"In general the thought of either you drive a vehicle or the vehicle drives itself is a stubborn one. But of course, there's a big, grey area as well, depending on lots of different circumstances. Where do you want to travel, through urban area's or mainly motorways? What's the weather like? Which available technologies are on board? Can we use signals from other vehicles? And so on. Depending on these circumstances, you can imagine that different levels of automation can be offered. Our part in this equation is to figure out how, and in what way, the driver needs to be informed, and how this information culminates to create a safe journey. You would think that informing the driver beforehand about what the possibilities of the vehicle are and what is expected from the driver, could help to eliminate a lot of issues. Unfortunately, we found out early in the project that it doesn't exactly work like that. Whether we gave the

Our research revealed a complex set of questions for everybody involved in the automotive society.

test subjects some simple information beforehand, or really elaborate, with specific examples and a test afterwards, once in the simulator most of the information was already forgotten, assumptions were made and situations misinterpreted. That was a significant learning lesson."

Education

"So the question remained, how can you train or educate drivers to understand, and be comfortable, with automated driving? Again, we went back to the basics of learning how to drive: how does a driving instructor educate his pupils? In what way is information being fed to people learning how to drive? The situation is actually quite the same; being able to drive comfortably in an automated vehicle requires a process of education and learning of new skills. You have to become familiar with the technology, an instructor has lots of experience in how and when to offer the right amount of feedback. We learned a lot from that: the way an instructor adapts the amount of information to the experience of an apprentice. The timing of the feedback is important; in hectic situations people need all their energies to act. It's better to receive feedback when the nerves have calmed down. For us this was an eye-opener, it's necessary to search for the right moment to provide assistance and information and that might not be in the heat of the moment. A driver might have too much on his mind to do anything with it. So, with all this information gathered, we set out to develop an in-car tutoring system. Introducing a step-by-step learning system could help the driver to get acquainted with automated systems. Once you learn to operate (and trust) the first, you are ready for the next."

"In the meantime, a lot of technologies have already found their way into vehicles, which means that a lot of technology is still being developed with driver and passenger safety in mind, but could in effect be unsafe for other participants in traffic. I therefore hope that the impact of human factors on technological developments will increasingly play a role in the design and creation of future vehicles. I'm thrilled to be part of programmes like I-Cave that will make these crucial contributions to the future of mobility."

5

Subtle communication

DEBARGHA DEY

Observing traffic participants in complex situations: PhD graduate Debargha Dey has spent many hours with his camera at the side of various intersections. He ended up with interesting and even surprising conclusions that completely alter our understanding of the way we think we interact with other participants in traffic.

“My background lies in computer science, but the field of automotive Human Factors always had my special interest, especially following my own experience of a car crash which was as result of driver distraction. That compelled me to pursue my academic career in this field, because sometimes human factors tend to be overlooked when pursuing technological development, especially when it comes to advanced driving aids. Hence, when a position in the Human Factors project group of the I-Cave programme opened up, it was the perfect next step for me. The idea of automated vehicles had already captured the mind of the academic research community in general and so whilst the concept was far from new, a lot of questions in various fields still remained open, among those being questions involving communication of the vehicle with the world outside, meaning other road users, pedestrians, cyclists and so on. Research had mostly been focused on interaction between cars and drivers or passengers, but research in communication between a vehicle and its environment was still an open book."

Eye contact and gestures

"That particular angle was what excited me the most and thanks to the relative emptiness of the field at that point, I could start from scratch and look at this whole domain from a communication perspective. Communication is everywhere, and it was my job to research communication in this very specific context. Because of this 'blank slate' however, at times in the early stages of the research I found myself overwhelmed, struggling to find a direction and a 'point of entry'. In these situations, it's always best to go back to basics, and it this case that meant starting by observing how vehicles and other participants in traffic actually communicate in the real world at this moment. Seeing what people want and need in terms of communication. The first thing we had to do was distance ourselves from the assumptions that we already made, especially when it comes to eye contact and gestures. Every conversation we had in our labs about communication in traffic seemed to assume these factors as a 'given' in creating a mutual understanding within complex traffic circumstances. But when we started to look at

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Communication between a vehicle and its environment was still an open book.

this from a more theoretical standpoint, it soon became clear that eye-contact and gestures actually play a very small role in anticipating the course of action another vehicle will take. There are all kinds of reasons for this type of communication not being that useful, or even possible. It could be darkness in the vehicle for instance, reflections make it impossible for a pedestrian to look inside of the vehicle, rain can block a clear picture and so on. With these conversations, the question soon became a lot clearer: is eye contact in traffic situations as important as we still seem to think it is?"

Subtle mess

"My first order of business was to go outside and conduct an observation study which involved setting up a few cameras on busy intersections in and around Eindhoven to observe what actually happens in traffic situations. Undeniably it wasn't the most exhilarating of tasks but the insights I gained were both interesting and revealing! I had never observed traffic situations at length like that, which goes for most of us no doubt. We interact when we need to interact and then we go on our way, out of sight and out of mind. Now I was waiting for hours at a time, sitting next to my camera and watching people interact with each other. One of the interesting things we found, is that this interaction seems to contain a lot of very subtle, implicit and dynamic 'mess' that is ongoing constantly. The interaction is not limited to observing one another's signals, having eye contact or sending out gestures, but people are constantly communicating on many more levels and most important, they are constantly adapting to the situations that are presented to them, with experience in traffic as a basic guideline. For instance: a person standing at a pedestrian crossing knows that he has right of way, sees the vehicle in the distance, observes its movements and if it slows down, this might be enough of a reason to cross the road. This all happens without any eye-contact. If the vehicle doesn't slow down enough however, pedestrians would automatically alter their path and they will choose to go behind the car. This is all happening so smoothly, so that the vehicle doesn't need to brake aggressively as well, because some form of understanding is already there. This interplay is happening all the time, and disproves our assumption that explicit communication is so vital in traffic in every situation."

A new language

"As humans, we are very adapted to picking up these subtle changes in movement and motion and we don't even actively recognise that we are picking this up. To give an example; as a vehicle comes towards a pedestrian, the pedestrian needs to anticipate what could happen next and react accordingly. Subconsciously, the pedestrian will pick up even a slight dip of the nose of the car as it brakes, while the driver of the vehicle picks up the intentions of the pedestrian just by looking at subtle changes in body language. This kind of behaviour comprises most of the communication in traffic. Only when this isn't sufficient, when there has to be some kind of exceptional 'negotiation', or when we detect 'not being seen', do we move towards more explicit gestures. Most of the time, we seem to treat the vehicle as a whole, not as a human driving a vehicle."

"To translate this knowledge into the field of self-driving vehicles, we basically have to create a whole new language. How can we adapt these subtle, but human-driven messages to a vehicle that drives without a

To translate this knowledge into the field of self-driving vehicles, we basically have to create a whole new language.

human driver? Now we have to think of an interface, to allow the vehicle to communicate its intentions with the outside world. While subtle, natural movements of the vehicle seem to work in a lot of situations, other scenarios may require more specific communication. We experimented with light signals on the car, but the more we dove into that subject, the more apparent it became that this raises many questions as well. Traffic lights for instance, work perfectly as a static object, but once you translate this to a dynamic vehicle, lots of uncertainties occur. Does it mean the vehicle will stop when the light is red? Or does it want me to stop? Can I give some form of feedback? What happens when I'm crossing the road and the light turns green again? I am happy to report that the results from our studies have led to concrete steps towards new communication interfaces that address these issues. There's still so much research to be done in this field alone, let alone in all the other fields of research on automated vehicles, that I wonder if we will ever fully solve this puzzle. But it proves to be a great focus point for research, which will eventually lead to safer and more efficient vehicles and better driver aids. I'm delighted to have been a part of that."

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Setting new standards

MARK VAN DEN BRAND

In order to move humans safely from A to B, the systems controlling and executing cooperative and autonomous vehicles need to be as transparent, efficient and safe as possible. That is of course, easier said than done, particularly in a world where large players in the automotive world all develop their own systems, that somehow must work when sewn together by millions of lines of code. So therein lies a fundamental challenge: figuring out how to design a new, efficient, universal software model which can be used across all stages in the production process, from architectural design to implementation. Project leader Mark van den Brand explains the complicated road to designing less complicated software.

“As the title of project 6, Architecture and Functional Safety makes clear, there is an aspect of functional safety existing in every mechanical and electrical device that people interact with. Our challenge was to make sure that functional safety plays a central role in creating the right architecture in the first place. Implementing functional safety within the design of the architecture is a relatively new way of thinking. Typically, software is written and implemented, and only once problems start to occur, is the software code adapted. However, functional safety can be implemented far more efficiently when included in the process from scratch.”

A safe way of thinking

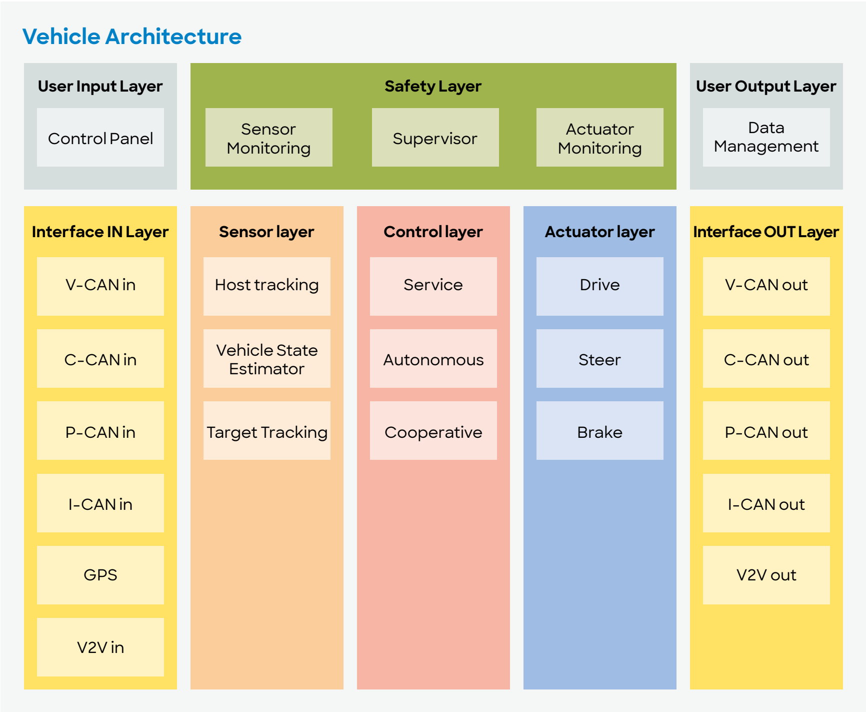
“How do you ensure that a vehicle remains safe, even if some parts of the system no longer function as they should? What are the alternative systems that can take over, how can you get the driver back on track or even bring the vehicle safely to a standstill on the hard shoulder? The key challenge for us was to address these questions within the basic software architecture of the vehicle to make sure not to endanger the driver, passengers and its surroundings.”

“In the automotive industry we follow the set standards from ISO 26262 - an international standard for functional safety of electrical and electronic systems that are installed in serial produced road vehicles- to give us a general outline of requirements for functional safety. The limitations with existing standards like this however, are that they still assume there is a driver in the vehicle. Take for instance, when tire pressure drops below a certain level, existing standards require action in the form of a warning light switching on for the driver. The appropriate action to fix the problem is left in his capable hands. The driver is still the main redundant element in the vehicle. As we continue to develop our vehicles for cooperative and autonomous driving however, the more we will have to deal with a human driver that’s being pushed further

How do you ensure that a vehicle remains safe, even if some parts of the system no longer function as they should?

back in the line of redundancy. And if or when the driver is called into action, the reaction time has grown dramatically as well, because he first has to fold up his newspaper and find the cupholder for his coffee…”

“In order to tackle these issues, it’s clear that new standards have to be developed and new chains of redundancy identified. That is different from the current situation when it comes to building a vehicle. The design and assembly of components is done by the car company’s themselves of course, but if you start to reverse-engineer a vehicle, you’ll soon ascertain that of 100 components, maybe as many as 20 different manufacturers can be involved. Each of these manufacturers is highly specialised in creating a certain piece of the vehicle. Take an airbag for instance, there are only a few manufacturers that provide this crucial safety measure to every manufacturer around the world. The same applies to most vehicle parts- electronic units for ABS and ESP, brake systems and even engines are shared between brands. All these different components and even different versions of the same components, present us with a continuously growing challenge: how can we ensure that all these systems can communicate with each other and in the near future: communicate with other vehicles as well?”



Making use of existing research

“So how did we start? Fortunately, we had already made quite a few steps in the field of functional safety before I-Cave started. The year prior to the start of I-Cave, Yanja Dajsuren, one of the co-writers of the I-Cave Project, wrote a dissertation on the quality of Automotive Software Architecture. That was a project done in conjunction with DAF trucks, aimed at developing a hybrid truck. Of course, that has some influence on the software architecture we were looking to develop, presenting Yanja with a new question: how can you determine whether an existing architecture is suitable for expansion? Also another PhD student, Yaping Luo, had already been working on modelling functional safety standards and provided us with her dissertation ‘From Conceptual Models to Safety

Imagine a book, full of methodologies and recommendations that software engineers use to write code.

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Assurance’. Imagine a book, full of methodologies and recommendations that software engineers use to write code. It describes all kinds of definitions and process flows, for example ‘what is a hazard?’ Or ‘how do we define an item?’ And that inevitably led to the following question: is it possible to create a tool from these models, that an engineer can use to apply these functional safety standards when creating the basic architecture. A tool that tells the engineer exactly what the definitions are and what they stand for, so he can implement them relatively easy.”

“As we already had those two research projects at our disposal, it was quite easy to fit in functional safety standards in the development of this new architecture. To be able to start creating a new architecture, we also needed to have access to a relatively ‘dumb’ test vehicle- the Renault Twizy demonstrator vehicle provided by Project 7. This would help us to determine how data flows through the can bus wires, before you start adding sensors and other systems. Can we detect for instance, that there is a component that is not working properly by examining certain data in the Twizy? Will that be registered, will there be a check mark? And what action should be taken next? What you actually want to achieve is the following: can you detect, for example due to hitches in the data flow, that a sensor is about to break down, before it actually breaks down? Our objective was to measure this and act accordingly, even before a component stopped working all together. That way you can already enable redundancy before any damage occurs. This is safer than only taking action after a component fails. You probably easily compare it with your own 'gut feeling'. Like when you notice a strange sound coming from the engine, or feel a vibration in the steering wheel that you didn't feel before. The vehicle might still function as normal, but you know something could be wrong. It is exactly this feature that you would want to build into the basic software architecture."

Challenges and Opportunities ahead

"It is of course important to build in enough redundancies, to ensure that there is always a plan B on which the system can fall back. But what happens if plan B doesn't work? Is there still a plan C, or is it time to engage the human driver? These questions are complex and far from being answered yet. Today's vehicles are full of electronic assistance systems, but they lack the redundant systems to fall back on. As the amount of autonomous and cooperative functions in vehicles increase, there is a much greater need for this. New guidelines and standards have to be developed for this, functional safety is still in its infancy in the automotive world, so it's very important to develop ways of incorporating this in the early stages of vehicle design. Ultimately you want to be able to say 'this vehicle is safe', and to be able to trust that the systems are well put together with human safety in mind."

"To keep up with developments, a lot research will be needed to ensure that vehicle occupants are protected. An acceleration in this research however, can only take place if we include functional safety as part of the software architecture from the very beginning. Through the I-Cave Project, we have succeeded in developing a number of architectural patterns that increase functional safety. Being able to detect a possible breakdown in the future however, proved to be a lot more difficult and

There is however, one big problem that gets in the way of really getting to work with the available data, and that's the industry itself.

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there is still much work to be done to actually make that work. We need to obtain a lot more data from the vehicle and that's easier said than done. Although we were not able to validate them, we did manage to bring a lot of ideas and theories to the table, so there's quite some material for further investigation. With new techniques, like Artificial Intelligent Machine Learning, whole new possibilities are available. The sheer amount of data that's being generated by modern day vehicles will also help this part of the research ahead."

"There is however, one big problem that gets in the way of really getting to work with the data, and that's the industry itself. Manufacturers and suppliers are still holding on to 'their' data and are not willing to share it. If we want to develop new standards and move forward, we will need this data as well. It puzzles me, because there's not a lot of intellectual property involved. I do know that manufacturers eventually have to release this data, because agencies like the RDW an EuroNCAP need to be able to verify and check safety standards of all vehicles in the future as well. This will increase as more and more autonomous and cooperative features are added to vehicles. To be able to check if the vehicles are actually safe for users, these agencies will need access to all data and software involved. A start has been made in the form of ISO 26262, but regarding autonomous features it's still in its infancy."

The best proving ground is the public road

"Nowadays, lots of software and features are already implemented in vehicles by the manufacturers themselves, without proper standards for the whole industry, so lots of brands are creating a head start for themselves. This is a bit disturbing on the one hand, but on the other, it is also necessary to find out experimentally, what works and what does not. It is precisely by pushing the boundaries that technology is further developed. Of course, you can try to predict safety issues and scenarios, but it is mainly practice that will show where the problems and challenges lie. The best proving ground is always the public road. Just think back to the development of the safety belt. In the early days of vehicles, the speeds were quite low and the roads were quiet. There was little necessity for extra safety measures. However, circumstances changed, more and more accidents involved people being thrown out of the vehicle due to higher speeds and busier roads and it was only then that the requirement for extra safety measures was clear."

"A similar process will happen here. The more common autonomous driving features become, the more safety-issues will occur and need to be addressed. At the moment, legislation, regulation and standardisation are still lagging behind. But there comes a time that we have to address these factors. We need to think differently about the system of the vehicle as a whole. Right now, more and more individual systems are

It is precisely by pushing the boundaries that technology is further developed.

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added to vehicles, with their own microprocessors and software also needing to talk to each other, creating even more code and software until eventually the whole system collapses. To give you an example: the most advanced fighter aircraft in the world at this moment, the Joint Strike Fighter uses between 5 and 8 million lines of code to operate all these extremely advanced features. The average vehicle nowadays uses about 20 million lines of code and that number is growing exponentially. That says something about the efficiency of all these features being 'glued' together by even more code. Even the amount of computer processors is enormous and could easily be brought back to one or two, if systems are designed with proper basic architecture.'

The system as a whole

"The speed in which automated and cooperative driving features are being developed is mind-blowing. The challenge however, remains the same: how do you make sure that vehicles are still safe? What will happen when these features fail? What will happen if the data flow between system A and system B is interrupted somehow? Did the manufacturers take that into account when they sold their system to manufacturer X? I think we'll need a revolution of some kind, a simpler, more efficient system that will provide the vehicle manufacturer with a new way to develop electronic systems, as part of a standard architecture instead of 'stand alone'. And don't forget the potential for the surrounding environment to play a big role as well when we think about autonomous vehicles. Data and information from sensors in the road, from traffic lights and other vehicles, will greatly improve the quality of data available and increase the chance of driving safely. To my surprise, the focus is still largely on a completely autonomous vehicle, when there's so much to be gained from sharing data instead of creating only your own data. There's still a lot of work to be done, and the key lies in a new way of developing software architecture and looking at the system as a whole.

"I would also like to mention some very capable partners who assisted us in our research. Alexandru Serban, PhD student at Radboud University Nijmegen has been working on security aspects of the cooperative driving and he did his research in close cooperation with he Software Improvement Group (SIG) in Amsterdam. Alexandru was partly working at the SIG and the research on the security aspects of automotive architectures was new but highly relevant for SIG. Sangeeth Kochanthara, PhD student at Eindhoven University of Technology, has been working closely in cooperation with TNO Automotive on identifying the safety requirements to apply the learnings from the I-Cave programme to the wider settings of the Dutch highways, starting with the A-270. Another direction we worked was on methods to ensure the robustness of AI-based systems employed for perception systems. Whilst I-Cave may have come to a closure, the research still continues in all these different fields of software development. There are fascinating times ahead!"

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Creating new architecture

YANJA DAJSUREN

For the self-driving car to have any chance in the future, a revolution has to take place in the automotive industry, says Yanja Dajsuren in Project 6 and a firm believer in reshaping the world of automotive software. She and her team developed a new, basic architecture framework from scratch, laying the basis for the next generation of cars.

“Right before the I-Cave programme started, I was finishing my PhD on automotive software architecture. The biggest innovations in the automotive industry are coming from the software engineering field, in particular in software and electronics, notably thanks to advancements in sensors and actuators technologies which are a driving force for 90 percent of innovation in the industry. I’ve always been fascinated by the automotive domain and the growing complexity of its software. During my PhD I identified a set of key directions computer scientists should pursue to push the boundaries of innovation in this field. It was whilst I was writing my thesis that I became involved in the core team of the I-Cave Programme, bringing in my insights regarding the key research challenges around software architecture and safety-related research challenges. My next role, as a member of Project 6 of the I-Cave programme, was therefore a continuation of my research in collaboration with Sangeeth Kochanthara, my first PhD student and other Project 6 team members."

Over-complicated systems

"Given that the development of software architecture does not typically incorporate any considerations of safety, the point of departure for my research relied on adopting a novel approach to software engineering. My objective was to embed safety as an integral part of the design process even before the building the software. Incorporating key quality aspects including safety in the early phases of software development, means that significantly less maintenance needs to take place on the final product, avoiding a lot of unnecessary costs and extra hassle. Take for example, the numerous recalls that take place in the automotive industry. As the amount of software requirements increase to enable smart features in the cars, software related recalls have likewise gradually increased, with 60% to 70% of the car-recalls due to software glitches. Providing a software fix after a complicated product like a car is introduced in the market, is time consuming and very costly."

"So, there is an inherent problem concerning software; we cannot simply continue building software on top of software endlessly, because the number of faults grow with the number of lines of code in the software.

We cannot simply continue building software on top of software endlessly.

If you then start applying patches to get the systems to work, you end up with millions and millions of lines of codes, that need to be integrated and tested again against key quality attributes including safety. Traditional car manufacturers face challenges in building and maintaining cars using a software-driven approach. It is no surprise that software companies and startups like Tesla, Google and Uber are driving the future of automotive industry with their innovations and creating new opportunities. Even in fixing and remedying recalls, many big Original Equipment Manufacturers (OEMs) have limited support for over-the-air (OTA) software updates and spend months to complete software-related recalls."

A fresh start

"The solution: start all over again and take a fresh look at the base design. In the automotive industry, the main problem for researchers is the limited access to real-life car data, especially if they don't have collaborations with OEMs and their suppliers. This is a vital element when vehicles are also going to make use of sharing data. Therefore, if the OEMs and suppliers open their data to more researchers, the challenges they are facing can be addressed collaboratively in a shorter time. In our project however, we did manage to create a new, basic architecture that could be tested on the Renault Twizy demonstrator vehicles in Project 7. The beauty of the automotive domain is that researchers and practitioners from different fields come together to make changes, as in the I-Cave Project. Having a Project 7 helped researchers from other projects including our team validate our ideas and identify new research challenges. It made the project quite fun to collaborate with the team working on real-life cooperative and autonomous vehicles. For example, my PhD student Sangeeth Kochanthara supervised six honor-track students from different departments to build an automatic generation of runtime health monitors for making vehicles safer."

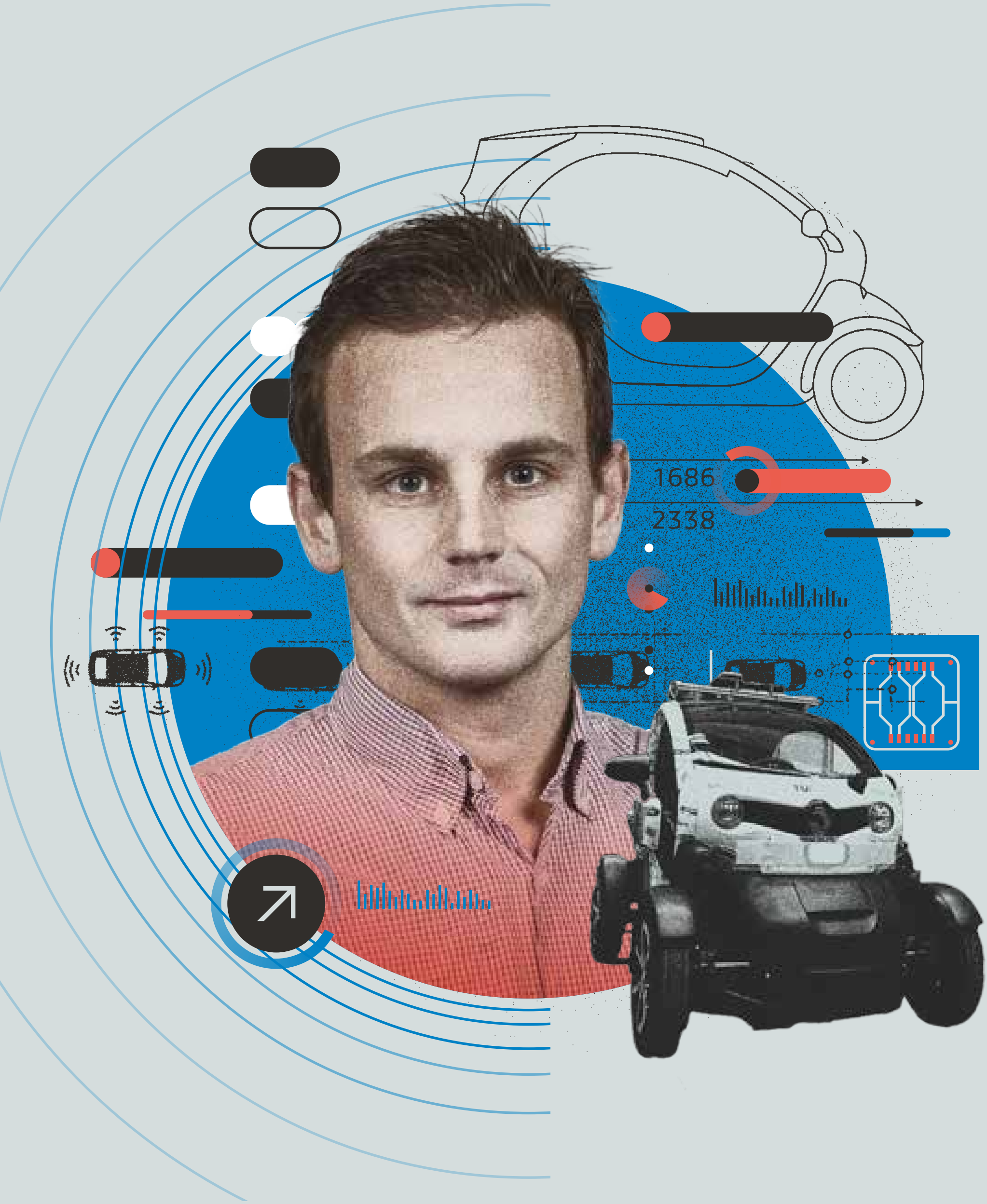
"Having access to a real-life demonstrator helped us realize which ideas could come to fruition and which needed further research and we have written our results in more than 30 publications. With the general functionality of the car in mind, we were able to focus on the autonomous and cooperative driving of the vehicle and we designed a new architecture from scratch with functionality, functional safety and quality attributes driving the design. Obviously, the system is still being researched and applied only in a small scale on the demonstrator car, but the results look promising."

Challenges for the industry

"Creating a new architecture was not the only task we had on our list. Being able to address functional safety issues in this architecture from the beginning was also one of the challenges we had set ourselves. How can we ensure that safety methods are applicable to the autonomous and cooperatively driving car and that safety drives the software design? How can we make sure that the car is inherently safe, no matter how complicated the systems added would be? The existing ISO 26262 safety standard does not support autonomous and cooperative driving cars. While new standards e.g. SOTIF were being developed we came up with solutions and recommendations. To be able to develop new generations of vehicles, capable of performing several tasks autonomously and cooperatively, the mindset of the industry and society has to shift to

We designed a new architecture from scratch with functionality, functional safety and quality attributes driving the design.

sharing and cooperating. Together with project leader Mark van den Brand, I've written a book, published in 2019, that addresses challenges and future trends in automotive software engineering which covers all essential aspects of this field. It's great to be able to mention that this book, called Automotive Systems and Software Engineering, has become one of the 50 best-selling automotive engineering books. There's no doubt in my mind that developments in this area of the automotive industry will continue to evolve, and I'm thankful and excited to say that the I-Cave Programme has really contributed in creating new insights."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Science on wheels

TOM VAN DER SANDE

The I-Cave Project has always been about going back to the basics, figuring out new standards and ways for vehicles to operate automatically in their surroundings, using communication to improve cooperative and autonomous behaviour. In order to achieve a safe and reliable automated vehicle concept, a seventh research line was created to put new systems and ideas that had been developed from the other six research lines to the test: a living lab evaluation, a platform vehicle that would function as a working testbed. Tom van der Sande, caretaker of this living laboratory using Renault Twizy test vehicles, talks us through the work, the challenges, the results - and sometimes sheer fun - of testing the ideas and concepts on a real-life vehicle.

In order to develop new technology, you need a basic driving platform that preferably does not 'think by itself' - the Twizy proved to be the perfect vehicle for that.

"Self-driving vehicles have always fascinated me, and you could even say that a project, involving the Renault Twizy test vehicle, led to the I-Cave programme in the first place. This vehicle was already part of my team, functioning as a multifunctional testbed for different systems involving self-driving cars. For the project members of project group 7, it was of the utmost importance that the vehicle we chose was as 'clean' as possible, which meant: real basic electronics, no complicated systems or driver-aids that could risk interfering with systems that were being developed and installed by us and all of the other projects. In order to develop new technology, you need a basic driving platform that preferably does not 'think by itself' - the Twizy proved to be the perfect vehicle for that. It doesn't even have ABS and Traction Control, which might be not so nice for a client, but fantastic for us. Pure, basic, small, easy to work on and also crucial- capable of moving around in a semi-closed off environment like the campus of Eindhoven University of Technology."

"The first question we asked ourselves when we initially started working with the demonstrator vehicle, was: how are we going to automate all of the tasks, normally operated by humans? We started with the three

most obvious mechanical tasks - the operation of the throttle, brake and steering wheel. Exploration of other human inputs, like perception, would have to come at a later stage in the programme. The first task was relatively easy, adding electrical motors and sensors to the steering wheel and pedals for braking and accelerating. From this point on, the I-Cave Project took off, and we made sure the vehicle became a functional testbed for the PhD-students of the other subprojects. The first to work closely with us was research group 4, led by Frans Willems focusing on radar-based communications. Together with NXP, a firm specialised in automotive radar systems, we prepared the vehicle to function with their radar system."

Radar and camera data

"You might think that the boundaries between the groups and ours, the demonstrator platform, were quite solid, but in practice it doesn't work like that. Knowledge flies back and forth and we all learn from each other as we go. To come back to the radar systems: the way this works, is probably best explained by the way a blind person uses his cane to 'feel' which way to go. You know something is near, a solid object, at a certain distance and with a certain velocity, but what kind of object this is, is difficult to determine. In addition to this, if the radar receives a reflection from an object, it is impossible to determine what the motion of this object will be in the future and whether it belongs to the same object that was detected one time-step ago. One of the main challenges was therefore to create a reliable image of the surroundings based on simple measurements and to predict how this image will evolve over time."

"By the time the I-Cave Project had been going for a year or two, we had already completed some research on the radar systems. At that point the camera systems came into sight and there comes a moment when you have to make some decisions of how you are going to direct and process all this data in a system. We decided to go for a real-time computer, one device that can do everything at the exact moment that you require action. This is vital, because you can't have a computer saying 'hold on, I'm updating' when you need to turn a corner or make another critical decision. A vehicle, and especially an automated vehicle, needs

Knowledge flies back and forth and we all learn from each other as we go.

an operating system that comes into action at the right time, no matter what the circumstances are. There is no room for delay. Unfortunately, once we made this choice, we discovered that research Project 1 needed a completely different computer. One that can handle neural networks and can process enormous amounts of data to teach itself step by step. That requires a lot more 'computing power' and different graphic adaptors than we initially needed in the vehicle. So, we couldn't avoid the fact that we were going to have to use different computers side by side in the vehicle. And a Renault Twizy isn't the largest vehicle platform on the planet, even forgetting the fact that the battery capacity for energy-hungry computers is of course limited. Back to the drawing board then for us!"

Developing Twizy 2

"To advance our research we decided to start designing a second testbed, also based on a Renault Twizy, subsequently called the Twizy 2. This would also make it possible for the cooperative driving techniques developed in Project 2 to be tested properly. Cooperation with only one vehicle involved is obviously impossible. With this second vehicle there would be more space for computers and more possibilities to further enhance safety. Being a test vehicle, we wanted the vehicle to check its own systems before and during driving. Are the motors working as they should? Are the actions we require being executed properly? And since there would still be a 'driver/passenger' in the vehicle to intervene when necessary, we would also want to make absolutely sure that he or she would be as safe as possible. We wanted Twizy 2 to behave a lot better than 1, so to speak. Credit for this development really goes to Wietse Loor, and Frans Hoogeboom. Together they formed a great team. Frans from the software side and Wietse as technician. Together they basically adopted the Twizy 2 as their pet project."

"When both Twizy's were finished, we finally had a platform to install vehicle to vehicle (V2V) communications as well. First, we had to figure out what 'language' these vehicles were going to speak to each other. Then we had to establish what kind of data the vehicles would share and implement while driving. For that part, we concentrated mostly on cooperative driving and we basically started with a blank sheet of paper. A number of car manufacturers and suppliers, including of course Tesla, have been developing software in this field for years, but no one has yet reached the 'gold standard'. They mainly work according to 'trial and error' and if or when something doesn't work, they simply send out an update over the air. But what if you really start from scratch in a rigorous way? I'm not discounting the fact that enormous progress has been made in recent years, but we are trying to establish how to incorporate cooperative and, to some extent, autonomous driving in a smarter and especially a safer, way. Project group 7 was therefore intended to enable the application of the various subprojects, i.e. to test innovative techniques that have been developed and put them into practice."

New technologies tested

"Not all of the project groups were involved with the demonstrator vehicle, but for most it functioned really well as a test vehicle, even though lots of research still needs to be continued after I-Cave. For instance, Project 1 (Sensing, Mapping and Localisation) was able to install a version of vision

When both Twizy's were finished, we finally had a platform to install vehicle to vehicle (V2V) communications as well.

processing onto the Twizy, which in the future may lead to the creation of maps, based on environmental and camera data. They succeeded in recognising lines and other vehicles, which is quite an achievement. From Project 2 (Cooperative Vehicle Control), the cooperative controllers they developed ended up on the vehicle and were tested extensively by every PhD student working on the project. For Project 3 (Dynamic Fleet Management), our fleet of two unfortunately wasn't big enough to get some real testing done, for Project 4 (Communication) however, we were able to work closely together with the researchers, investigating different types of radar systems and techniques on the vehicles. There still remains a lot of testing to be done, radar communication is still in its infancy and we would like to explore that further in the future."

"Project 5 (Human Factors) focused on the human-vehicle symbioses, a whole different subject. The Twizy was being used to experiment with light interfaces, a screen on the vehicle that tells other participants in traffic its intentions, using various lights, colors and patterns. A screen was also used to show pedestrians what the vehicle actually sees, so as a pedestrian or other participant, you can actually check if you're in sight of the vehicle. And of course, there was also the 'seat suit', developed by Project 5 to fool traffic participants into thinking that the Twizy was actually driving without a driver, so they could gather information on their reactions. With the driver in this suit, he genuinely looked like a car seat. The Architecture and Functional Safety project team, Project 6, were mainly concerned with the fault tolerance of the control system. Checking for example, that the system does not end up in a loop, a vicious circle of faults where it loses the ability to function properly, when some sensors break down or other things don't work as they should. Even a part of the software that we created by ourselves was verified on safety norms set by Project 6."

Cooperative driving in the near future

"When we started the I-Cave Project, we all had ideas about the progression we could make within our own research groups, but it's not until the end that you can verify if your assumptions were right. I'd hoped

In cooperative driving, with two vehicles or more together, we have made big steps forward.

that maybe, we could make some big steps towards a fully functioning autonomous vehicle, but the further we got, the further this possibility seemed to disappear into the future. I myself had expected that we would have made more progress with the sensors around the vehicle, so that we could have a clearer vision of the environment in which the vehicle has to operate. In my perspective, it would have been nice to see a Twizy being able to drive a lot more autonomously than where we started from."

"In cooperative driving, with two vehicles or more together, we have made big steps forward. But for one autonomous vehicle to find its way on its own, without data from other vehicles or the surroundings? I'm afraid that's still far away into the future, or never going to happen at all given the complexity of the outside world. However, we have come a long way in simply 'figuring stuff out'. Much more time is needed on this complex subject, from the development, application and tuning of all those algorithms, camera systems and sensors, to get it to function like it should. Even with a big project like this, the amount of 'manpower' is still limited whilst the research area is enormous. For the time being, the greatest gain can be achieved with cooperative driving. By sharing data and using information from other road-users and the road and infrastructure itself, you can get from A to B very efficiently in certain situations. There is still a lot to be gained from this however, also from an academic point of view. Driving in a straight line, close together in a platoon is something we're able to do well now, but it still gets complicated when we include corners in the equation, or if you have to merge into other traffic for example. We have actually only just started figuring out how this can be done properly and safely. When you start investigating these issues, soon you'll end up with having to incorporate some level of autonomy."

"For us, the days of actual testing outside, on various test locations as our proving ground, were challenging and exciting at the same time. When you're testing the vehicles, driving cooperatively very close together, you still have to trust systems which you know are not perfect yet. So we kept our heads cool, our feet hovering over the brake pedal, testing whether the vehicle would react as it should react. How does it feel, being just 0,2 seconds behind the other Twizy? The Twizy's never collided, and nobody was harmed in the process, but there were certainly times when we inadvertently tested the suspension of the Twizy in the grassy roadside of the test tracks…"

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Demonstrator car

WIETSE LOOR

The I-Cave programme has been quite a journey, with numerous innovations being developed and new concepts created. But actually, putting the theory into practice is easier said than done. Getting new systems implemented and getting them ready to be tested on the Renault Twizy demonstrator, required a lot of practical knowledge and the supervision of someone who could make the translation between science and application. That's where technician Wietse Loor comes in.

"I've been involved at the Eindhoven University of Technology for quite some years now and I've somehow grown into this role of 'getting things to work'. When the I-Cave programme started to take shape, it became quite clear that we had to develop a proper vehicle that was able to handle all kinds of different and experimental systems. We had a Renault

Twizy at our disposal that was already being used to test some self-driving systems, prior to the start of I-Cave. But in all fairness, this Twizy wasn't ready yet to be put to work for experimenting on a larger scale. You can do a lot with tape and tie-wraps, but that's not good enough if you want testing to be conducted in a safe way."

The car

"In order to proceed we decided to acquire another Twizy, called Twizy 2, and really start all over again, creating proper CAN-bus connections and good, functioning actuators and motors to operate the car. Since the Twizy is quite a simple electric car, it's not equipped with any complicated systems, so it was easier to separate all of the car's 'own' electronics from the systems that we were about to test. By doing this we created a platform to experiment on without running the risk of interfering with the Twizy's own system. I'm actually proud that we were able to achieve this because the safety aspect in research is sometimes overlooked when conducting experiments. We had to make sure that no matter what system was being tested, the Twizy could always return to 'normal' with one click of a button. That's extremely important, and was checked by the RDW, the Dutch institution for road safety, to be able to test systems on the public roads as well."

"Taking a closer look at the vehicle, the Twizy's construction is more reminiscent of a tuned electric forklift truck than an actual car. All the better for us. The downside of a Twizy however, is that as a vehicle it's pretty small and rudimental and open to the elements, which meant an extra challenge to incorporate sensitive systems onto it. You cannot just put some computers on the backseat and work comfortably with the heater on, because the car hasn't got either of those features. This places much more demands on the quality of the systems being developed. And with six different project groups, each with their own demands, well… that proved to be quite a ride on its own."

You can do a lot with tape and tie-wraps, but that's not good enough if you want testing to be conducted in a safe way.

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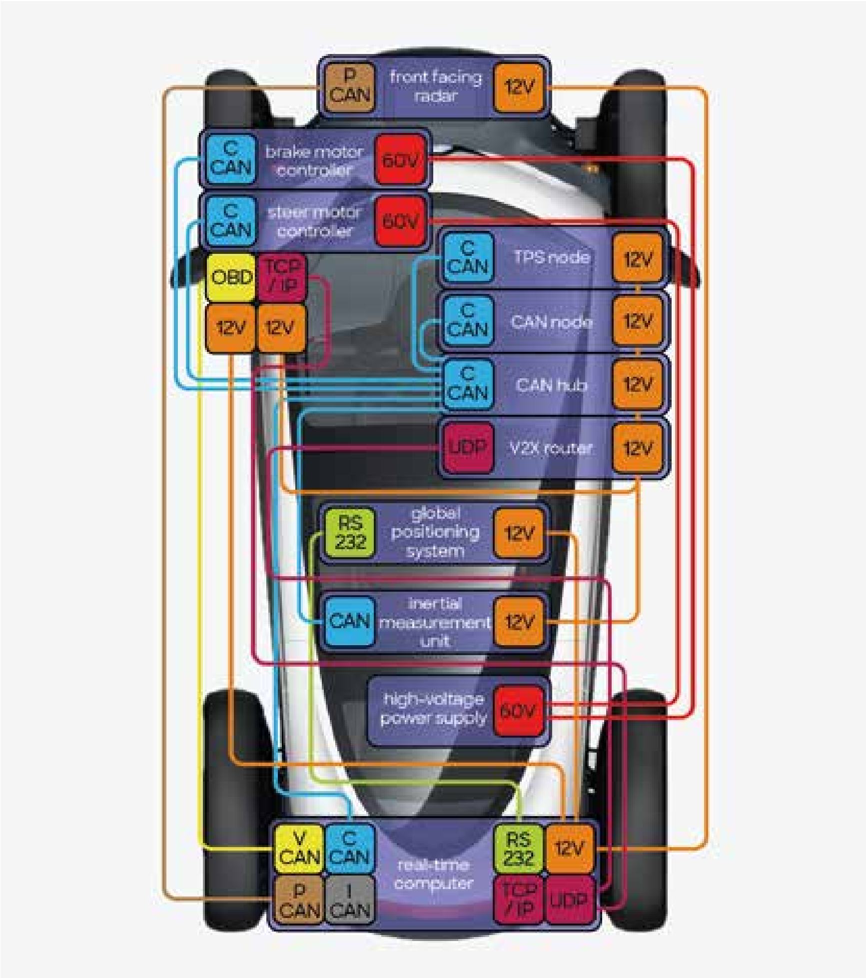
Trial and error

“Implementing experimental systems on the Twizy involves lots of trial and error and you'll end up having to overcome a lot of difficulties that arise. This of course is quite logical as there is always a gap between a theoretical concept and its practical application. To give you an example: we've been testing several different systems for autonomous driving, but we kept having problems with existing GPS-systems. For our research needs, the systems we work with have to be extremely accurate, but the GPS systems on the market now, have a tendency to 'drift', meaning that the location is never the same and moves around within a circle of several meters. For our research objectives therefore, the existing GPS systems weren't adequate, because autonomous systems need to be able to rely on a fixed location. Likewise, with the accuracy of radar systems, so we've tested many, even pulling them out of existing cars, altering the software and trying to make it work on our Twizy. It's our job to figure out a way that tests can still be executed, and most of the time that comes down to finding creative solutions, even simple ones. That's what makes this job challenging and sometimes frustrating but really great nonetheless”

“Looking back on the project, I have to say that these little cars stood up to the challenge and nothing really went wrong, a big plus, considering



the sheer amount of tinkering with the car over the past years. However, although some of the systems I've been involved are very innovative, in my opinion, we're still a long way from a fully autonomous vehicle. From the technological side there's still a lot of work to be done and even with vehicle to vehicle (V2V) communication there are some problems

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But all in all, I-Cave has been a great learning platform and provides us with some new questions for the future. I'm looking forward to it.

to be addressed. I can't even get my home Wi-Fi working as it should, so the autonomous car developers have their work cut out for them. I've certainly learned a lot when it comes to using different systems to actually operate the car and we've made some big steps into finding the right way to control the steering, brakes and accelerator to improve the overall safety of the car.

Together with PhD student Frans Hoogenboom, who took care of the software-side of those systems, we've built a very reliable test vehicle, capable of testing many systems. But we also had to learn by doing and experimenting. As I'm the hardware guy and he was responsible for the software we liked to compete with each other, and a case of beer for the one who proved to be right was our usual prize. Let's just say he's still got some drinks in the fridge. But all in all, I-Cave has been a great learning platform and provides us with some new questions for the future. I'm looking forward to it."

Bringing I-Cave to the outside world

BRAM HENDRIX

When performing in-depth research in the world of the autonomous and cooperative driving vehicles, the scientists involved from different project groups also relied on partnerships with 'the outside world'. Partners from different corners of the automotive domain proved to be extremely valuable and helpful, both in funding and adding knowledge, facilities, software and hardware to make the research possible. One of the people involved in this is Bram Hendrix, associated to the I-Cave programme through RAI Automotive Industry NL, the Dutch cluster organisation of the Dutch automotive industry. Together with Bram, we take a look back on the I-Cave programme and the impact it's had, and still has, on the Dutch automotive domain.

And I can assure you- I-Cave has made, and continues to make, a big impact.

“As one of the few ‘non-technicians’, I was privileged to join the I-Cave Programme on behalf of RAI Automotive Industry NL (formerly Automotive NL), representing almost 200 different companies engaged in the Dutch automotive domain. At RAI Automotive Industry NL, it’s our job to optimise mutual contact within the automotive domain and to search for new ways of collaboration and opportunities to benefit this sector as a whole. Introducing new projects to our partners, instigating further developments and helping to bring these new concepts to the market. So basically, I’m the ‘man in the middle’, tasked with searching for opportunities to implement the research being undertaken in the seven projects within the I-Cave programme.”

“Another job of RAI Automotive Industry NL consists of writing the ‘Dutch Automotive Roadmap’ together with our partners, which is meant for setting directions for the industry as whole but is also used as an assessment framework for projects like I-Cave. In this way, I-Cave also plays a big role in the directions we’ve defined for the Dutch automotive domain. And I can assure you- I-Cave has made, and continues to make, a big impact. Take for instance the increased road safety that autonomous and cooperative vehicles will inevitably provide, aiming for zero deaths in traffic in the future, zero emission transportation and the elimination of traffic jams. The fundamental

As a partner of the I-Cave programme, we were keen to engage in a meaningful way.

research in I-Cave gives our industry, important roadmaps to greatly improve mobility in the future and helps us to guide this roadmap in the right direction."

Finding relevant connections

"From the very beginning, I-Cave has worked with many partners as part of its programme. Several project groups already had good relationships with external parties in the automotive domain and ,as the I-Cave programme rolled on, more and more connections with industrial partners were identified and explored. The value gained through these relationships was mutually beneficial, and a lot of partners were instrumental in advancing the research being done within the I-Cave programme. It's the classic 'one plus one is three' concept, providing insights and facilitating communication between different stakeholders enhanced the research and created new opportunities for the Dutch automotive domain. As a partner of the I-Cave programme, we were keen to engage in a meaningful way. To do so, the user committees of each project, each of which also included several other companies, met regularly-once every six months, to be updated on the progress being made in the various project groups. From the findings presented, we could then try and find relevant connections to the Dutch and international automotive industry, trying to find out how our members could benefit, while the companies in this committee could focus more on the practical usage within their own field."

"One of the fascinating parts of my job, is therefore making these connections. At a general level, scientists tend to become completely absorbed by the challenges within their own field of research and I-Cave was no different in this sense. And whilst that might be absolutely necessary for coming up with new concepts and ideas, finding a practical use and translating this to the outside market is also critically important. Certainly, a new piece of technology isn't of much use when it never leaves the lab. So, I brought with me a helicopter view, helping to find relevant partners for all of the I-Cave projects, who can put the brilliant I-Cave concepts to practical use. To give an example; we managed to acquire one of the Covid-19 recovery subsidies for R&D projects, for a project called the Driccam project. This is developed to create a digital road infrastructure, in which a lot of research done in the I-Cave programme is being put to practical use. Thanks to partners like TomTom, NXP, TNO, TUD and TU/e, who were all also heavily involved in the I-Cave programme, we were able to bring this one step further ensuring that the outcomes of I-Cave became even more relevant."

Creating future jobs

"But the impact of I-Cave doesn't end there. If you look at the 'human capital', the number of bright minds doing research in the automotive field, this too helps the Dutch automotive industry be a world leader in terms of its high-end expertise and capabilities. Many students and PhD's involved in the I-Cave programme over the years have ended

The I-Cave programme may have been finished, but it will be a while before we will see the results from I-Cave in physical products.

up working for our partners, thereby increasing the knowledge we obtain and making sure the automotive field is a very relevant part of the Dutch economy. This is an important factor, because in the general mind, the Dutch automotive industry is not very well known, because except for DAF trucks, there are no large vehicle manufacturers based in the Netherlands. But within the worldwide industry, we are very well known for our high-end suppliers and innovative parts industry. For example, NXP makes chips that are used all over the world, TomTom provides maps for lots of OEM's and VDL creates car parts for a number of brands. Make no mistake, as a whole, the Dutch automotive industry creates a revenue of 20 billion euro every year, so having a programme like I-Cave working alongside with our partners is extremely relevant. The big trends in the near future within the automotive industry are about digitization and sustainability. Two trends in which the Dutch automotive domain is really good at, looking at the highly innovative nature of our universities and industry. The level of knowledge here is very high. I-Cave also helps us to stay on that level and create jobs in the future as well."

“The I-Cave programme may have been finished, but it will be a while before we will see the results from I-Cave in physical products. So, our role at RAI Automotive doesn’t end here, because we’re still making efforts in connecting the I-Cave research and results to the rest of the world, to get the industry to implement the results of I-Cave. If we peak into the future, one thing the I-Cave programme has taught us is that autonomous driving as a concept is by no means ready to implement yet. There’s a tremendous amount of work still to be done and whether the ‘robot car’ is ever possible is something we’re still not sure of. When the I-Cave programme started, the industry was a lot more focused on ‘the hype’ of the self-driving car than it is now. But the development of smarter driver aids, or cooperative driving capabilities, really could bring mobility a step further into the future. The new hype now however is sustainability, and many of the concepts developed in I-Cave can have a big and positive impact in this field as well. Innovation is still the driving force behind the industry, and I-Cave has played a major role in setting new picket posts for the automotive field to follow. And that means good news for the Dutch automotive industry as well.”

I-Cave contributors

The I-Cave programme is a combined effort by many contributors, to whom we owe a big thank you. Without their relentless efforts, even during difficult times due to Covid-19, I-Cave simply could not have pushed the boundaries of science the way it did. Below is the list of main contributors, though certainly others have contributed on a less frequent basis as well.

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The future of moving forward

In 2015, the NWO 'Perspectief' research programme Integrated Cooperative and Automated Vehicles (I-Cave) was instigated to address the challenges of throughput and safety in transportation by adopting an integrated approach to automated and cooperative driving. This programme, led by prof. dr. Henk Nijmeijer and rolled out over seven different projects, combined the scientific knowledge of researchers from Eindhoven University of Technology, University of Twente, Delft University of Technology, University of Amsterdam and Radboud University of Nijmegen. For more than five years, these researchers invested their time and effort to rethink existing notions of mobility and automation, researching and designing the concept of Cooperative Dual Mode Automated Transport and ultimately applying their findings in a living-lab evaluation. Within this book, we take a closer look at each of those projects and reflect on their findings, results and the fundamental questions regarding the future of mobility.