International Journal of Engineering Education Vol. 32, No. 2(A), pp. 726–737, 2016
Printed in Great Britain

0949-149X/91 $3.00+0.00

Prototyping Tangible User Interfaces: Case Study of the Collaboration between Academia and Industry*

Peter D. Conradie[1,2]
[1] Department of Industrial System and Product Design, Ghent University campus Kortrijk, Graaf Karel de Goedelaan 5, 8500 Kortrijk, Belgium. E-mail: Peter.Conradie@UGent.be
[2] iMinds-MICT-Ghent University, Korte Meer 7-9-11, 9000 Ghent—Belgium.

CESAR VANDEVELDE
Department of Industrial System and Product Design, Ghent University campus Kortrijk, Graaf Karel de Goedelaan 5, 8500 Kortrijk, Belgium. E-mail: Cesar.Vandevelde@UGent.be

JOLIEN DE VILLE
Department of Industrial System and Product Design, Ghent University campus Kortrijk, Graaf Karel de Goedelaan 5, 8500 Kortrijk, Belgium. E-mail: jolien.deville@gmail.com

JELLE SALDIEN
Department of Industrial System and Product Design, Ghent University campus Kortrijk, Graaf Karel de Goedelaan 5, 8500 Kortrijk, Belgium. E-mail: Jelle.Saldien@UGent.be

Paradigms such User Experience (UX) based design approaches, along with the rise of Tangible User Interfaces, can present hurdles for traditional product manufacturers. Industry collaboration with university potentially allows exploration with such emerging themes, while students are exposed to design challenges from industry. In this paper, we discuss a course, Mechatronic Product Design, where students create Tangible User Interfaces (TUIs) in close collaboration with industry. An interdisciplinary design method is described with an emphasis on iterative prototyping—within a project-based learning approach. This includes the importance of (1) a network of industry, (2) a design method using project roadmaps and, (3) the availability of tools and platforms in an exploratory lab environment. Close collaboration between industry and academia made it possible to implement this approach with a total of 77 design cases. Students worked on realistic open-ended design problems using an iterative design approach, while working in multidisciplinary teams. Companies, in turn, are able to explore new ideas at low risk. We found our approach successful, with design cases that lead to novel research, technologies and commercial products. Four specific cases are presented in more detail, while the general insights and guidelines can be used to improve future development of TUIs.

Keywords: tangible user interfaces; project-based-learning, methodology; embodied interaction

1. Introduction

More practitioners and academic researchers are adopting a User Experience (UX) centred approach to the design of interactive systems, emphasizing elements such as 'fun', 'emotion', 'joy' and 'pride' [1]. Because of the limitations of traditional usability frameworks—focusing primarily on user cognition and user performance—we see a shift towards UX that highlights non-utilitarian aspects such as user affection, sensation, meaning and value of interactions in human-technology of everyday life [2].

Simultaneously, changes are occurring in how we manipulate digital information. While traditional computer interfaces consist of a keyboard and a pointing device—typically a computer mouse [3]—a shift is occurring where computers and interfaces are changing to include a wide variety of input and output devices [4]. These emerging Tangible User Interfaces (TUIs) could allow the *direct manipulation of bits* [5] facilitating a shift away from the desktop paradigm of computing. This change is also resulting in products that are interactive, connected to the internet, adapted to our needs and responsive to our behaviour [6, 7].

The shift towards interactivity of everyday products such as umbrellas, tables, lights, or kitchen appliances [8] presents new design and engineering challenges. Additionally, when designing interactive products there is a need to design more than merely the functionality and usability of the product. These shifts present opportunities for educators to expose design and engineering students to new design paradigms, while also involving local industry. Especially for SMEs, the shift towards smart products can prove to be challenging. Traditionally, universities have played an important role as sources of new knowledge and technology [9]. Companies are also increasingly relying on external Research and Development (R&D) organizations, such as universities, to support innovation [10]. As

* Accepted 15 January 2016.

stressed by Chen & Hsu [11], fostering creativity among students—in addition to more traditional skills such as logical thinking—is viewed as an important skill for engineering students. Exposing students to the challenges posed by new interaction paradigms is a way of fostering this creativity.

This presents an opportunity for SMEs interested in adapting their products to increase emphasis on UX, while also exploring how new modes of interaction can be realized. This change presents challenges to educators as to how students and industry can collaborate. Within this paper we present a case study following a three-year project, where the aim was to create TUIs in close collaboration with local SMEs. The project organised 77 design cases that resulted in TUI prototypes, developed by master level students during a project-based learning (PBL) course, Mechatronic Product Design. Each design case followed a similar design approach using different techniques and technologies. In most cases, a close collaboration with the industry took place.

The remainder of this paper is structured as follows: In section two we will briefly elaborate on key concepts such as User Experience Design, Tangible Interfaces, and PBL. Following this, in section 3 we describe how students and SMEs were involved, also providing more detail on the course and its learning objectives. Section 4 presents four selected cases. Our results are presented and discussed in section 5, with section 6 concluding the paper.

2. Background

2.1 User experience design

Previously, interactive systems were primarily designed to improve performance or decrease errors. Recently, a new design paradigm, UX, has emerged that emphasizes hedonistic goals [12]. This design approach does not exclude basic usability principles such as learnability or productivity, but recognizes the added value of emotional experiences associated with product use [13] and has been adopted both by researchers of HCI and design practitioners [2]. For example, Macdonald [14] notes the importance of sensorial qualities in products and introduces a design process that aims to facilitate product design that can evoke empathy between users and products. The author stresses elements such as culture, storytelling, aesthetics and designing for the senses.

Kouprie and Visser [15] also evoke the notion of empathic design and introduce a framework for empathic design that can act to help designers relate to their users' experience. The framework includes methods to discover a user's context by immersing oneself in their world. The importance of users emotional reaction is also emphasized by Barnes and Lillford [16], who introduce a framework that supports *the development of emotionally appealing products*. Artacho, Ballester, and Alcántara [17] also stress how small changes in product design can affect the user's emotions. These brief examples highlight the importance given to emotional aspects of products, and introduce frameworks that support the creation of products that appeal not only on a functional level, but also target the user's emotions.

2.2 Tangible user interfaces

Alongside the rise in importance of more hedonistic user goals, is the changing nature of what we perceive as computing. Weiser [18] played an important role in challenging the notion of computing as an activity that only involves a pointing device (such as a mouse), a keyboard and a screen [19]. Ishii and Ulmer further stated that the advent of the personal computer has contributed to a loss of the richness offered by a variety of man made objects [20]. The authors present a future vision of the world as an interface, where different types of objects can be used as input and output devices.

Accompanying this vision is the notion of interactivity embedded into ever more products [6, 7]. Satyanarayanan [6] discusses the movements within research in the domain of pervasive computing and notes the introduction of "smartness" in certain spaces and the disappearance of technology into our environment. The resulting effect of this invisible technology is an ever increasing amount of intelligence in our surroundings, including various intelligent appliances, floor surfaces or environmental sensors in our domestic or work environment [7].

While an extensive review of cases that represent this vision (e.g. see Shaer & Hornecker [21]) is beyond the scope of this paper, we introduce some state-of-the-art examples below to illustrate this. Recently, Fortmann et al. [22] introduced the MoveLamp, an ambient display aimed to encourage office workers to move more. The system tracks how long the user is stationary and subsequently provides cues when stretching is recommended. REENACT, also uses ambient information to encourage history learning, focussing on allowing students to re-enact, replay and debate [23]. Using tactile mobile devices, the system provides students with augmented reality vision, allowing them to see historical events. Peschke et al. [24] focussed more on providing tactile feedback for DepthTouch, an installation that provides elastic feedback on touch surfaces, enabling rich interaction with future displays.

2.3 Applying project-based learning

The above-mentioned examples of TUIs illustrate how interactivity is increasingly becoming part of our surroundings. We also notice their emphasis on emotional aspects rather than improving efficiency or reduce errors. For SMEs wanting to explore how TUIs can impact their products, universities—especially courses with an engineering focus—can act as a source of knowledge [9]. As argued by Agrawal [9], there is a rich history of university to industry knowledge transfer spanning various domains. Ahrweiler, Pyka, and Gilbert [25] also emphasize the importance of university and industry collaboration, asserting that university-industry links *improve conditions for innovation diffusion*.

This aligns well with the view that organizations are increasingly using external R&D as innovation source [26]. Furthermore, Flores et al. [27] note the importance of universities as facilitators to achieve *collaborative environments,* where industry and university work together and where the university plays a role to diffuse knowledge and technology to the industry. As argued by Lehmann et al. [28], the increasing complexity of systems mandates thinking beyond solely technical solutions: engineers must also be skilled in non-technical aspects [11].

Given this background, and our involvement of stakeholders from industry, we argue for a project-based learning (PBL) approach within this course. As mentioned by Dahlgren [29], PBL facilitates contextual learning, i.e.: *a meaningful context that also relates to the students' future professional work,* making it suitable to involve SMEs as part of this process. As proposed by Krajcik et al. [30], benefits of project-based learning include helping students cultivate integrated knowledge about content and process, while simultaneously and collaboratively solving problems and learning independently. Frank et al. [31] stresses that PBL approaches emphasize achieving learning objectives through experience, while also introducing students to different areas of mechanical engineering. Students are also exposed to various design processes [31]. A learning-by-doing approach could also be advantageous because it leads to higher student motivation and deeper understanding of the subject matter [32–34].

The course thus also aligns with Kolb's educational model [35] where experiential knowledge is combined with theory, allowing students to acquire practical skills. The case presented in this article is comparable to Meek et al. [36], where student teams develop a mechatronics system in a PBL setting. Following Wang et al [37], the course has a strong emphasis on applying theoretical knowledge to solve problems in a real world context. This approach is inspired by the call towards more PBL learning, teamwork and close contact with industry [38]. In summarising characteristics of PBL, Graaff & Kolmos [39] emphasizes problem-based learning, often based on real life problems. The authors further propose experience and activity learning; multidisciplinary, spanning subject boundaries in a group setting as important characteristics. Typically, PBL is characterised by teamwork, under supervision of a mentor [40]. Frank et al. [31] also frame the instructor as someone that offers guidance and help—acting as a mentor—rather than *provider of facts.*

The design and development of TUIs is suitable when teaching students to manage multiple disciplines in one project, and aligns with the PBL approach outlined above. For example, Camarata, Gross, and Do [41] present a course centred on the development of physical computing experiences in multidisciplinary teams. The authors emphasize a studio setting, where students can physically meet to collaborate on projects. Similarly, Klemmer, Verplank, and Ju [42] also note the benefit of a studio setting, where there is less emphasis on lectures, but a stronger focus on supervising projects. Broad themes such as *(Nearly) Invisible Computing* or *Urban Computing* were introduced to students. These themes guided the types of projects developed by students. Projects ranged from chairs with built in sensors to alert users of bad posture [42], to a musical couch that generates sound using embedded sensors [41].

These examples of higher education courses show the emphasis on TUIs within higher education and the collaborative nature of these efforts. However, they are limited in their involvement of industry, SMEs specifically. We contrast this with our own approach, where students and industry collaborate much more closely. In the following section, we will provide details on how this collaboration is created and embedded into the course.

3. Platform

3.1 Course description and assessment

At the beginning of the academic year a call is launched to the companies to submit a case. These cases were introduced in the course, Mechatronic Product Design, aimed at undergraduate Industrial Design students. Central in this course is to teach students how to use sensors, actuators and microcontrollers to create interactive products [36, 37]. The course is PBL focussed.

The course was scheduled in the first semester (12 weeks), meeting once a week for a 5h session. All industry cases where presented in the first week.

Students could indicate their case preference. Descriptions of cases varied from broad, open questions such as "making time tangible", to more specific: "Design a tangible interactive cube for elderly to navigate within a digital photo book". Students work in teams on the design and materialization of a working interactive prototype. The inputs for this course are the product ideas generated by the SMEs (described below). A few months before the start of this course a call is launched to the SME partners asking them to submit an exploratory idea.

The course series starts with an introduction of mechatronics and the basics of Arduino. Depending on the specific case other platforms—such as Raspberry Pi, Makey Makey, Beaglebone—are also suggested. It was important to have these kinds of tools and platforms available in the lab, making immediate technical and user testing with quick go or no-go decisions possible. If sensors or platforms needed to be ordered, the team lost a lot of valuable time.

To overcome communication difficulties between multiple stakeholders (teachers, students, companies, etc.), a blog was used to document the progress of a case and to offer feedback at any time by anyone who had access. At certain moments the lecturers issued medals to the blogs of the student groups, according to the progression of their case. During the concept phase a top three medal could be earned based on the following points: practical approach, motivation and concept. A student group could also get a yellow warning, meaning "watch out" or a red one meaning "unsatisfactory, try a different approach". Later in the process new medals could be earned for functionality and best prototype. A team could also lose their medal to another team making it more competitive and stimulating them to do their best.

Broadly, the learning objectives are in line with similar mechatronics courses, for example the focus on addressing open-ended real world problems, with close collaboration with industry [37], but also teaching students technical skills, and creatively solving open-ended problems under time and budgetary constraints [43]. More specifically, students learn technical skills such as how to creatively use sensors, actuators and microprocessors for the design of interactive products. Students who complete the course should be capable of assimilating and implementing new prototyping technologies, while being able to transform a customer design brief into design specifications. Finally, working prototypes are expected at the end of the course. As noted, students work in teams, and it is thus expected that they could design a product in a team context, from realisation to integration and materialisation, where a methodological approach is important. Teams are multidisciplinary. Lastly, students present and defend their (research-) results in front of a jury. The jury comprises both combining lecturers and representatives from SMEs.

We also aimed to involve students from different backgrounds in the cases, including Digital Design & Development, Digital Arts and Entertainment, Industrial Engineering and Social Sciences backgrounds. In doing so, we stress the multidisciplinary character of the project and course.

Our aim within the platform is to connect students with SMEs for the design and development of interactive products while taking a positive user experience into account. To achieve this, our approach contains three elements: (1) a network of companies and collaborating higher education institutes, (2) a method used during the process and finally, (3) an accessible lab with the necessary infrastructure and materials. Below we will expand on each of these components.

3.2 Network for involving SMEs

A network consisting of 4 large-scale companies, 10 SMEs, 2 freelancers and 5 educational institutions was built for this project. To facilitate idea sharing between partners, our first aim was to create an open network where concepts could be openly discussed with other companies and educational institutions.

Competitiveness between participating companies was a concern within the project, as it inhibited discussions about company strategy, innovation and goals. To overcome this, we focused on creating a network where everyone knows each other's expertise and therefore knows if a certain company can become an interesting partner or might become a competitor.

This was done through the creation of personal profiles, which indicated the area of expertise of every partner, helping our partners to position everyone within the network. Partners supplied information about their core focus and expertise. The focus of an organization was selected from the following areas: strategy, concept generation, research, development, consulting, production, marketing, distribution and sales or end-users. Next, the domain of expertise was drawn on a radar plot relative to their TUI knowledge about the physical form, the technology, the user or the software (Fig. 1). Finally, they indicated their quantity of product units on a scale from one custom-made product to mass production.

Bringing together these diverse stakeholders leads to complementary cooperation, stimulating partnerships between multiple partners with different kinds of expertise, and thus combining the

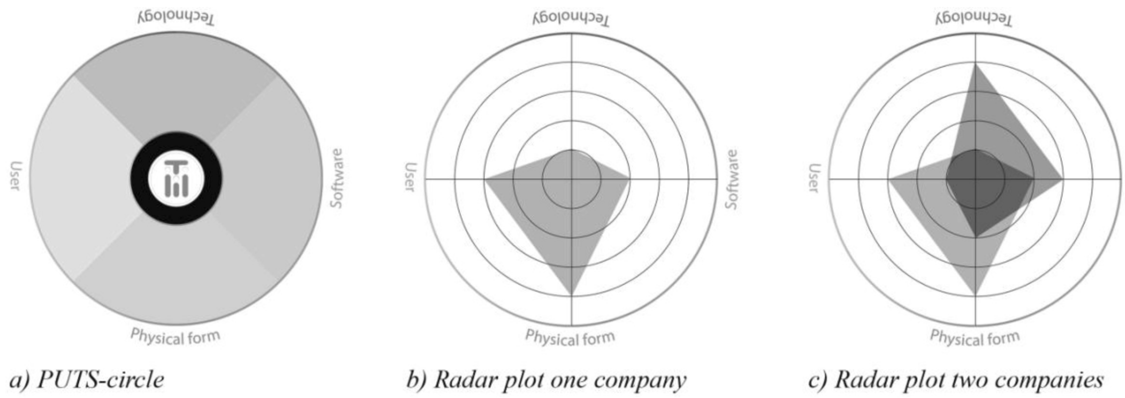


Fig. 1. Visual representation of the four domains of tangible interfaces in relation to the expertise of a company.

expertise needed to create TUIs. This also emphasizes the multidisciplinary nature of the network.

To create this open platform we organized several events. The first one was a creative session. Partners were analysed according to their domain of expertise and were grouped into interdisciplinary teams to allow them to brainstorm about their needs. This way companies from the same domain—possible competitors—are not in the same team.

We used images for certain tangible interface domains to inspire teams. Each team was asked to generate ideas per image and to put them down using post-its. After 15 minutes we rotated the teams, giving each team the opportunity to add ideas to every domain. Each team got to talk about TUIs while getting to know each other's expertise.

In the afternoon we presented a template that guided every team into describing one defined idea. We found those ideas inspiring but broad and not specific to the core activity of that partner. From this we learned that it would be hard to focus on generating new project ideas for a company in an open environment because a partner would always feel threatened on some level when it comes to their company's internal ideas. Academic partners mitigate this effect.

Our role was to inspire and guide our network, and to act as an objective, non-competing partner. As long as an idea or project is exploratory, it can be discussed openly within the network and then further explored by students. From the moment a network member has a well-defined idea that they wants to pursue within his company, it becomes confidential for all partners involved. The platform then offers guidance by offering assistance in the development of a fitted roadmap and the composition of an appropriate interdisciplinary team for that specific case. This required that a certain method be developed.

To keep our partners motivated, other types of events were organized, such as seminars, brainstorm sessions, expos and workshops with TUIs as the recurring theme. We found the feedback during these events important to gain insights in the obstacles our partners experienced and which topics we could address more within the project. In order to create a close working relationship with the other partners we found it important to keep them triggered and to communicate openly about the project and its progress. A central online platform was created focusing on offering information about the project, the design cases and current state of the art.

3.3 Method used during the process

3.3.1 TUI development roadmaps

To get insight into the optimal work method for the development of TUIs, workshops were organized to guide the participants in the definition of a project roadmap, which consists of the challenges that need to be solved in order to bring about a successful TUI at the end of the project. The idea here is that it is more important to first look for the right questions and challenges rather than to come up with solutions already. This was inspired by the Usewell [44] method, in which challenges are selected that are relevant and recognizable. Examples of challenges include: "The customer is not always the user." or "We want to make our product easier to use." After selecting a challenge, Usewell provides solutions in the form of techniques that allow you to tackle your challenge by involving different stakeholders.

We organised 2 workshops with a total of 7 domain experts and 11 partner companies. Previous discussions with the partners lead to a workshop format that starts with an assignment (e.g. "a TUI to improve the indoor tracking of a person"). The group was divided into 5 interdisciplinary teams. Based on the assignment each team selected the set of challenges related to the domains that needed to

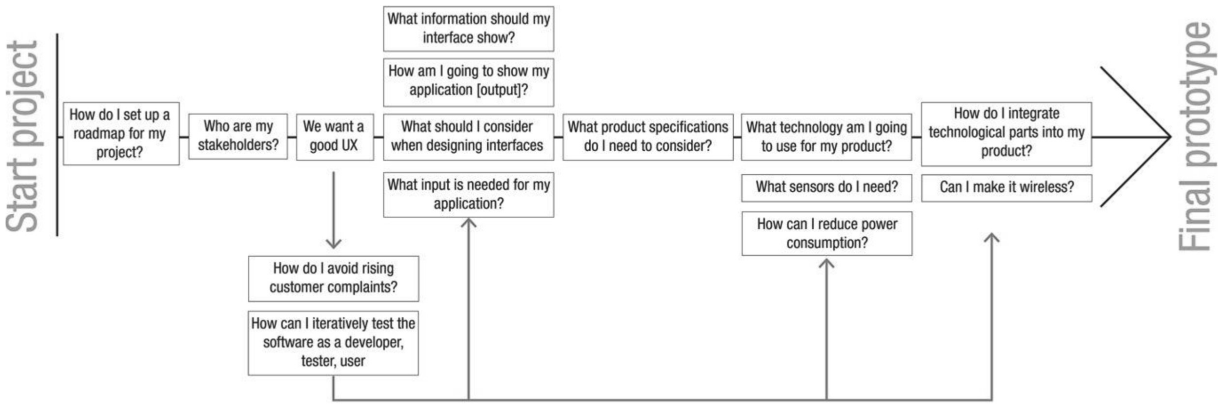


Fig. 2. Example of one of the TUI Development roadmap resulting from the workshop.

be tackled in order to develop the envisioned TUI (Fig. 2). Workshops were based on the generative brainstorm method, a tool that bundles strategies that visualize the needs, wants and expectations of those that participate.

3.3.2 Understanding partner needs

While the roadmaps assist in understanding the broad needs of the partners and contribute to understanding how TUIs could be designed and developed, they do not focus on individual partners. To better understand each partner SME, every individual TUI project was framed as a design case. Partners submitted project ideas that could either become a student case, or a professional case. Student cases are exploratory product concepts within a defined context. Usually these cases have the duration of several weeks, with a maximum of one semester.

After this first exploratory phase, partners can better gauge the potential value of their initial idea. If they see potential in the concept, steps can be undertaken to set up a professional case. If a concept is well-defined and the partner has plans to pursue and market the idea, the case becomes an individual closed project.

With professional cases, when a partner has a better-defined idea of what they want to develop, we organize several meetings to first discuss the partner's expectations and to then map that partner's internal knowledge and missing expertise, using the previously-defined roadmaps. If applicable, requests for funding for innovative projects are submitted. Based on the company's missing expertise, complementary partners with the necessary expertise are linked to the project. For these types of cases, we developed a general framework to be applied at the start of the process to facilitate project definition and communication between the involved partners.

3.3.3 Rapid prototyping

Prototyping is a crucial aspect of designing products [45]. Through prototypes, usage can be simulated without the high costs associated with building a complete product [46]. Throughout the process of each design case there is a strong emphasis on rapid prototyping of TUIs. This allows hands-on testing with users and enables students to discover interaction flaws early during the design process. Through continuous design iterations and through user testing, an optimal user experience can be achieved.

The iterative design process has the benefit of identifying the limitations of interaction early on in the design process, but also functions to identify potential technology issues. Initial concepts might be prototyped using paper or cardboard, while interactions might be simulated through techniques such as experience prototyping [47]. Following these early steps, first working prototypes can be developed using technologies such as Arduino or Phidgets. Students with non-technical backgrounds were also encouraged to start exploring the possibilities of these tools as soon as possible. Partners in the project were also given access to these tools and technologies. We sought a strong link with the DIY (Make) culture, relying heavily on open source hard- and software. We stimulated students to document their results, facilitating sharing and re-using of the results.

3.4 Lab

The physical component of our platform is our lab, a collaborative environment to work on interactive prototypes. The lab setting fosters a studio culture, as mentioned by Camarata [41], Klemmer [42] and Wang et al. [37] where students can meet and collaborate on projects. It acts as a place where students and companies can explore various technologies, but also where prototypes can be built and

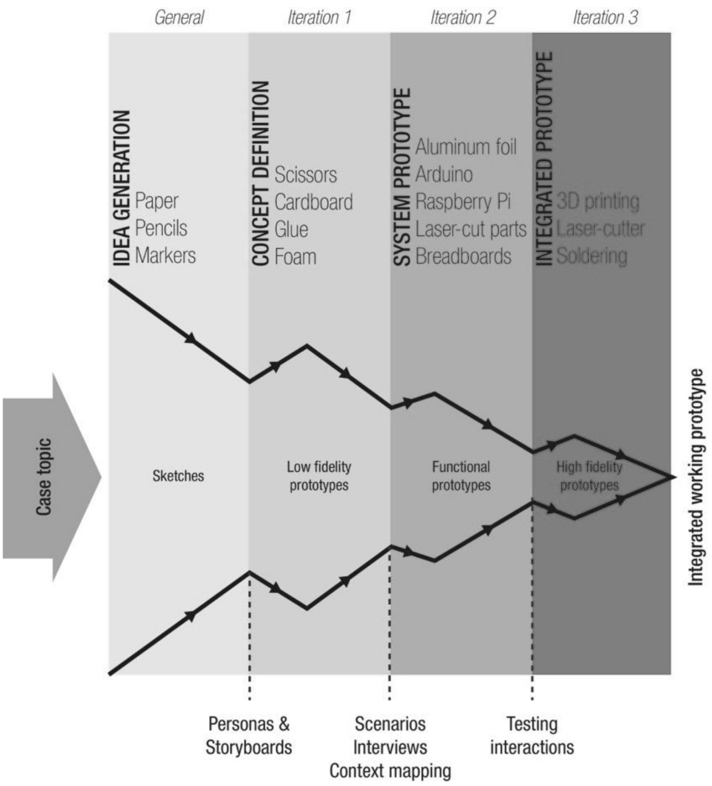


Fig. 3. Schematic overview of the development process of a TUI based on the design funnel by Pugh [49].

tested. Our lab offers different kinds of electronics boards, such as Arduino, Raspberry Pi and Beaglebone (see Pearce [48] for an overview). A large range of state of the art sensors is also available, such as new gesture recognition sensors and others. It also offers a number of high-level development platforms, such as Android, iOS and Sifteo devices. Furthermore, it also offers basic tools and equipment to create electronic prototypes, such as wire, soldering tools, measurement equipment, and basic electronic and mechanical components. Although the components described above are not very expensive for companies, we found that it is still less of a risk for them to experiment with our material and to discover the potential of a certain technology for their own company before buying them. Oftentimes, companies are also not aware of all the types of sensors and actuators that are commercially available. In this sense, the lab also serves as an important source of inspiration for both students and industry partners.

4. Design cases

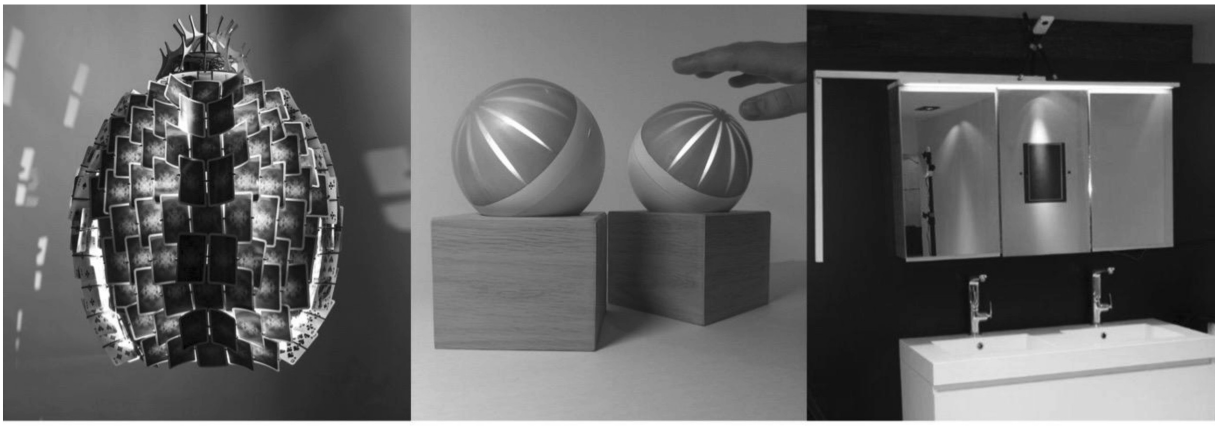
During the design process of the cases, students prototyped their ideas in an iterative manner, making it possible to test user interaction of a concept throughout the different design stages (Fig. 3). We define four phases:

Phase 1: Idea generation: Brainstorming techniques are used to generate ideas related to the case. In this phase we noticed many student groups contacting their company to help them define the boundaries and scope of the case description. Personas and storyboards were used to generate ideas for a specific user group. [sketches]

Phase 2: Concept definition: Low fidelity prototypes were materialized using paper and cardboard to assess the feasibility of the concept with end-users and other stakeholders involved in the process. User insights were obtained through scenarios, interviews and context mapping. [Low fidelity prototypes]

Phase 3: System prototype: The concept was divided into mechanical and technical sub-problems. Aluminium foil, Arduino and laser-cut parts were used to prototype technical solutions making it possible to test the effect of a certain interaction on its user. [Functional prototypes]

Phase 4: Integrated prototype: All sub-solutions are integrated into one final working prototype. A flow chart was used to map communication between different components and to visualize the interaction of the system into a schematic overview. 3D printing and laser-cut where often used to materi-



a) Whist *b) Caars lamps* *c) Innovative mirror*

Fig. 4. Pictures of three example cases.

alize and finish the final prototype. Sensors and circuit boards were custom made to fit the prototype, creating a highly finished end-result (high fidelity prototype).

From all 77 cases, 4 specific cases are highlighted and discussed in more detail. Each of these design cases resulted in a different outcomes leading to new research, new technologies or new products.

4.1 Whist

In this case, the students were asked to come up with concepts for interactive playing cards for a playing card manufacturer. The manufacturer had been experimenting with the integration of new technologies (e.g. RFID) into traditional playing cards, and was looking for concepts of part physical and part digital card games. Over the course of the project, the students redefined this initial design brief: in consultation with the company, they decided instead to create a technology demonstrator for the manufacturer to use at trade fairs. They ended up creating an interactive luminaire named Whist, which uses playing cards as a construction element for the luminaire's shade. The shade of Whist consists of six petal-like elements that can be opened or closed through a DC motor. Each petal is made up from a flexible laser-cut backbone that holds 68 playing cards. The petals of the lamp can be opened or closed through hand gestures: an ultrasonic sensor at the centre of the lamp detects the motion of the hand and controls the DC motor accordingly. Fully opened, Whist acts as a functional light source; closed, it creates a soft, ambient glow. Overall, this project shows that allowing students to freely interpret and expand their initial assignment can lead to unique and valuable end prototypes.

4.2 CAARS lamps

In this project, the students were tasked with the creation of a technology demonstrator that combines the technologies of two companies: a light fixture manufacturer and a membrane and capacitive switch manufacturer. The end result, CAARS, is a light source that is designed to assist during an indoor night walk. The system is made up from a network of wirelessly connected spheres. The spheres use capacitive sensing to detect when a user is approaching and light up accordingly. When one sphere is picked up, all other nearby spheres (measured using ZigBee radio signal strength) start to glow, allowing the user to navigate his surroundings in the dark. Caars uses a custom made sensor in a new and interesting way.

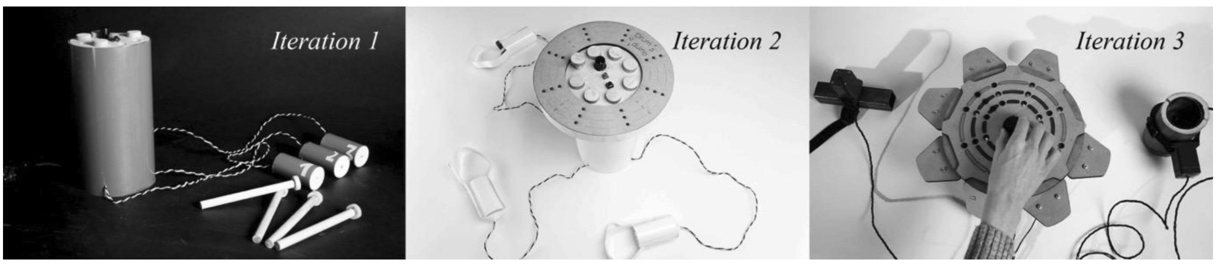


Fig. 5. Three iterations of the Drum Duino.

4.3 Drum duino

The Drum Duino [50, 51] was conceptualized in the first year of our mechatronics course. As mentioned earlier, the first year's cases were not connected to any external organisations or companies. Instead, students were completely free to create any sort of interactive device. One of the groups wanted to create a new type of musical device, which instead of a speaker uses solenoids to produce sound. The device consists of a central console, functioning as a music sequencer, and 3 solenoid modules, which can be connected to various objects using Velcro straps. Users can change musical patterns by inserting control batons into the central console. The resulting beat pattern is sent from the central console to the solenoid modules, which strike an object to produce sound. The students' efforts during the mechatronics course resulted in a working prototype, which inspired us to continue our research on the Drum Duino. We presented a second iteration of the device at a conference offering us input for a third iteration that further refined the functionality and interactivity of the device.

4.4 Innovative mirror

Our last design case is the "Innovative Mirror" project. This project was done in collaboration with two SMEs; a mirror manufacturer specialised in developing high-quality mirrors, and a furniture manufacturer with expertise in the development of bathroom furniture. However, both SMEs have very little experience with electronics and concepts such as user experience design. For this project, they wanted to explore what the bathroom mirror of the future could look like. As a first step, a student group worked on this as part of the mechatronics course. They created a prototype bathroom mirror with an integrated LCD screen and three IR-sensors. The interface offers a newsfeed, radio, weather report and toothbrush timer. Users can navigate through the different functions by waving their hand, which is detected through the IR-sensors integrated behind the mirror. Thus, the interface could be controlled without touching the mirror, eliminating the problem of smudges and fingerprints. Partially due to the prototype that was created by these students, funding was secured for a feasibility study, the goal of which was to determine relevant features and specifications for the product's target user group. This study showed that users are not interested in news and weather updates on their mirror. Instead, they would rather have features that enhance the basic functionality of a mirror, such as showing a zoomed-in view of the face or showing the back of the user's head.

5. Results and discussion

5.1 Student experiences

Within our educational program for industrial design we found collaborating with the industry for prototyping TUIs to be enriching. Through a PBL approach, students worked on open-ended real-world design problems introduced by industry. Through this, students encountered challenges similar to those they might experience as professionals.

Our ambition was to integrate our vision on prototyping TUIs across the courses of several disciplines. We analysed the curriculum of the students Industrial Design, Digital Design & Development, Digital Arts and Entertainment, Industrial Engineering and Social Sciences to find an overlap with the design cases and to find possibilities to let students work interdisciplinary. Although the coordinators of these courses were enthusiastic, we found it hard to integrate the cases into the curriculum because of an inflexible educational system where course content needs to be described and approved at least one year in advance. Another difficulty was to match interdisciplinary projects into unilateral courses; consequently we tried to merge students from different disciplines into one course. Aligning the timetables for the different courses proved troublesome and only succeeded in the academic year 2012–2013. An interdisciplinary course of mechatronics design was offered simultaneously to a mix of Industrial Design students and Electronics students working together in interdisciplinary teams. Additionally, a balance had to found between cases that were too strictly defined and cases that were completely open—allowing students more flexibility to explore creative solutions.

Working in a multidisciplinary team poses the challenge that different perspectives and skills need to be accounted for within a team. In spite of these challenge, this approach allowed students to develop functional prototypes of much higher quality, owing to the collaboration between students with a design engineering background and those with backgrounds in ICT and computer science.

The strong focus on functional prototypes subsequently also forces students to make design decisions early on during the process. The limited time (one semester) also means that students are not able to work endlessly on concepts. Because prototypes had to be working, students were also restricted in what could technically be built within the course. As a result, there was a strong focus on technical feasibility. Through their iterative design process, students could explore design concepts and evaluate technical feasibility and thus change and update their goals. While challenging, getting a prototype working was also highly satisfying for students, as opposed to merely presenting concepts. Furthermore, companies are provided with a functional prototype at the conclusion of the course. Prototypes could thus function as demos and proof of concepts, stimulating follow-up steps. Mechatronics courses rely on physical infrastructure to develop and test prototypes. Our lab provided various software and hardware platforms, such as Raspberry Pi, Makey Makey, Beaglebone and Arduino. These platforms not only allow students to experiment, but also expose companies to new platforms and technologies.

As part of the process, students were required to keep an online project diary. This was be used to monitor progress, but more importantly to give feedback. An open forum allows both lecturers and companies to follow the process and provide students with support and direction.

Before the start of this project, the course was run, without the collaboration with industry. Students lacked access to the more advanced electronics available in the Lab and without the commercial context of companies; the students only explored well known techniques, crafting prototypes in wood and cardboard. Generally, the product concepts were also more linked to arts and crafts rather than industrial relevance.

With the Lab and the involvement from industry, the context and the prototypes really matured together, with student's finding a good balance between the creative play and the added commercial value created by new kinds of smart products. Furthermore the support from industry and the availability of the TIII Lab combined in a general vision created an upward spiral for the students. Students and teachers tried to improve each year to outperform the cases from last year. This not only resulted in better grades but also a high motivation and sense of pride was observed in the students

5.2 SME collaboration

From an industry perspective, the cooperation lowered the threshold for the creation of TUIs while exposing companies to importance of involving users in the development process. By offering SMEs a low-risk opportunity to explore new ideas and technologies they had the chance to evaluate the feasibility of a product at an early stage. Students indicated that involvement of external partners in combination with the use of real world cases helps to focus efforts, though the open-ended nature of the assignments is perceived to be challenging.

A risk of the close collaboration between industry and students is that students may not always be skilled enough to deliver useful results—especially when given challenging assignments. Simultaneously, companies are required to invest time and other resources when mentoring a case, without guarantee that the results will be usable.

We found that companies were sceptical about the importance of involving the user at an early stage in the product development process. Typically they develop a product and perform user testing in a final phase, making only the smallest of changes

Table 1. Overview of the lessons learned for both students and companies

Subject	Education	Industry
Working with the industry	Offers a good insight of real-world design problems	Low risk for exploring TUIs and new technologies
Working with students	It is not guaranteed that the results are going to be useful	Mentoring a case requires time and involvement of the company
Integration in student curriculum	It was hard to integrate interdisciplinary projects into unilateral courses	It was not always possible to approach a case in an interdisciplinary way
Gathering cases	Students got to choose their preferred case to enhance their motivation	Close contact with the industry is needed to guide them to submit a case
Case description	As opposed to well-defined cases, broadly described cases lead to more creative results	New opportunities can be found through creative explorations
UX testing	By prototyping interactions the user experience could be tested, resulting in novel ideas	Companies were convinced of the importance of incorporating user testing into the development process
Availability of tools	Students had quick access to platforms and tools to test with.	Companies learned about the possibilities of new platforms and technologies through the resulting prototypes
Feedback	Students got feedback on their blog from fellow students, teachers and companies	By reading the blog, companies could follow the status of a case from a distance and offer feedback
Prototyping	Through iterative prototyping the students got to test technical aspects of a concept	The result was always a working prototype that the company could use

possible, even though the whole concept could be wrong or unappealing for the user, resulting in a product that is not viable. With these student cases, companies could see the innovation potential of the end-results making it easier to convince them of the added value and the importance of implementing user testing into the development process of their company.

The end result was always a finished working prototype that offered the companies the opportunity to use it for further user testing and to facilitate the process of adapting the concept to a commercial product.

6. Conclusion

In this paper we introduced our design platform for tangible interfaces, a case study for the development of user centred TUIs in close collaboration with SMEs. Due to the increasing importance of UX and the prevalence of TUIs, there is a need for SMEs to better incorporate these principles in their products. We discussed how SMEs were involved in a PBL course—Mechatronic Product Design—and how students experienced the collaboration. We reviewed our platform, consisting of a Network, a Method and a Lab, while introducing four cases to illustrate this process. Finally, we reflected on our experiences within this project. Our main contribution is the process and lessons learned in this project, specifically the close involvement of SMEs.

Overall, this close collaboration helps to expose students to working contexts they might experience as professionals, not only because of the practical nature of the assignments, but also due to the requirement to develop working prototypes under budget and time constraints. We remain convinced that working in multidisciplinary teams—while challenging—also greatly improves the quality of the work and that close industry involvement offers students a practice based perspective during their education.

References

1. M. Hassenzahl and N. Tractinsky, User experience—a research agenda, *Behaviour & Information Technology*, **25**(2), 2006, pp. 91–97.
2. E. L.-C. Law, V. Roto, M. Hassenzahl, A. P. O. S. Vermeeren and J. Kort, Understanding, scoping and defining user experience, in *Proceedings of the 27th international conference on Human factors in computing systems—CHI 09*, 2009, p. 719.
3. M. Wiberg and E. Robles, Computational Compositions: Aesthetics, Materials, and Interaction Design, *International Journal of Design*, **4**(2), 2010, pp. 65–76.
4. B. Ullmer and H. Ishii, Emerging frameworks for tangible user interfaces, *IBM Systems Journal*, **39**(3.4), 2000, pp. 915–931.
5. H. Ishii, Tangible bits, in *Proceedings of the 2nd international conference on Tangible and embedded interaction—TEI '08*, 2008, p. xv.
6. M. Satyanarayanan, Pervasive computing: vision and challenges, *IEEE Personal Communications*, vol. 8, no. 4, 2001, pp. 10–17.
7. D. Saha and A. Mukherjee, Pervasive computing: a paradigm for the 21st century, *Computer*, **36**(3), 2003, pp. 25–31.
8. O. Shaer and E. Hornecker, Tangible User Interfaces: Past, Present, and Future Directions, *Foundations and Trends® in Human–Computer Interaction*, **3**(1–2), 2009, pp. 1–137.
9. A. K. Agrawal, University-to-industry knowledge transfer: literature review and unanswered questions, *International Journal of Management Reviews*, **3**(4), 2001, pp. 285–302.
10. O. Gassmann, E. Enkel and H. Chesbrough, The future of open innovation, *R&D Management*, **40**(3), 2010, pp. 213–221.
11. C. Chen and K. Hsu, Creativity of Engineering Students as Perceived by Faculty: a Case Study, *International Journal of Engineering Education*, **22**(2), 2006, pp. 264–272.
12. I. M. Moczarny, M. R. (Ruth) de Villiers, and J. A. (Judy) van Biljon, How can usability contribute to user experience?, in *Proceedings of the South African Institute for Computer Scientists and Information Technologists Conference on—SAICSIT '12*, 2012, p. 216.
13. M. Hassenzahl and N. Tractinsky, User experience—a research agenda, *Behaviour & Information Technology*, **25**(2), 2006, pp. 91–97.
14. A. S. MacDonald, Aesthetic intelligence: Optimizing user-centred design, *Journal of Engineering Design*, **12**(1), 2001, pp. 37–45.
15. M. Kouprie and F. S. Visser, A framework for empathy in design: stepping into and out of the user's life, *Journal of Engineering Design*, **20**(5), 2009, pp. 437–448.
16. C. Barnes and S. P. Lillford, Decision support for the design of affective products, *Journal of Engineering Design*, **20**(5), 2009, pp. 477–492.
17. M. A. Artacho, A. Ballester, and E. Alcántara, Analysis of the impact of slight changes in product formal attributes on user's emotions and configuration of an emotional space for successful design, *Journal of Engineering Design*, **21**(6), 2010, pp. 693–705.
18. M. Weiser, The computer for the 21st century, *Scientific American*, **272**(3), 1991, pp. 94–104.
19. G. Bell and P. Dourish, Yesterday's tomorrows: notes on ubiquitous computing's dominant vision, *Personal and Ubiquitous Computing*, **11**(2), 2006, pp. 133–143.
20. H. Ishii and B. Ullmer, Tangible bits, in *Proceedings of the SIGCHI conference on Human factors in computing systems—CHI '97*, 1997, no. March, pp. 234–241.
21. O. Shaer and E. Hornecker, Tangible User Interfaces: Past, Present, and Future Directions, *Foundations and Trends® in Human–Computer Interaction*, **3**(1–2), 2009, pp. 1–137.
22. J. Fortmann, T. Stratmann, S. Boll, B. Poppinga and W. Heuten, Make Me Move at Work! An Ambient Light Display to Increase Physical Activity, in *Proceedings of the ICTs for improving Patients Rehabilitation Research Techniques*, 2013.
23. Y. Blanco-Fernández, M. López-Nores, J. J. Pazos-Arias, A. Gil-Solla, M. Ramos-Cabrer and J. García-Duque, REENACT: A step forward in immersive learning about Human History by augmented reality, role playing and social networking, *Expert Systems with Applications*, **41**(10), 2014, pp. 4811–4828.
24. 24. J. Peschke, F. Göbel, T. Gründer, M. Keck, D. Kammer and R. Groh, DepthTouch: An Elastic Surface for Tangible Computing, in *Proceedings of the International Working Conference on Advanced Visual Interfaces—AVI '12*, 2012, p. 770.
25. P. Ahrweiler, A. Pyka and N. Gilbert, A New Model for University-Industry Links in Knowledge-Based Economies, *Journal of Product Innovation Management*, **28**(2), 2011, pp. 218–235.
26. O. Gassmann, E. Enkel and H. Chesbrough, The future of open innovation, *R&D Management*, **40**(3), 2010, pp. 213–221.

27. M. Flores, C. Boër, C. Huber, A. Plüss, R. Schoch and M. Pouly, Universities as key enablers to develop new collaborative environments for innovation: successful experiences from Switzerland and India, *International Journal of Production Research*, **47**(17), 2009, pp. 4935–4953.
28. M. Lehmann, P. Christensen, X. Du and M. Thrane, Problem-oriented and project-based learning (POPBL) as an innovative learning strategy for sustainable development in engineering education, *European Journal of Engineering Education*, **33**(3), 2008, pp. 283–295.
29. M. A. Dahlgren, PBL through the looking-glass: Comparing applications in computer engineering, psychology and physiotherapy, *International Journal of Engineering Education*, **19**(5), 2003, pp. 672–681.
30. J. S. Krajcik, C. M. Czerniak and C. Berger, *Teaching Children Science: A Project-Based Approach*, Mcgraw-Hill College, 1999.
31. M. Frank, I. Lavy and D. Elata, Implementing the project-based learning approach in an academic engineering course, *International Journal of Technology and Design Education*, **13**(3), 2003, pp. 273–288.
32. Y. B. Kafai and M. Resnick, *Constructionism in practice: Designing, thinking, and learning in a digital world*, Routledge, 1996.
33. S. Papert, *Mindstorms: Children, computers, and powerful ideas*, Basic Books, 1980.
34. G. Stager, Papertian constructionism and the design of productive contexts for learning, in *Proceedings of EuroLogo 2005*, 2005.
35. D. A. Kolb, Experiential Learning: Experience as The Source of Learning and Development, in *Prentice Hall, Inc.*, 1984.
36. S. Meek, S. Field, and S. Devasia, Mechatronics education in the Department of Mechanical Engineering at the University of Utah, *Mechatronics*, **13**(1), 2003, pp. 1–11.
37. Y. Wang, Y. Yu, H. Wiedmann, N. Xie, C. Xie, W. Jiang and X. Feng, Project based learning in mechatronics education in close collaboration with industrial: Methodologies, examples and experiences, *Mechatronics*, **22**(6), 2012, pp. 862–869.
38. I. C. Peden, E. W. Ernst and J. W. Prados, Systemic engineering education reform: An action agenda, *Washington, DC: National Science Foundation*, 1995.
39. E. D. E. Graaff and A. Kolmos, Characteristics of Problem-Based Learning, *International Journal of Engineering Education*, **19**(5), 2003, pp. 657–662.
40. B. Galand, B. Raucent and M. Frenay, Engineering students ' self-regulation , study strategies , and motivational believes in traditional and problem-based curricula, *International Journal of Engineering Education*, **26**(3), 2010, pp. 523–534.
41. K. Camarata, M. D. Gross and E. Y.-L. Do, A Physical Computing Studio: Exploring Computational Artifacts and Environments, *International Journal of Architectural Computing*, **1**(2), 2003, pp. 169–190.
42. S. R. Klemmer, B. Verplank and W. Ju, Teaching embodied interaction design practice, in *DUX '05 Proceedings of the 2005 conference on Designing for User eXperience*, 2005.
43. Y. Reich, E. Kolberg, and I. Levin, Designing contexts for learning design, *International Journal of Engineering Education*, **22**(3), 2006, pp. 489–495.
44. Usewell, ''Usewell,'' *2013*, 2014. [Online]. Available: www.usewell.be.
45. M. C. Yang, A study of prototypes, design activity, and design outcome, *Design Studies*, **26** (6), 2005, pp. 649–669.
46. S. Houde and C. Hill, What do prototypes prototype?, in *Handbook of human-computer interaction*, Amsterdam: Elsevier Science, 1997, pp. 367–382.
47. M. Buchenau and J. F. Suri, Experience prototyping, *Proceedings of the conference on Designing interactive systems processes, practices, methods, and techniques—DIS '00*, 2000, pp. 424–433.
48. J. M. Pearce, The case for open source appropriate technology, *Environment, Development and Sustainability*, **14**(3), 2012, pp. 425–431.
49. S. Pugh, *Total design: integrated methods for successful product engineering.* Prentice Hall, 1991.
50. J. Saldien and J. De Ville, Drum Duino: a Tangible Interface to Create Rhytmic Music with Everyday Objects, in *Proc. TEI 2013*, 2013, pp. 1–7.
51. C. Vandevelde, P. Conradie, J. De Ville and J. Saldien, Playful Interaction: Designing and Evaluating a Tangible Rhythmic Musical Interface, in *The Second International Conference on Live Interfaces*, 2014.

Peter Conradie is researcher at Ghent University—Department of Industrial System and Product, where he focuses on user involvement strategies for new product design, with an emphasis on tangible and interactive products beyond the desktop. He has previously worked as researcher at the Rotterdam University of Applied Science in Rotterdam and the Fachhochschule Potsdam, Germany.

Cesar Vandevelde graduated as M.Sc. Industrial Engineering—Industrial Design at Ghent University in 2012. Immediately following his graduation, he started his PhD under prof. Jelle Saldien, which he is currently still pursuing. His research focuses on the design of a low-cost, hackable toolkit for social robotics. Other research interests include robotics in general, 3D printing, human-computer interaction and mechatronics.

Jolien De Ville received her masters degree in Product Development at the University of Antwerp in 2010. Her research interests include user experience design, intelligent textiles, tangible user interfaces and the internet of things. She is currently working as a user experience designer at KBC bank, Belgium.

Jelle Saldien received his M.S. degree in Industrial Science ICT at DeNayer Institute in 2003 and an additional M.S. degree in Product Development at Artesis in 2005. In 2009, he received his Ph.D. at the Vrije Universiteit Brussel on the design and development of the social robot Probo. From 2010, he was lecturer in Industrial Design at the Howest University College West Flanders. Since 2013 he is appointed as Assistant Professor Industrial Design at Ghent University and since 2014 steering member of Flanders Make VD4. Jelle Saldien is author of over 30 technical publications, proceedings, editorials and books. His research interests include mechatronic design, interaction design, human computer interaction and social robotics.