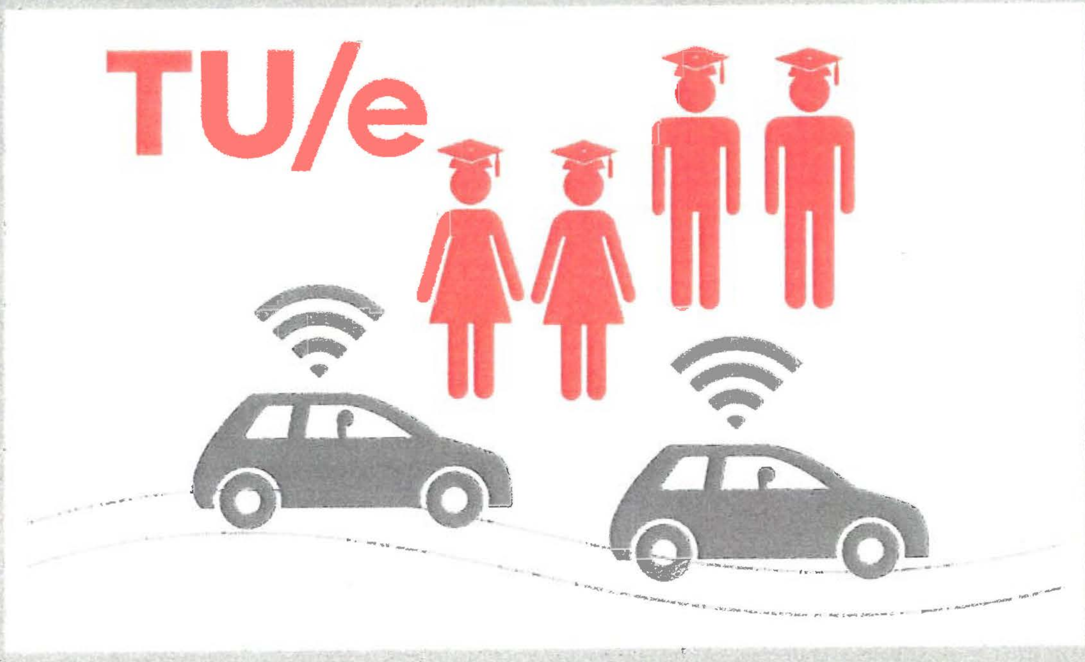
Challenge-based education for future control engineers: A semi-autonomous car project



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Control Systems group

Control & Semi-autonomous Driving as Challenge-based Education

Applicants

Main applicant: S.Haesaert, M.C.F Donkers, Siep Weiland, W.H.A. Hendrix.
Capacity group: Control systems group

Background and justification of the project

Preparing future engineers for real-life challenges.

With new technological advances, the market for high-tech products incorporating advanced computer electronics is growing. Pushed by the downscaling of sensors and processors, a ubiquitous embedding of digital components has been observed. These advances allow for new and anticipated smart systems that can operate autonomously and interactively with their environment. In control engineering, this has caused a shift from classical control engineering which mostly focused on stabilization, disturbance attenuation, and reference tracking of dynamical systems to a new era of engineering systems where control, computation, and communication are tightly integrated into so-called cyber-physical systems [1]. Additionally, with the increasing embedding of autonomy in the daily lives of people, adaptability to new scenarios and the interaction with humans is becoming a new challenging element in control engineering – an example of such a control system is given in Figure 1. The control structure of this autonomous car includes aspects of control and planning but also sensing and perception. Moreover, the structure is built up in a networked-based way and build by a multi-disciplinary team of people.

TU/e promises to educate future proof academic engineers [2]. To follow and anticipate the new technological advances in control engineering and the requirements this imposes on future engineers, we would like to pilot a small-scale challenge-based education project. As pointed out in [3], challenge-based education takes a prominent role in the educational vision of the university. By 2030, challenge-based education will be a core part of the student's portfolio [3].
The university's support of challenge-based education is visible in the TU/e innovation space, where students can be part of student teams solving open challenges while improving their system-level thinking and engineering skills.

Project goal

With this educational proposal, we would like to explore challenged-based learning for control. We will enable students to learn about real-life challenging control problems present in semi-autonomous driving and to get hands-on experience.
The pilot will be embedded into the curriculum of students graduating at the control systems group that are doing their master's in either the *Electrical engineering, Automotive Technology* or the *Systems and Control* masters program. For this group of students, working in a team on a complex control problem that interfaces with real societal issues will be a valuable addition to their curriculum.

The topic "semi-autonomous driving" for challenged-based education will be accompanied with a small-scale set-up for semi-autonomous driving. This challenge-based project will be innovative in control engineering education as this set-up represents the increasing complexity in control design, the multidisciplinary aspects, and the human-in-the-loop and data-driven technologies. And, though many steps have been made towards autonomous and semi-autonomous driving, a lot of open challenges remain. As such the set-up will offer an ideal pilot for hands-on challenge-based learning. The set-ups have been chosen to be safe, affordable and dummy proof so that students can learn how to solve open problems in engineering.
The project will give the staff of the control systems group the opportunity to gain experience in challenge-based learning. This experience is crucial to develop a long-term strategy for incorporating challenge-based education.

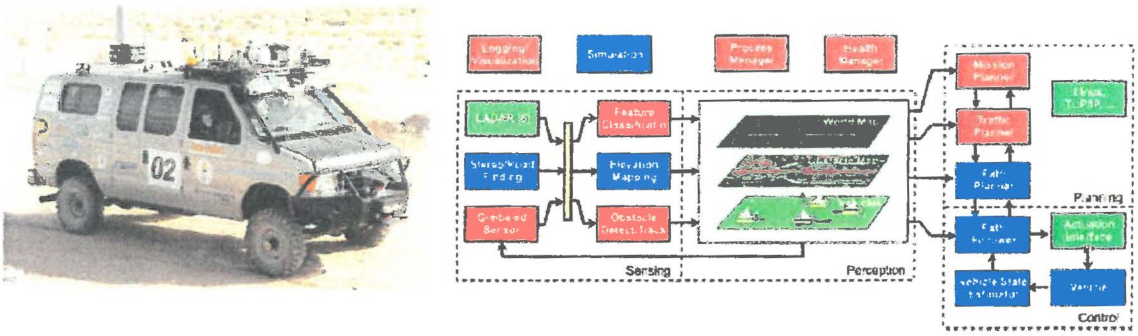


Figure 1: DARPA Grand Challenge "Alice" Caltech's entry in 2005 & 2007 and its networked control architecture Figure 1.23 in Feedback systems: An introduction for Scientists and Engineers By K.J. Astrom and R.M. Murray.

Objectives and expected outcomes of the project

To enable a transition to challenge-based learning by 2030, the Control Systems (CS) group of the Department of Electrical Engineering would like to experiment with new challenge-based learning objectives focusing on semi-autonomous driving. For this, we propose a challenge-based learning pilot for graduate students that are specializing in systems and control. The pilot will target small groups of students that are diverse, representable, and contain graduate students from the 3 MSc programs mentioned.

The pilot has as objective to introduce a number of educational innovations. The primary innovation is the enhancement of student-driven learning by embedding challenge-based education in the master's program. This proven learning method will be used to improve the students' view on the field of control systems and the connections with other areas.
As a secondary innovation, the project will develop the professional skills of the students including their understanding of code as project deliverables. These skills will prepare the graduate students for industry and graduation.

Additionally, if this project is successful, we would like to enlarge the scope to all our graduate students. In the following sections, we detail the challenge-based project, the embedding in the curriculum and the CS-EE group.

Challenging-based learning: Tackling challenges in semi-autonomous driving

For students in the Electrical engineering, Automotive Technology or the Systems and Control masters program that are specializing in control systems, we will launch a challenge-based pilot project titled

Semi-autonomous driving using RC f1:10 cars.

This challenged-based project uses pairs of versatile programmable cars of scale 1:10 to allow students to explore a diverse set of challenges, including problems of

- Control with data-driven aspects
  How do you drive at high speed through an uncertain environment?
  Can you recognize unsafe road conditions?

- Control with aspects of psychology
  How do you drive a car like a human would and is this efficient?
  How do you warn drivers about upcoming obstacles?

- Safety-critical control in human-in-the-loop situations

How and when do you take over control from a human driver?
How do you give control back to a human and how would you test this?

- Managing complex control engineering
  Can stability be proven under failures of parts of the system?
  How do design choices on filtering and control make a difference?
  How to certify performance?

For these problems, we plan to allow the students to gather, use real-world data and to test their idea. This hands-on experimenting will be enabled by investing in support for an infrastructure that includes the basic software and hardware for tracking driver behavior and for autonomous driving. This specifically includes RC F1/10th cars that students can use to validate their results.

Challenge-based learning pilot: a project on control in semi-autonomous driving for student groups
In this section, we detail how the project will be set up. That is, we sketch the project planning and supervision by the staff of the CS group. Furthermore, we also detail the learning outcomes of students participating in the project:

"Semi-autonomous driving using RC f1:10 cars"

Initially, students will have one quartile for the project. If needed this can be extended to 2 quartiles. The phasing of the project will be as follows. The project will consist of a start-up phase where students are coached intensively. After this, there will be the challenge phase. Finally, students will have a knowledge transfer phase.

1. **Start-up phase:** During the start-up phase students will be provided an F1/10th car with ROS software. Through hands-on sessions with a TA, they will be taught the necessary driving skills and programming blocks. This includes driving over a line and following a basic circuit. This phase will also require the students to find an interesting challenge-based problem and coaches to support them in solving this problem.
   Deliverable: Challenge-based problem with coaches written in a GoTCHa chart.
2. **Challenge phase:** During this phase students will work on their challenge. They will meet biweekly with their coach. The students will have to further define and solve a sub-problem in semi-autonomous driving. Generally, this will include changes and adaptations of parts of the controllers in the F1/10th cars. Therefore, they will learn how changes in parts of the architecture can permeate through the behavior of the autonomous behavior.
   Deliverable: Review each other's work in the team.
3. **Knowledge transfer phase:** During this phase students will present and compile the knowledge that they have gathered during the project. Beyond a standard report, this will also include all ROS code fragments and bug fixes. Students will learn the importance of reusability of their results. By publishing this code on Github and making reports of previous groups available to the next groups, visibility of the student's effort is made visible to the student community. Additionally, this allows students to tackle more challenging or diverse projects over the years.
   Deliverables: Presentation, code, video, and report.

Learning objectives:
We expect that the students will learn to

- Position the methods and knowledge available in control systems to solve specific engineering problems.
- Merge methods from control systems with methods from machine learning, psychology and/or vision.
- Get a deeper understanding of what it means to apply system thinking to real unsolved problems.
- Do a literature survey and critically judge applicability of different methods.
- Value the importance of knowledge transfer in engineering projects.

Furthermore, we expect that by working in a group on a challenging topic, students will gain the professional skills they need for successful independent work in their graduation project for becoming a successful communicative engineer. More precisely, we expect the student to learn

- to write technical reports: structured reports, organized presentation, grammar,
- to present their results,
- organize tasks in a team,
- work in a structured way adhering to planning,
- formulate clear problems and subproblems to work on and define individual tasks, and
- to organize meetings with supervisors and interested clients for their project.

Students grades will be evaluated based on the quality of their deliverables and their communication with both their coaches in the control systems group and with potential external interested partners and clients in the project.

Place in curriculum

The Control Systems (CS) group at the Department of Electrical Engineering provides systems and control courses to

- Bachelor students from Electrical Engineering,
- Master students in Electrical Engineering (EE) ,
- Master students in Systems and Control (S&C),
- Master students in Automotive Technology (AT) with specialization "Electric and Hybrid Vehicles and Transmissions.", and
- Master students in the SENSE programme.

This pilot will target students in the Masters EE, S&C and AT that are interested in graduating in our group. An overview of their individual MSc programs is given in Figure 3 together with the diverse set of courses offered by the CS group.

MSc program overview

1st year	Core program S&C : 25 EC EE : 15 EC AT : 30 EC	Specialization courses S&C : 20 EC EE : 10 EC AT : 15 EC	Electives S&C : 15 EC EE : 30 EC AT : 10/15 EC
2nd year	Internship S&C : 15 EC EE : 15 EC AT : 20/15 EC		Graduation project S&C : 45 EC EE : 45 EC (I) AT : 45 EC

- Model predictive control (5LMB0, M. Lazar)
- Modeling dynamics (5CSA0, S. Weiland)
- Robust control (5LMC0, R. Toth)
- Model reduction (5LMA0, S. Weiland)
- Model-based control (5SMA0, L. Ozkan)
- Advanced Process Control (5LME0, L. Ozkan)
- System Identification (5SMB0, P. Van den Hof)
- Selected Topics in Systems and Control (5LMD0, tbd)
- Machine Learning for Systems and Control (5SC27, R. Toth)
- Integration Project Systems and Control (5SC26, S. Weiland)
- Secondary batteries and hydrogen storage (5LEJ0, D. Danilov)

Figure 2: MSc program overview

Currently, the lectures provided by our group include a set of traditionally taught courses given on the right of Figure 3. For Systems and Control students this is supported by the <u>Systems and Control Integration Project</u> (5SC26, S. Weiland)

<u>Systems and Control Integration Project</u> (5SC26) has as learning objective to fully control a laboratory set-up (of the students choice). This includes aspects of modeling, model validation, model-based control, implementation, performance analysis and verification of the design.

For S&C masters, the integration project has a proven track record in helping students to integrate the courses that they studied in their masters. At this moment this enables students to apply and combine the knowledge taught in the courses. The project course (5SC26) is a *problem-based learning assignment* and is very much appreciated by the students.

The EE-CS group wants to start experiment more with challenged-based learning which is currently largely missing in the courses we offer. Additionally, the project course (5SC26) now only reaches students in the systems and control masters. Students in electrical engineering and automotive design miss out on the opportunity to use their systems and control mind set on a real control engineering problem. To ameliorate this lack, we would like to initiate this pilot project that is accessible to students from EE, SC and AT.

We have seen that a lot of students lack the professional skills needed for a successful graduation project. They have little experience in project management, presentation, and academic writing. By having a group-based project, in which they can learn from each other, we hope to remedy this situation. More frequent experience to and experience with these skills can only improve quality.

Embedding in control systems group of electrical engineering

The Control Systems group at the Department of Electrical Engineering has a lot of experience teaching diverse topics in control systems. Additionally, the group has a proven track record in both theoretical and applied research in data-driven control engineering.

This pilot in challenge-based education will be carried by the staff of the CS-EE group. As detailed in Figure 4, the group covers a wide area of expertise. As such, the available staff forms a heterogeneous pool of experts that can coach a very diverse set of problems in formulated by the students on semi-autonomous driving.

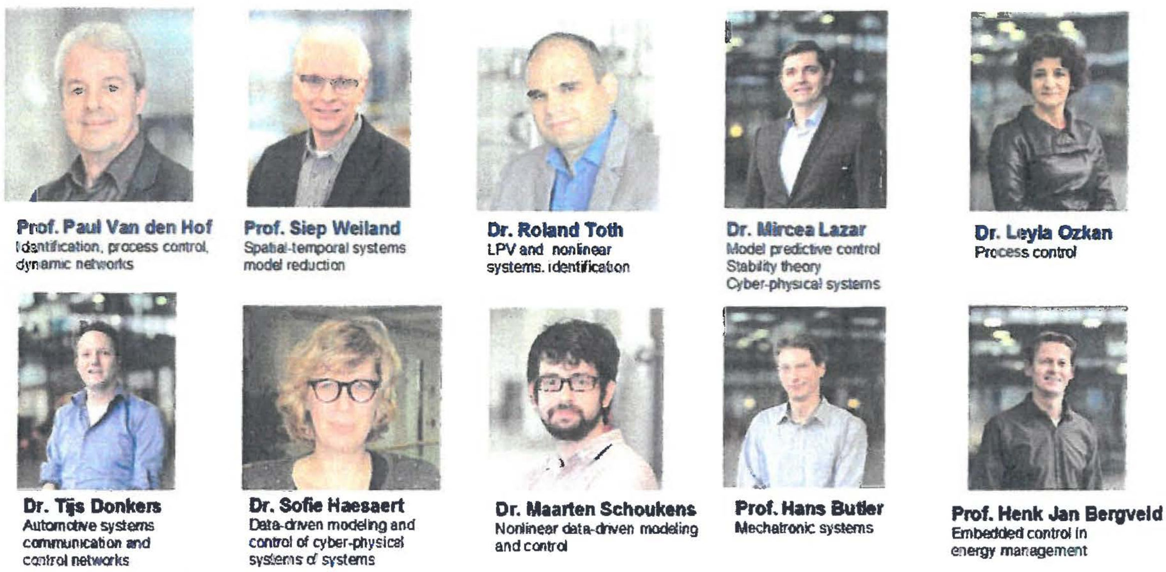


Figure 3: Control systems group members

This thrust towards challenge-based education will be primarily supported by Sofie Haesaert, Tijs Donkers, Siep Weiland, Maarten Schoukens and Will Hendrix.

Sofie Haesaert is an assistant professor at the CS-EE group. She has a background in the formal methods and control design. As a coach, she brings relevant research experience the interplay between high-level planning and low level-control, control in uncertain environment and safety-critical design.

Tijs Donkers has experience with building RC cars. He led the design process of the RC cars that are now used for the Automotive Design Project: Electronic Differential (5XSC0), which is an elective course taken by automotive, electrical and mechanical engineering Bachelor students He is also the responsible lecturer for this course that uses these RC vehicles. As a coach, he also brings relevant research experience in the application of distributed optimisation techniques for vehicle energy management, eco-driving and multi-vehicle routing.

Maarten Schoukens is an assistant professor at the CS-EE group. His research interest and background are focused on the measurement and identification of dynamical systems. As a coach, he brings relevant research experience on signal design, measurement, estimation and identification.

Siep Weiland is a full professor at the CS EE group. He is an expert on education and on the control systems curriculum. As a coach, he brings relevant research experience in modeling and control for complex systems.

Will Hendrix is a senior member of the group who has been involved in the design, realization, and maintenance of all experimental set-ups operational at the EE-CS group. He also has education experience coaching student groups when doing OO projects and Lab assignments.

Project design and management

Approach

We propose to build up the challenge-based pilot over two years. The timeline of the project is sketched in Figure 5. During **the first half of the project (Year 1)** referred to as the implementation phase, we will build the set-up and try it out in the S&C integration project (5SC26). The results will be evaluated, and this will prepare us for the second half of the project.

In the **second half of the project referred to as the experience phase (Year 2),** we will offer challenge-based projects to multi-disciplinary groups consisting of Systems and Control students, EE students, and Automotive students that are specializing in Control systems. The project will be offered in 3 quartiles and would be ideally suited to be an elective for 1st year MSc students. Every quartile we will only supervise 2 student teams. By having multiple small batches of students, we will have several evaluation cycles. Also, this will give the students the opportunity to present their results to the students that will do the group in the next quartile. This is detailed in Figure 6.

By **the end of the pilot**, we will evaluate and decide whether and how the challenge-based education can be a part of control systems. Options include inter alia

- Extending the number of set-ups and making it a project accessible to all graduate students specializing in control systems
- Finding alternative set-ups to offer more diverse opportunities
- Including coaches from signal processing, machine learning and other specializations.

In case the project is by the end not mature enough to become a full challenge-based project, it will be merged with the integration project and build set-up will become available as a setup for the integration project and for the graduation projects and internships.

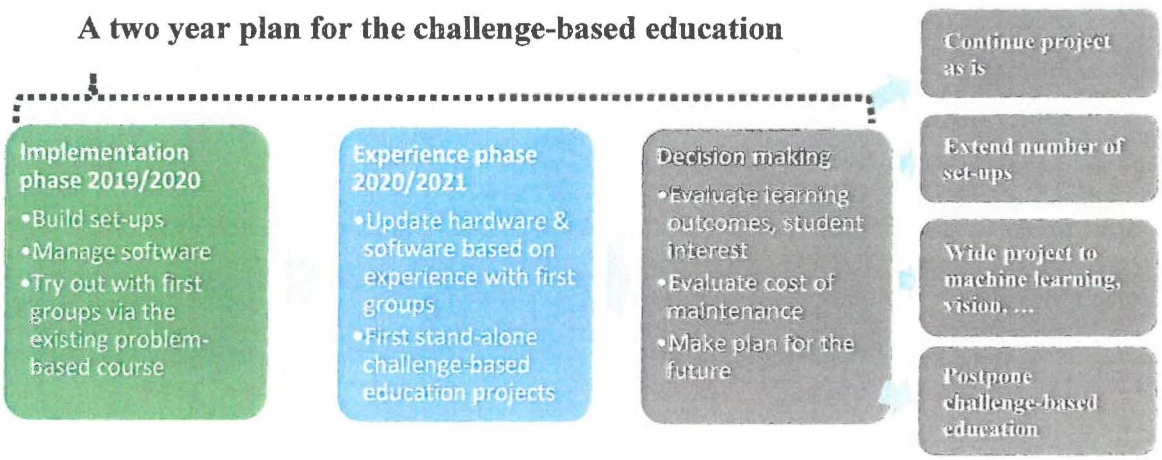
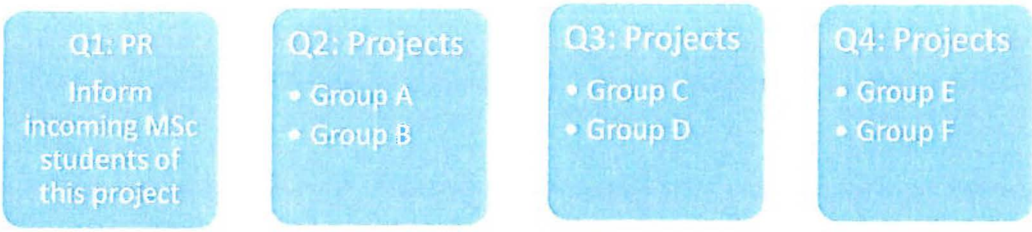


Figure 4: Timeline project

Experience phase: roll-out of challenge-based projects in 2020/2021



Challenge-based projects
- Max of 2 teams with 3 to 4 students each
- Students present their results to the next groups

Figure 5: Timeline experience phase

Project Workpackages

The project will be implemented through the following work packages:

WP1 BUILDING THE REQUIRED LABORATORY INFRASTRUCTURE

Task 1.1 Building and preparing the F1/10th cars

To do this pilot, we have chosen to follow the open source racing platform described by the F1/10 student competition. This provides us with an affordable and student-proof set-up as given in Figure 2. The system architecture is complex enough for students to experience complex engineering.

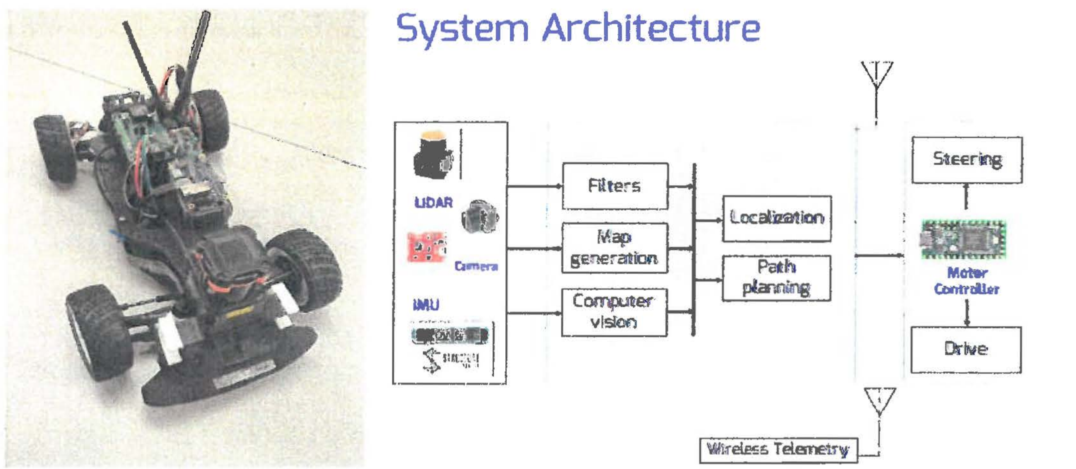


Figure 6: F1:10 hardware and software (www.f1tenth.org)

F1/10th cars have been extensively used for student competitions in which students receive a meaningful and challenging design experience. For these small cars, there is a lot of information available on how to build them and how to get them to drive. By reusing the building plans for these cars, the investment in this project can go towards the needed software support for the students and the supervision of students.

These cars have been used successfully in engineering education at KTH. Students at KTH in automatic control use these cars in an automatic control project course (see Project website). In KTH this project is supported by the smart mobility lab. The CS group has connections with Professor Bo Wahlberg and Professor Dimos Dimarogonas at this lab.

Task 1.2 Setting up the ROS software framework and basic software for driving on loop/circuit
The Robot Operating System (ROS) is often used middleware for robots. ROS consists of tools and libraries developed by the robotics community and offered with the open source BDS-3 license. Students will be allowed to use, develop and adapt packages in ROS to control the F1/10th cars.

Throughout the project, we will maintain open-source ROS libraries for the students to use. Though there is already software available for the f1/10th cars, we expect that getting the software to run for the latest version of ROS will require quite some work. To enable semi-autonomous driving, students need to be able to experiment with the people driving cars semi-autonomously. For the students, the real people will likely be themselves and the cars will be tiny toy cars. Still to make this more realistic for experiments, we will provide them with access to our motion capture system (task 1.3) and also with a steering wheel set-up whose measurements can be read out (task 1.4).

Task 1.3 Interfacing with the Motion Capture system
The control systems group at electrical engineering systems has recently invested in a new Autonomous Motion Control Lab. This lab will combine research with drones, cars and other autonomously moving systems supported by the staff of the control systems group. The new lab includes a top-notch motion capture system in which different objects can be tracked in 3D (6DOF) with high precision and high bandwidth. By embedding the challenge-based learning Lab in the AML, the students will be connected to and get to know the research and the people in the autonomous motion lab and have the opportunity to use the professional motion capture infrastructure for realizing their solutions. Thus, without becoming a full-time research project, this project will serve to inspire and motive students by giving them exposure to the ongoing research in the control systems group and to the top-notch lab space.

Task 1.4 Build steering-input and camera input for semi-autonomous driving
In addition to the F1/10th cars, we will enable the use of sensors to measure and use driver behavior. This will include a basic steering wheel and camera. For this, a TA will program in Python an interface that measures the steering angle. These programming will be made available to students as blocks and tools in ROS. Available resources for this include the following thread in ROS, several open source Linux packages for commercial gaming wheels (url) including the available Python based driver package in Github, and the online available instructions for creating an analog circuit url.

Task 1.5 Evaluate and update laboratory environment
Based on experiences and possibly new insights the laboratory environment (car's HW/SW, sensor systems) might need small modifications.

Task 1.6 Documentation and manuals
All software and hardware components and their system integration will be documented and made available as open source (GitHub).
Manuals needed for students doing their challenged-based assignment will be made.

WP2 CHALLENGE-BASED ASSIGNMENTS AS PART OF THE CURRICULUM

Task 2.1 Design challenged-based assignment for pilot in Integration project (5SC26)

This task prepares for offering the first challenged-based assignment to a pilot group of students in the Integration project (5SC26), this includes:

1. Working out possible solutions ourselves (TA with CS-staff)
2. Deriving the required software components and documentation from the developments in WP1 to offer the students as starting point
3. Prepare introduction and training session
4. Agree on coaching style with all people involved.
5. Selecting students

Task 2.2 Supervise first groups in integration project

Supervision of the students based on the agreed coaching system, while recording all the relevant aspects of the project for evaluation. Especially the progress through the different phases (start-up phase, challenge phase and knowledge transfer phase) will be closely monitored.

Task 2.3 Design challenged-based assignment for Q2, Q3, Q4

Similar to task 2.1 but now with possible adjustments based on the evaluation done in T3.1.

Task 2.4 Supervise Q2, Q3, Q4 pilot groups

Similar to Task 2.2 but now with possible adjustments based on the evaluation done in T3.1.

WP3 EVALUATION & DISSEMINATION ACTIONS

Task 3.1 Evaluate via pilot in integration project for S&C students

In this task, the set of evaluation criteria will be defined as a first step. These criteria will be input to T2.1. As a second step the evaluation of the pilot done by the selected students from the integration project (T2.2) will be done. This will result in points for further improvement in both the educational part and possibly the laboratory environment (input to T1.5).

Task 3.2 Evaluate pilot challenge-based assignments Q2, Q3 Q4 for S&C, EE, and AT

Similar to T3.1 but now for the new pilot groups (T2.3).

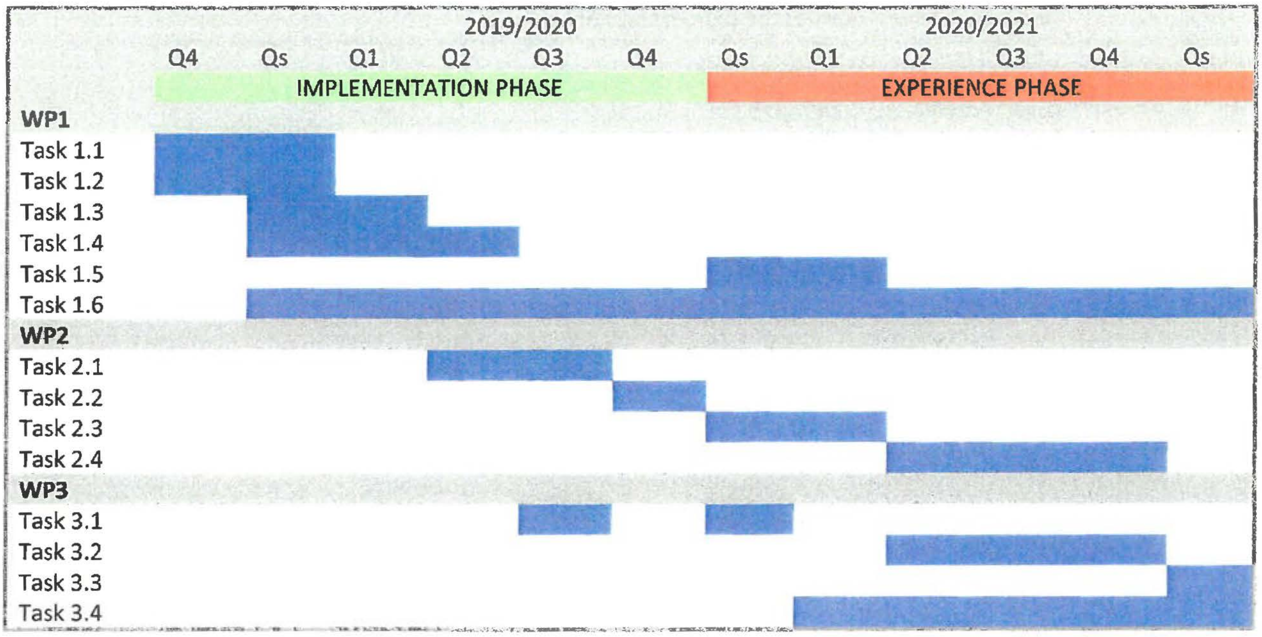
Task 3.3 Evaluate project and decide on next steps

Final evaluation of the project.

Task 3.4 Disseminate experience

Dissemination will take place during and after the pilot groups in Q2, Q3 and Q4 are working on the challenged-based assignment. We will report about this activity on our website and will present our results to colleagues at EE education day and other events.

WP1	BUILDING THE REQUIRED LABORATORY ENVIRONMENT	WP3	EVALUATION & DISSEMINATION ACTIONS
Task 1.1	Building and preparing the F1/10th cars	Task 3.1	Evaluate via pilot in integration project for S&C students
Task 1.2	Setting up the ROS software framework and basic software for driving on loop/circuit	Task 3.2	Evaluate pilot challenge-based assignments Q2, Q3 Q4 for S&C, EE, and AT
Task 1.3	Interfacing with the Motion Capture system	Task 3.3	Evaluate project and decide on next steps
Task 1.4	Build steering-input and camera input for semi-autonomous driving	Task 3.4	Disseminate experience
Task 1.5	Evaluate and update laboratory environment		
Task 1.6	Documentation and manuals		
WP2	**CHALLENGE-BASED ASSIGNMENTS AS PART OF THE CURRICULUM**		
Task 2.1	Design challenged-based assignment for pilot in Integration project (5SC26)		
Task 2.2	Supervise first groups in integration project		
Task 2.3	Design challenged-based assignment for Q2, Q3, Q4		
Task 2.4	Supervise Q2, Q3, Q4 pilot groups		



Assessment and Risk Analysis

Assessment of the project is part of the Workpackage structure presented in the previous paragraph, in particular, WP3 will deal with project evaluation. As this project is an exploration of how challenged-based learning can be used in the Control Systems domain, all results of WP3 are useful as they will be structured to give feedback and points for improvement on all main characteristics of the project, being the:

- Lab environment
- Coaching styles
- Assignment formulation
- GIT-based collaboration environment

The project has failed if:

- We cannot get the lab environment up and running
- Cannot find student groups that will start and complete the pilot assignments.

These are the actual risks of the project. Risk mitigation will include:

<u>Complexity of the setups</u>:

- Assembling the setups and creating a student-proof environment is harder than expected.
    - Probability: low (as setups exist elsewhere and documentation is available online)
    - Mitigation action: recruit adequately skilled student assistants to assemble setups
- ROS as software platform
    - Probability: low (ROS is the state-of-the-art)
    - Mitigation action:
        - Change DSP to one that can be programmed with Simulink (more experience is available)
        - Consult Rene v.d. Molengraft (ME-CST). PI involved in a project using ROS

<u>Student motivation</u>:

- Project is too simple / too complex.
    - Probability: high
    - Severity: moderate
    - Mitigation action: evaluate frequently and adapt complexity accordingly
- Students are not interested in project
    - Probability: low (unlikely as similar projects are well received)
    - Severity: high
    - Mitigation action: make convincing demo / improve PR and dissimilation
- Too many students are interested and number of setups and space is limited
    - Probability: medium
    - Severity: low (luxury problem)
    - Mitigation action: further invest and move to bigger lab

Dissemination and sustainability of the project

If the project is successful, then the Control Systems group at the Department of Electrical Engineering will continue and enlarge the scope of challenge-based education in the masters program. There are currently only limited challenge-based learning options in the masters programs, the success of this project will help establish more challenge-based learning. To this end, the experience and results of this project will be shared with colleagues at the TU/e.

Challenge based education is already adopted in medicine and on some automotive projects but is not commonly used in control systems education. The results of the pilots will be discussed and published in educational outlets within the control engineering community.

The focus on semi-autonomous learning has been chosen with sustainability in mind. After the initial investment phase with respect to software and supervision, we expect that the project can continue for a large number of years. Firstly, there are many levels of semi-autonomous driving and each one of them come with a large set of still unsolved problems. This will give a pool of unsolved problems for the years to come. Secondly, the actual cars used are sustainable, since they are student-proof and affordable to build, change and update throughout the years. Thirdly, the integration of the open source ROS software in the project makes this project a timely and needed project.

Possibly paper on control conference can be published to disseminate the challenged-based project.

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