The 3TU Embedded Systems master in the Netherlands

Gerard J.M. Smit[1] Gerrit F. van der Hoeven[1] Jan Friso Groote[2] Ralph H.J.M. Otten[2]
Hans Tonino[3] Ben H.H. Juurlink[3] Boudewijn R.H.M. Haverkort[4,1]

[1]University of Twente, [2]Eindhoven University of Technology, [3]Delft University of Technology, [4]Embedded Systems Institute
g.j.m.smit@utwente.nl, J.F.Groote@tue.nl, b.h.h.juurlink@tudelft.nl

Abstract

The three technical universities in the Netherlands (Eindhoven University of Technology, Delft University of Technology and University of Twente), abbreviated as 3TU, started a joint master on Embedded Systems in 2006. Embedded Systems is an interdisciplinary area of Electrical Engineering, Computer Science, Mechanical Engineering and Applied Mathematics. This paper discusses the background of the master and presents the curriculum of the masters at the three sites.

Categories and Subject Descriptors C.3 [*Special-Purpose and Application-Based Systems*]: Real-time and Embedded Systems; K.3.2 [*Computers and Education*]: Computer and Information Science Education—Computers Science Education

General Terms Design, Human Factors, Measurement, Performance, Reliability

Keywords Multi-core SoC design, system design, Embedded Systems education

1. Introduction

Exponentially increasing computing power (due to Moore's law), ubiquitous connectivity and convergence of technology have resulted in hardware/software systems being embedded within everyday products and places. As a consequence, new functionalities have become viable, and new mass markets for embedded systems have emerged. Yet, such market successes create new challenges that themselves need to be addressed by innovative technology and education. As systems become ever more intelligent and distributed, they also become more complex and interdependent. Security, dependability and interoperability requirements continue to grow. Timely and cost-effective system design, development and interworking all have become major research challenges. These can only be addressed effectively through a new generation of students educated in Embedded Systems research.

Past developments in computing technology have caused Computer Science to drift away from the more classical engineering disciplines, such as Electrical Engineering, causing a significant gap in concepts and methods. In mathematical terms, Computer Science has become a discrete science, based on graph-theory, combinatorics etc., whereas the traditional engineering sciences use means such as differential equations, various continuous transformations like Fourier and Laplace transforms. Within most Computer Science curricula topics such as differential equations have been removed, as they are considered of insufficient importance with respect to other topics.

Actually, this gap is even widening. Typically, students in Computer Science are increasingly taught to first understand systems from a high-level (the architecture) viewpoint. Once developed, this initial high-level viewpoint is then refined in order to understand the working principles of modules, algorithm and programs. This is fundamentally different from Electrical Engineering, where the focus is on the efficiency and effectiveness of components.

As a consequence, in the area of Embedded Systems, where both disciplines meet, engineers from differing backgrounds find it difficult to effectively communicate and work together. Within many companies we have actually seen cases where traditional engineers could not understand and appreciate the more abstract approach of Computer Science, whereas the computer scientists in turn lacked the imagination and mathematics to bridge the ensuing gap.

The absence of a dedicated programme that bridges the gap described above constitutes a strong motivation for an MSc programme in Embedded Systems. The master's programme in Embedded Systems contributes to the realization of the strategic goals of the 3TU to educate engineers who meet today's business needs, while providing the researchers of tomorrow with an excellent academic foundation. A master programme can only be successfully implemented in a curriculum that is embedded in a strong research environment, as formulated by the Dutch ICT forum "To ensure that these people are familiar with the most recent developments in the field, it is essential to ensure that their education is conducted in an excellent research environment." [5]

The industrial community is in need of experts who are able to discuss and deal with large distributed systems implemented in a combination of software and hardware. The 3TU Embedded Systems master is coordinated by a steering board in which all three universities participate. Furthermore, an industrial advisory board is installed to keep the curriculum consistent with the needs from industry. One of the main advantages of offering the embedded systems master at all three technical universities in the Netherlands is that students can choose from a wider spectrum of specialisation courses.

WESS '09, Oct 11-Oct 16, 2009, Grenoble, France

2. What is special for Embedded Systems?

In this section we elaborate on four 'qualities' that we believe are characteristic for Embedded Systems engineers: systems approach, multi-disciplinarity, resource boundedness and dependability.

1. Embedded Systems can no longer be designed by two separate threads of hardware and software that are merged at a later stage [3]. A *systems approach* is required that mixes functional

and non-functional requirements right from the start. Central to this approach is the need to understand the interaction of the system with its physical and network environments. This new point of view requires engineering teams that possess skills in a wide range of disciplines such as: computer science, electrical engineering, mechanical engineering, real-time computing, systems architecture, control, signal processing, security and privacy, computer networking, mathematics, human machine interaction, sensors and actuators. Engineering teams are currently unable to effectively assess fundamental design issues from all these perspectives, because they lack the common background and technical language to interact efficiently. Creating these cross-disciplinary skills requires fundamental changes in engineering education (and also the organisation of academic research). This is one of the main motivations for this master programme.

2. As evidenced by the discussion above the field of Embedded Systems is by definition *multidisciplinary*; it consists of cooperation between technical disciplines such as Computer Science, Electrical Engineering, Mechanical Engineering and, possibly non-technical, application domains. Application domains can be found in infotainment, transport and logistics, health and wellness, security and safety, industrial control systems for copiers or wafer steppers, etc. The Embedded Systems master programme should stimulate a multidisciplinary attitude.

Furthermore we have identified two 'engineering qualities' that are characteristic for Embedded Systems: resource boundedness and dependability.

3. The most distinguishing characteristic of an embedded system, as opposed to a "normal" ICT system, is that it is embedded in a physically environment, that poses constraints on the operation of the system. Characteristic for Embedded Systems is their *resource boundedness*, where resources can be: cost of devices, chip area, size, energy costs, but also development costs. Typical in embedded systems the designers have to face these resource constraints. Next to functional specifications they have to deal with non-functional (or extra-functional) properties such as time, cost, energy, size, dependability, and the like determined by the application domain. For instance, the embedded system has to respond timely, without using too much energy. Despite the importance of such quantitative constraints for the well-operation of embedded systems, the proper assessment of cost, resources, performance, robustness, etc., too often comes as an afterthought.
4. Many distributed embedded computer systems have tight cost constraints that make traditional *dependability* techniques infeasible. Adding additional hardware for fault tolerance mechanisms such as dual or triple modular redundancy often cannot be justified. Moreover, adding redundancy often leads to more software complexity and hence more software errors. However, our society has become increasingly dependent on complex, distributed embedded systems. Despite the fact that systems are sold based on their features, these systems must continually provide dependable services in the face of harsh environmental conditions, partial system failures or loss of resources, or human errors. People will no longer tolerate products that do not meet a certain level of dependability. Embedded Systems are often software intensive. Millions of lines of code in an embedded system is not an exception. But the use of embedded systems requires a software quality that is far better than that of common software (e.g. pacemakers, brake-control-components, etc.). The infrastructure around embedded systems does not allow frequent software updates. Hence, the dependability of the software, and that of the software in cooperation with the hardware is extremely important.

An important side remark is that it is not the intention (nor possible) of this master to 'retrain' CS Bachelors to EE masters, nor EE Bachelors to CS masters. The main motivation of a master Embedded Systems is that a graduated master student with a CS Bachelor diploma better understands the language of EE engineers, and gets a better feeling of the EE problems, and visa versa. In this way they can effectively work together on future Embedded Systems.

3. Admission and programme structure

3.1 Admissions

The Embedded Systems master provides direct admission (no bridging courses) for students who have completed a Bachelor in Computer Science or in Electrical Engineering (e.g. of the University of Twente (UT), Eindhoven University of Technology (TU/e), Delft University of Technology (TU Delft), or other Dutch universities). Students with a Bachelor in Computer Science or Electrical Engineering from international universities with a known reputation (such as Imperial College London, ETH Zürich, RWTH Aachen, and ParisTech) are in principle also directly admissible but that is decided individualy by the Admission Committee.
Students with a BSc degree in Computer Science or Electrical Engineering from other non-Dutch technical universities are in principle admissible to the programme. In general, admission to the master's programme of these students is accompanied by a tentative individual programme that is decided upon by the Admission Committee, based on an analysis of the academic level of the BSc degree, the subjects studied by the applicant and preferences of the applicants. In this decision a possible bridging programme (up to 30 EC that is *not* part of the master's programme), the need for industrial training, an individual project and a number of electives is set. Also for students from Polytechnic Universities (in Dutch HBO), bridging courses are offered to prepare them for this masters programme. For example, Dutch HBO students with a BSc degree in computer science or electrical engineering are admitted with a bridging programme of 30 EC.
All international applicants should have a IELTS of comparable score of at least 6.5 for speaking and writing in the English language. All the lectures and course material are in English. Also the students should give presentations and write reports in English.
It will take admitted full-time students two full years to complete the 120 EC[1] of the programme.

3.2 Different background

For an admission to the master programme Embedded Systems we assume that the admitted student has sufficient background knowledge in mathematics (in particular discrete and continuous mathematics), programming, computer networking, computer architecture and in modeling of physical systems. Students with a EE or CS bachelor degree have sufficient background in their own domain of expertise. This background knowledge should have been obtained in the preceeding (EE or CS) Bachelor programme. However, they sometimes lack background knowledge in other domains. Therefore, a limited amount of deficiencies (up to approximately 20 EC) can be filled in during the homologation phase.
Because of the different background of the enrolled students, the first part (approximately ½ year) of the master programme will contain a number of homologation and compulsory courses. Some

[1] One EC stands for 1 point in the European Credit Transfer and Accumulation System and is equivalent to 25-30 student hours. One curriculum year is equivalent to 60 EC.

of these courses are compulsory for students with a certain background. For example: students with an EE background get extra courses in software engineering and formal design methods whereas students with a CS background will get courses on basic electronics, control theory and modeling of physical systems.
After the homologation phase and the compulsory courses the student has a basic knowledge of the following main themes:

1. Modeling and analyses of embedded systems
2. Theoretical computer science: automata theory, complexity theory
3. Software engineering, software specification, real-time
4. Hardware architectures, SoC design
5. Basic electrical engineering, control theory

The remaining part of the masters programme builds on top of this knowledge.

3.3 Overview of the Master's programme

The final qualification levels of the master programme are based on the Dublin descriptors [1]. At all three participating universities the programme has the following basic overall structure:

- *Homologation courses* (approx. 20 EC)

  These are courses to fill in the deficiencies of students.

- *Mandatory courses* (approx. 20 EC)

  These are courses for all enrolled students.

- *Elective courses* (approx. 20 EC)

  As elective courses the student should select a coherent set of courses, taken from the set of EE or CS master courses of the three sites. The student will discuss his/her choices with the Admissions Committee. Elective courses can also be chosen from master courses of other universities, provided the selection is coherent and relevant in the opinion of the Examination Committee.

- *Industrial internship* (15 - 20 EC) or an equivalent of elective courses.

  The internship is carried out preferably in an international company or research institute. Students with a non-Dutch university bachelor degree or HBO degree are usually advised to take homologation or elective courses instead of an industrial traineeship.

- *Thesis project*(10 + 30 EC)

  At TU Delft and UT the student has to take an individual project (10 EC) as a preparation for the thesis. This project is tailor-made for the student and may contain: a literature survey related to the thesis subject, some initial research study or an additional specialist course so the student is well prepared for the thesis. Eventually the individual project leads to a well-defined thesis assignment. The thesis project (30 EC) is a research-oriented individual project where a last proof of engineering and scientific attitude must be given. The final project will be performed under supervision of one of the involved research groups. It is typically carried out as part of one of the research projects of the groups participating in the master degree course in Embedded Systems, and may involve third parties like industry or research institutions.

To stimulate the cooperation between the three universities and for quality enhancement it is recommended that one of the supervisors is a staff member of one of the other technical universities. The three universities have videoconferencing facilities, e.g. for live broadcasting of lectures or the final presentations of MSc students to the other universities. In the study year 2009-2010 we will start with tele-lectures, such that a lecture from a certain university can be attended remotely by students from the other universities. At TU/e most lectures are already recorded and can be viewed by the students at any moment.
For details on the courses and programme see web-sites of 3TU [9], UT [10], TU/e [11] and TU Delft [12], respectively.

4. Programme of the University of Twente

The embedded systems programme of the University of Twente consists of a homologation phase, mandatory courses, elective courses and a final year with an internship and a master thesis.

4.1 Homologation phase (20 EC)

For a student with a Bachelor CS the following courses are compulsory in the homologation phase:

(156080)	Systems and Transformation (5 EC)
(121000)	Instrumentation of Embedded Systems (5 EC)
(121044)	Control Theory (5 EC)
(121034)	Physical modeling of Embedded Systems (5 EC)

For a student with a Bachelor EE the following courses are compulsory in the homologation phase:

(213505)	Programming (5 EC)
(214012)	System validation (5 EC)
(213510)	Software Engineering Models (5 EC)
(211045)	Operating systems (5 EC)

When one or more courses already have been taken as a Bachelor elective course, or a course elsewhere with a similar content, a free choice can be made from the elective courses.

4.2 Mandatory courses (20 EC)

(21302)	Embedded Computer Architectures I (5 EC)
(213050)	Quantitative Evaluation of Embedded Systems (5 EC)
(121165)	Multi-disciplinary design project (10 EC)

This is a group project (ideally 2 EE and 2 CS students) in which the students follow a complete design trajectory from specification to implementation and testing.

4.3 Elective courses (20 EC)

As elective courses the student should select a coherent set of courses, taken from a list of master courses from the EE and CS master programmes of the three universities. The student needs the approval of the individual programme supervisor for the choices he makes. Elective courses can also be chosen from master courses of other departments or master courses from the TU Delft or TU/e, provided the selection is coherent and relevant in the opinion of the individual programme supervisor (who acts on behalf of the Examination Committee).

4.4 Industrial internship (20 EC)

Industrial traineeship (20 EC) is preferably carried out with an international company or institute. Optionally, the internship can be replaced by an equivalent of elective courses.

4.5 Master thesis (10 + 30 EC)

The *final project* (30 EC) is a research-oriented individual education project that must provide proof of an engineering and scientific attitude. It is carried out as part of one of the research projects of the

groups participating in the master degree course in Embedded Systems, and may involve third parties like industry or research institutions. Before the student can start the thesis project an individual project (10 EC) has to be finished. This project is tailor-made and is a preparation for the final project. It consists of elements such as literature surveys, preparatory research/studies, or additional, specialized techniques.

5. Programme of TU/e

The programme of the TU/e is structured in mandatory courses (45 EC), elective courses (45 EC) and a master thesis (30 EC).

- Mandatory courses: 45 EC, i.e. nine courses to develop a sufficient layer of theory and general or programme related knowledge.
- Elective and homologation courses: 45 EC. This elective part aims to prepare the student for his specialisation. It is possible to spend up to 15 EC on an internship with prior approval of the education director. Students with a slightly different background may need to allot (at most) 18 EC of the electives in a specific way to compensate for deficiencies.
- Master's project and thesis: 30 EC to be spent on a specialist topic of theoretical or practical nature. Here the student can demonstrate and further develop his independent engineering and academic skills in research and design.

5.1 Mandatory courses (45 EC)

The curriculum consists of both Computer Science and Electrical Engineering courses.
The list of mandatory courses is:

2II45	Architecture of distributed systems (5 EC)
2IN25	Real-time architectures (5 EC)
2IW25	Requirement analysis, design and verification (5 EC)
5KK60	Systems on Silicon (5 EC)
5KK70	Platform-based design (5 EC)
2IW15	Automated reasoning (5 EC)
4C390	Performance analysis of embedded systems (5 EC)
5KK03	Embedded systems laboratory (5 EC)
5KK80	Multiprocessors (5 EC)

5.2 Homologation courses

Students who have completed a bachelor programme in electrical engineering are required to include some courses as homologation courses in the elective part of the master programme:

2IP25	Software engineering (3 EC)
2IL05	Data structures (6 EC)
5HH00	Electronics for embedded systems (3 EC)

Students who have completed a bachelor programme in computer science are required to include the following courses in the elective part:

5DD17	Circuit analysis (3 EC)
5DD30	Signals (5 EC)
5HH00	Electronics for embedded systems (3 EC)

6. Programme of TU Delft

The programme of the TU Delft consists of:

- A homologation part of at most 18 EC. If no or partial homologation is needed the remaining EC are added to the electives part,
- A compulsory part of 28 EC,
- An electives part of at least 34 EC and no more than 42 EC including an optional internship of maximal 20 EC. Courses are to be selected out of a given list of electives,
- A Master thesis of 40 EC, consisting of a research project of 10 EC (IN4610) and a final project of 30 EC (IN4600).

6.1 The homologation courses

Depending on the BSc degree the master student has to take a number of deficiency courses. For example: for electrical enigneering students the following courses are mandatory:

ET4263	System Programming in C (3 EC)
IN2305-II	Embedded Programming (4 EC)
IN2611WI	Software Engineering (6 EC)
IN3205	Software Testing and Quality (4 EC)

For students with a computer science BSc degree the following courses are mandatory:

IN2405-I	Signal Processing (4 EC)
SC4180ES	Modeling and Control (6 EC)

6.2 Mandatory courses

ET4165	Embedded Computer Architecture (6 EC)
ET4367	Performance Analysis of Communications Networks and Systems (6 EC)
IN4024	Real-Time Systems (6 EC)
IN4073	Embedded Real-Time Systems (6 EC)
IN4087	System Validation (4 EC)

7. Implementation of the four qualities

In Table 1 the four characteristic qualities of Embedded Systems as mentioned in Section 1 are elaborated in more detail, and in particular how they are implemented in courses at the different sites. As mentioned before an optional course for all universities is the industrial traineeship (15-20 EC) which is preferably carried out with an international company or research institute.

8. Specialisations of the 3TUs

Each contributing university has its own specialisation. These specialisations are related to the research foci of the involved research groups (chairs). Below for each university a list of research groups (and group leader) that contribute to the 3TU master Embedded Systems.
The UT focus is on:

- Pervasive systems (Havinga)
- Energy efficient systems (Smit)
- Embedded control systems (van Amerongen)
- Dependable (networking) systems (Haverkort)

The TU/e focus is on:

- Formal methods (Baeten)
- System analysis and design (Groote)
- Embedded system design (Corporaal)
- System architecture and networking (Lukkien)

The TUD focus is on:

- Parallel and distributed systems (Sips)
- Computer Engineering (vacancy)
- Wireless and Mobile Communications (Niemegeers)

	TU/e	UT	TU Delft
SYSTEMS APPROACH	• Architecture of distributed systems • Requirement analysis, design and verification • Multiprocessors	• Quantitative Evaluation of Embedded Systems • Control Theory, Systems and Transformation and Physical modelling of Embedded Systems. • Multi-disciplinary design project	• Embedded real-time systems • Modelling and control
MULTIDISCIPLINARY APPROACH	• Embedded systems laboratory • Requirement analysis, design and verification • Platform based design	• Multidisciplinary design project • Physical modelling of Embedded Systems and Instrumentation of Embedded Systems;	• System validation • Embedded real-time systems
RESOURCE BOUNDEDNESS	• Performance analysis of embedded systems • Real-time architectures	• Quantitative Evaluation of Embedded Systems • Embedded Computer Architectures I • Energy-efficient Embedded Systems • Real-time systems I and II	• Embedded Computer Architecture • Real-time Systems • Performance analysis of Communication Networks and Systems • Embedded real-time systems
DEPENDABILITY	• Automated reasoning • Requirement analysis, design and verification	• Quantitative Evaluation of Embedded Systems • Reliability Engineering • Fault tolerant digital systems	• System validation • Software testing and Quality

Table 1. Implementation of the four qualities by the 3TU partners

- Networks and systems (van der Veen)
- Embedded Software (Langendoen)

9. Conclusion

This paper presents the background and the structure of the 3TU master on Embedded Systems in the Netherlands. All three technical universities in the Netherlands have a slightly different version of the programme installed depending on the research focus of the university. In the study year 2009-2010 we will start with tele-lectures, such that lectures can be attended by students at all three universities simulateously. The master programme is structured around four 'qualities' we believe are typical for embedded systems engineers: multidisciplinarity, systems approach, resource boundedness and dependability. Discussions are taking place to equalize the mandatory courses. This would allow even greater mobility of the students.

References

[1] Draft 1.31 working document on "Shared 'Dublin' descriptors on Bachelor's Master's and Doctoral awards" March 2004

[2] Itea Technology Roadmap for Software Intensive Systems 2^{nd} edition May 2004

[3] Artemis Strategic Research Agenda (see also `http://www.artemis-office.org/`)

[4] STW/Progress Embedded Systems Roadmap 2002 (see also `http://www.stw.nl/progress/ESroadmap`)

[5] Dutch ICT Forum Vision Report "Innovation through ICT" edition 2003

[6] NOAG-ict Nationale Onderzoeksagenda Informatie- en Communicatietechnologie 2005-2010

[7] EU-FP6 IST-Workprogramme 2009-2010

[8] A.W.M. Meijers, C.W.A.M. van Overveld, J.C. Perrenet "Criteria for Academic Bachelor's and Master's Curricula" see `http://www.jointquality.nl/content/descriptors/AC_English_Gweb.pdf`

[9] Webpage of 3TU. federation `http://www.3tu.nl/en`

[10] University of Twente, Embedded Systems Master's programme webpage `http://onderwijs.cs.utwente.nl/Studenten/Masters/EmbeddedSystems/Programmestructure`

[11] Eindhoven University of Technology, Embedded Systems Master's programme webpage `http://w3.tue.nl/en/services/cec/study_information/masters_programs/embedded_systems/`

[12] Delft University of Technology, Embedded Systems Master's programme webpage `http://http://www.es.msc.tudelft.nl`