An Open Platform for the Design of Social Robot Embodiments for Face-to-Face Communication

Cesar Vandevelde
Dept. of Industrial Systems Engineering and Product Design
Ghent University, Campus Kortrijk
Kortrijk, Belgium
Partner of Flanders Make
cesar.vandevelde@ugent.be

Jelle Saldien
Dept. of Industrial Systems Engineering and Product Design
Ghent University, Campus Kortrijk
Kortrijk, Belgium
Partner of Flanders Make
jelle.saldien@ugent.be

***Abstract*—The role of the physical embodiment of a social robot is of key importance during the interaction with humans. If we want to study the interactions we need to be able to change the robot's embodiment to the nature of the experiment. Nowadays, researchers build one-off robots from scratch or choose to use a commercially available platform. This is justified by the time and budget constraints and the lack of design tools for social robots. In this work, we introduce an affordable open source platform to accelerate the design and production of novel social robot embodiments, with a focus on face-to-face communication. We describe an experiment where Industrial Design students created physical embodiments for 10 new social robots using our platform, detailing the design methodology followed during the different steps of the process. The paper gives an overview of the platform modules used by each of the robots, the skinning techniques employed, as well as the perceived usability of the platform. In summary, we show that our platform (1) enables non-experts to design new social robot embodiments, (2) allows a wide variety of different robots to be built with the same building blocks, and (3) affords itself to being adapted and extended.**

Keywords—social robotics; design methodology; embodiment; human-robot interaction; platform

I. Introduction

One of the core concepts enabling the field of human-robot interaction (HRI) is the idea that we humans have a tendency to recognize and project emotions onto objects, requiring only the smallest hints of facial features or human-like behavior. Indeed, social interaction with robots works because humans recognize a part of themselves in robots, and robots without any socially expressive features are seen as cold or distant [1]. Duffy states that humans' propensity to anthropomorphize is not seen as a hindrance to social robot development, but rather a useful mechanism that requires further examination and employment in social robot research. [2]

Other research has shown the importance of physical embodiment in the design of social agents [3], [4]. Generally concluding that the physical embodiment of a social agent enhances its social presence and furthermore that tactile interaction is a key factor in human-agent interaction [5]. In the process of robot-human communication, the robot's face also plays a vital role [6], using facial expressions as a natural means to express emotions towards humans. Beyond that, a social robot should possess a character and personality, noticeable by humans [7]. Naturally, different target applications for social robots impose a different set of requirements on the personality and embodiment of the robot. According to Bartneck, the shape, size and material qualities of a social robot should match the task it is designed for in order to avoid false expectations [8].

Currently, researchers are often faced with the choice to either design their own social robot from scratch (e.g. Kismet [9], Mertz [10], Nexi [11], WE-4RII [12], Probo [13], EMYS [7], etc) or to use/buy a commercial robot (e.g. Aibo [14], iCat [15], Paro [16], or Nao [17]). The first option affords a large degree of flexibility, allowing researchers to fine-tune the embodiment of the robot to the exact specifications of their experiment, at the expense of development time and money. The second option allows for a much faster, less expensive development cycle and is often preferred in research contexts. However, this speed comes at another cost: customization is often limited to software and superficial embodiment changes

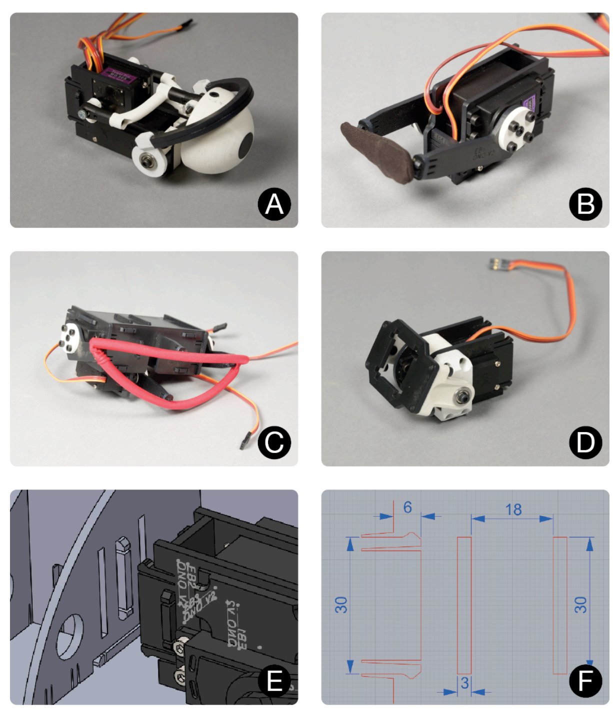

Fig. 1. Platform modules. A: Eye module. B: Eyebrow module. C: Mouth module. D: Joint module. E: Detail of snap connector between module and frame. F: 2D drawing of snap connector and associated mating connector.

(e.g. giving a Nao robot eyebrows [18]). This dichotomy is also reflected by Tilden's argument that the greatest barrier for breakthroughs in personal robotics is cost, in terms of both money and time [19]. Researchers need better tools to easily and rapidly design different embodiments for social robots in order to progress the insights in HRI. Already in 2003, Fong et al. stated that most research in HRI has not yet explicitly focused on design of embodiments and much research remains to be performed [20]. Currently, little progress has been made, some approaches can be found in modular humanoid robots, focusing on body motions (e.g. DARwIn-OP [21] and Poppy Project [22]), but with limited room for exploration of different embodiments and leaving the face virtual or static.

With the work presented in this paper, we propose an open platform for social robots (OPSORO) to aid in the design, construction and production of custom robot embodiments with a focus on face-to-face communication. Already in 2001, Von Hippel [23] hinted at the innovation potential of user toolkits in niche application areas and *"markets of one"*. HRI in general, and therapeutic applications in particular, are confronted by large amounts of *"sticky"* information; information that is difficult and costly to transfer from the user to the robot designer. To elaborate, a therapist (the user) might be well aware of what robot aspects (embodiment and functionalities) are important to a specific patient, aspects of which a roboticist would not be aware. Within the field of human-computer interaction (HCI), there already exists a large body of work on toolkits, e.g. [24]–[28]. As shown by Mellis et al. [29], traditional toolkits do suffer from a number of drawbacks: users are limited to the set of modules that the designers of the toolkit have provided. Furthermore, the shape of the modules also imposes a constraint on the shape and aesthetics of the artifacts designed with the toolkit. Instead they propose "untoolkits" as a potential answer: toolkits that are interpreted more as a design method rather than a set of building blocks. Examples of untoolkits include [29]–[32]. Yet a third approach is to design an artifact with the specific intent to be modified by the user, examples of these hackable devices include [33]–[35]. Our OPSORO platform draws elements from these three toolkit approaches. OPSORO's modules are in line with traditional toolkits, they package complex functionality into higher-level building blocks. The way these modules are combined is reminiscent of the characteristics of an untoolkit, relying heavily on laser cutting and software tools to realize custom embodiment designs. Finally, keeping in line with the hacking paradigm, we tried to keep as many elements of the platform open to modification. The next sections start with an overview of the OPSORO platform, and continue with its design methodology and the results of an experiment in which second-year Industrial Design students were tasked with the creation of novel social robot embodiments over the course of one semester, starting from the OPSORO platform.

II. Platform Overview

The OPSORO platform consists of (1) a set of modules, each of which implements a facial feature, (2) electronics to drive the modules and sensors, (3) a software environment to program and control the robots, and (4) a methodology to incorporate these elements into a custom embodiment. The standard modules are combined with a custom designed skeletal frame and skin in order to easily create a unique robot. The complex aspects of robot embodiment design are confined within the modules, leaving the user free to design the skeleton and thus the outer appearance as they see fit. As of yet, the platform offers four types of modules: eye modules (fig. 1A, 3 DOFs), eyebrow modules (fig 1B, 2 DOFs), mouth modules (fig 1C, 3 DOFs), and joint modules (fig 1D, 1 DOF). A fifth module, the neck, is currently under development. The modules of the platform focus primarily on facial features, rather than robotic limbs. This allows us to focus on face-to-face communication using low-cost hobby servos in the modules, rather than the more powerful motors that would be required for limbs. This approach minimizes the production costs indicated at 300 – 600 euro per robot.

The platform is derived from the social robot Ono [36], [37]. This robot was explicitly designed to be low-cost and reproducible, as a response to difficulties (e.g. cost, transport, repairs) encountered with other social robots. The design of the robot relies almost exclusively on two production techniques that are commonly found in many FabLabs: laser cutting and 3D printing (i.e. RepRap [38] and derivatives). As far as we are aware, no other social robot offers the same opportunities for hacking at a similar price-point, and as such, we decided to base our platform on Ono. Thus, the same techniques that were used in Ono are also used for the modules of the OPSORO platform. Each of the modules contains a standardized snap connector, shown in fig. 1E. This connector mates with two slots in the skeleton, shown in fig. 1F. In order to incorporate a module into a custom skeleton, these two slots need to be drawn at the desired module location.

The electronics system is based on the Raspberry Pi single-board computer combined with a custom OPSORO shield with circuitry to regulate power, control up to 16 servos, drive a speaker, read up to 12 capacitive touch sensors and 4 analog sensors. The Raspberry Pi itself has facilities for a camera input (e.g. for computer vision applications), though this is currently not yet activated in the platform. To comply with the hacking paradigm, the electronics of our platform offer many options for adaptation and extension, ranging from USB devices (e.g. a Bluetooth module or an Arduino), to I2C sensors (e.g. an accelerometer), to simple analog sensors (e.g. a button or a force-sensitive resistor).

On the software side, our platform is implemented as a web server running on the Raspberry Pi. When the board is turned on, the Wi-Fi dongle is put into access point mode and the web server is started. Users can then connect their device to the access point and control the robot through their browser. This approach allows users to operate the robot using any internet-capable device, without the need to install additional software. The interface itself borrows the "app"-metaphor of smart phones and tablets, with each task or scenario implemented as a distinct application. These apps range from simple control apps, to hardware configuration/debugging apps, to complex scripting apps. One particularly noteworthy app is the "Visual Programming" app, which lets the user implement simple scenarios using a visual programming environment. The programming environment is implemented in Blockly, a derivative of the Scratch programming language [39].

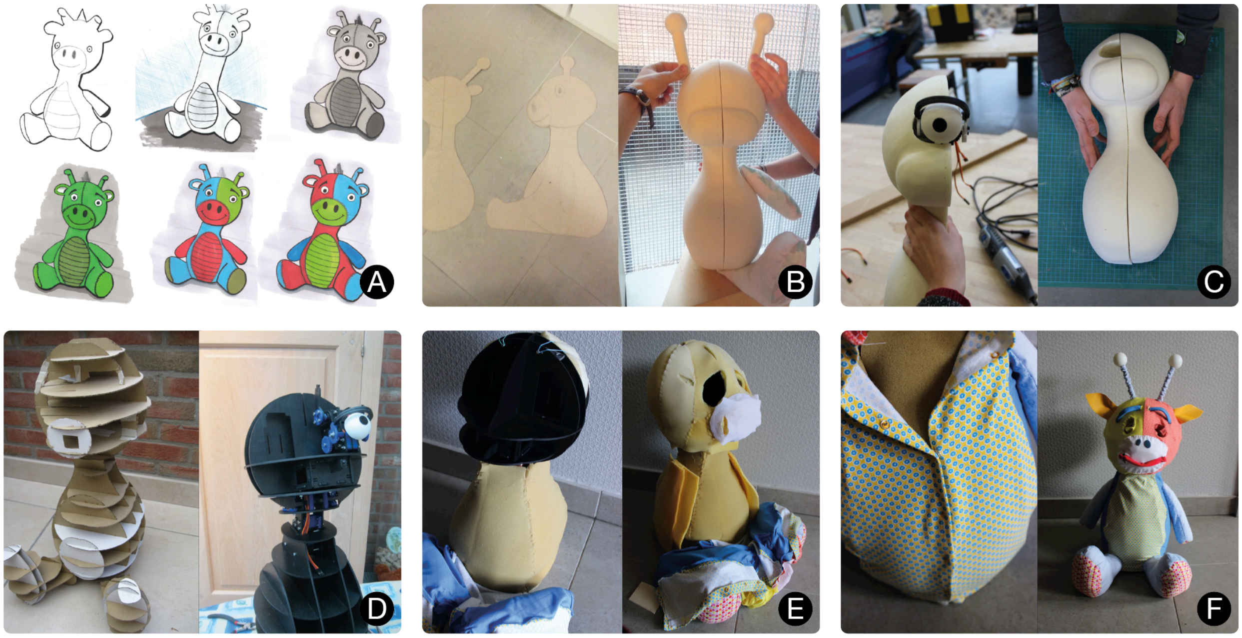

Fig. 2. Design process overview of one robot. A: Concept sketches. B: Foam mockup. C: Module test fitting. D: 1st and 3rd skeleton iterations. E: Skinning – foam padding. F: Skinning – outer textile layer.

The final element of the platform is our embodiment methodology. It can be seen as a step-by-step instruction manual to go from concept sketches, to mockups, to manufacturable plans for the skeletal frame and skin of the robot. The same snap connectors (fig. 1F) are used in the design of this skeleton as those used by the modules. As a result, the entire skeleton can be assembled without adhesives or fasteners. Once this frame is assembled, modules can be snapped into place and the result can be covered with the skin. Owing to the complexity of the design of social robots, our methodology emphasizes low-fidelity prototyping techniques in the design process in order to enable and encourage quick design iterations (the importance of which is also hinted at by Von Hippel [23]). In our experience, one of the pitfalls in robot design is to invest too much time up front on the implementation of a feature, only to find out afterwards that the feature is redundant, superfluous, or otherwise inappropriate to the user. We strive to avoid these situations by incorporating techniques that encourage trial-and-error and elicit quick design alterations, much akin to paper prototyping techniques in HCI [40]. The methodology that was used by the students during the assignment is described in more detail in the following section.

III. Method

To test whether or not our platform is a viable way to accelerate the design of novel social robot embodiments, we tasked 20 second-year bachelor students in Industrial Design with the design of new social robots over the course of one semester (12 weeks, 2 hours per week), as part of one of their Design Studio courses. While these students are not considered design novices, it should also be noted that these students have no expertise in the design of robots. The Industrial Design program is oriented toward general design and engineering. There is no special focus on human-computer interaction or mechatronics design. Considering the students' background, as well as practical constraints, we decided to limit the scope of our experiment to the physical design of social robots. Behavior programming was not part of the course, although this is something we want to include in future experiments.

To aid the students in their design process we imposed a fixed planning that corresponds to the different steps in our platform's methodology. In the first part of the course (week 1-4), all students worked individually. During this time, students worked towards a top-three of robot concepts that could be created with the platform. At this point, we selected the best concept per student, and grouped the students into pairs, with each pair having similar or complementary concepts. From week 5 on, students worked in teams to realize their concept using the platform. To encourage collaboration between teams during the assignment, students were explicitly told that they were allowed to share their own module designs with other teams. This served two purposes: (1) it reduces student workload, (2) it encourages the students to make their custom modules more flexible (i.e. *"How can I design my module so that it is not only useful for me, but for other people as well?"*). The sections below describe the planning used during the assignment. Fig. 2 shows one team's process in various steps along this process.

Week 1-2: Introduction & inspiration. Students are given background information on the HRI field, along with examples of existing social robots. During the introduction lesson, students were also given a presentation on the design process of Probo and Ono.

Week 3-4: Concept generation. During this phase, students worked individually toward a concept for a social robot. This process entails the design of an identity and personality that is linked to the functionality and appearance of the robot. After selection of the concepts, the students continued to work in teams of two.

Week 5: Quick & Dirty mockups. Starting from sketches, students created rough 1:1 scale foam models for the appearance of the robot. These foam mockups served a number of purposes: they allowed the students to quickly fine-tune the appearance, they provide an indication of the stability and the shape, they can be used to test-fit the modules, and they can be used as a basis for the skeleton design and skinning of the robot.

Week 6-7: Modules and skeleton design. Once the general appearance of the robot is established, a rigid frame needs to be designed to affix the modules, electronics and skin to. To create the design of the skeleton, students were first instructed to create a digital 3D model of their physical mockup. We recommended the use of sculpting software (e.g. MeshMixer [41]), though some students created their model with non-uniform rational B-spline (NURBS) surface modeling tools. For the first design iteration of the frame, the 3D model was converted into slices using Autodesk's 123D Make [42] and then cut out of 3 mm cardboard using a laser cutter. After test fitting the components, the slices were transferred to a dedicated mechanical CAD software package, which was used to further detail the skeleton. This detailing includes adding snap connectors for interconnecting the different parts of the skeleton and for connecting the modules to the skeleton, adding openings for cable routing, and adding reinforcement parts. This second iteration was then again cut from 3 mm cardboard, assembled, and tested by the students. Cardboard was chosen for the first two iterations because it is inexpensive (both in terms of material cost and machine time) and because the cut pieces can be easily modified afterwards using simple hand tools (e.g. scissors, knives, glue, tape). Once the frame designs were finalized, the designs were cut from 3 mm ABS plastic. Nearly all skeletons could be cut from three sheets sized 600x450 mm, which was the number of sheets we provided per team. Any additional sheets had to be provided by the students themselves. This encouraged students to design their frames with efficient material use in mind. During this phase, students also started work on any custom modules they might require for their robot. Most custom modules were simple modifications of existing modules, though some groups also designed modules from scratch. As mentioned earlier, teams were explicitly permitted to share their modules with each other. This resulted in an interesting dynamic where modules were traded between groups (i.e. *"We will design module A if you design module B, then we both can use the modules in our robot."*).

Week 8-9: Skinning and facial features. Once the frame and modules of each robot are finalized, an outer, aesthetic layer needs to be created. Techniques used by the students during this phase varied greatly. One method we suggested was to make a soft padding layer using sheets of soft PU foam, and to then cover this padding layer with an outer, visible layer made from stretchable fabric, such as Lycra. This approach was also used in the design of Ono and works well for soft robots that are created to interact with children. However, seeing that the students' concepts are quite diverse, most teams deviated from this approach quite significantly. While most teams continued to rely on fabrics and textiles, some experimented with radically different techniques, which was especially interesting to us. During this phase, the foam mockups again proved to be very useful, as they allowed the students that used fabrics to easily create patterns for the textile by pinning cut pieces of paper onto the foam mockup. These paper patterns could then be transferred to the textile to cut out.

Week 10-12: Skinning, module integration, final adjustments. During the last weeks of the course, students were mostly working on finishing their designs. Most still required some time to integrate the modules into the skin of their robot.

Week 13: Deadline. Students presented their work in the first week after the end of the course. Deliverables included (1) a presentation showing the concept, design process and intended interaction scenario, (2) 3D design files, and (3) a set of pictures of the robot depicting each of Ekman's basic

TABLE I. OVERVIEW OF ROBOT CONCEPTS, MODULE USE, AND SKINNING TECHNIQUES.

Name[a]	Concept Description	Standard modules[b]				Modified modules[b]				Custom modules	DOFs	Skin materials
		E	*EB*	*M*	*J*	*E*	*EB*	*M*	*J*			
TwinWin (B)	Telepresence system to communicate emotions between two friends, family members, or lovers.	–	–	1	–	2	2	–	–	Neck	10	Stretchable fabric, soft foam, stuffing
Professor Knowall (C)	Teaching (homework) system, to be used in conjunction with tablet for interactive quizzes.	2	2	–	–	–	1	–	–	–	12	Soft foam, EVA foam, hard plastic, stuffing
ReminderBot (D)	Planning and timekeeping aid for people with dementia, autism, or other memory-affecting diseases.	2	2	–	2	–	–	–	–	–	12	Stretchable fabric, soft foam
Kanga (E)	Motivator/coach to stimulate motor function exercises in children with Down syndrome.	–	–	–	–	2	2	1	–	Neck	10	Non-stretchable fabric, soft foam, stuffing
Mumble (F)	Encourages tolerant behavior in children. Gradually climbs out of its box as children get to know the robot.	2	2	–	–	–	–	–	–	Lift	11	Non-stretchable fabric, soft foam
DriveMe (G)	Co-pilot for people that spend a lot of time driving. Aids in navigation, communication, general car functionality.	–	–	–	–	–	–	–	–	Turntable, 2 × LED Eye, 2 × Ear	3	Stretchable fabric, hard plastic
Pillo (H)	Physical affection robot for adults. Inspired by phenomenon of lonely adult men in Japan.	–	–	–	–	2	3	–	–	–	8	Stretchable fabric, non-stretchable fabric, soft foam, EVA foam, hard plastic, stuffing
Poco (I)	Musical coach to encourage children to do their daily musical instrument exercises.	2	2	–	2	–	–	1	–	–	13	Stretchable fabric, soft foam, EVA foam
Walu (J)	Replacement for preschool class pets. Supports class activities and teaches children to care for animals without risk to animal wellbeing.	2	2	–	2	–	1	–	–	6 × LED dome	12	Non-stretchable fabric, soft foam, stuffing
AntiHero (K)	Clumsy hero with good intentions that tries to encourage children to help with small household tasks.	–	2	1	–	2	2	–	–	–	15	Stretchable fabric

a. Letters between parentheses refers to the picture of the robot in figure 3.

Fig. 3. Results of the course. A: Ono, the robot from which the OPSORO platform is derived. B – K: Robots designed by the students using the OPSORO platform.

emotions (i.e. happiness, sadness, anger, fear, surprise, disgust) [43].

In addition to the deliverables, students were required to hand in their robots at the end of the course (which was ultimately used to grade the students). We also asked the students to fill in a questionnaire to evaluate the process of the course assignment. This questionnaire comprised questions regarding the use of modules and skinning techniques, (2) questions concerning the difficulty of each phase, and (3) questions regarding subjective appreciation of the platform. After the final presentation, all students completed the questionnaire, resulting in two responses per robot. The questionnaire was not anonymized, so that data of team members could also be compared to each other. The questionnaire was taken in Dutch and the results were translated to English by the authors.

IV. Results

The results of the course assignment are shown in fig. 3. Fig. 3A shows Ono, the robot from which the platform is derived, B through K show the 10 robot embodiments designed by the student teams. Table 1 gives a summary of the intended functionality of each robot, the modules they used, and the materials used to make the outer skin.

A. Modules

In general, nearly all module modifications had one goal in common: they aimed to make the module smaller in order to be able to integrate that specific facial feature into their robot. This tends to be a trade-off between size and functionality. The standard modules are usually bigger than their modified counterparts, but offer more degrees of freedom (DOF). However, these extra DOFs are not always required to enable the intended interactions.

Many groups modified the length of the levers on the eyebrow (fig. 1B) and mouth (fig. 1C) modules to accommodate the outer shape of their robot. This is a very minimal modification and is therefore not included in table 1 under "modified modules". Groups C, H, and I used a modified eyebrow module as a mouth due to space restrictions in their design. These modules only have 2 DOFs. Consequently, they do not allow the mouth to open and close. Groups B, E, and H all use two eye-eyebrow modules. This module is an amalgamation of the standard eye and eyebrow modules, and is much more compact than the two separate modules together. The eye-eyebrow module has 3 DOFs, as opposed to the 3+2 DOFs of the standard modules. The eyeball is static; only the eyebrow and eyelid are actuated. Group K used two modified eyebrow modules – each with one servo removed – to actuate the bunny ears.

In addition to the module modifications, some groups also designed custom modules to be used in their robots. Groups B and E created a neck module to tilt the head of their robots. The module is based on a 2 DOF neck prototype that was designed as part of a master thesis. The pan mechanism was eliminated and the overall design was refined to correspond to the rest of the system. The mechanism uses the same type of servo as the rest of the platform, but relies on a 3D-printed lead screw for mechanical advantage. Group G created a turntable module to be able to turn their robot horizontally. This 1 DOF module is comparable to the neck module, except that it enables panning instead of tilting. The module is based on a Lazy Suzan bearing, with the servo transmitting motion via an internal gear. The course assignment yielded a number of cases where existing modules fell short, and thus had to be modified or replaced. The work done by students on the modules is a valuable source of inspiration for future elements of the platform and proves the easy adaptability of the platform.

B. Novel skinning techniques

As mentioned in section III, students experimented with completely new techniques and materials to create a skin for their robot embodiment. During the orientation presentations, we proposed a skinning method to the students, which involves covering the skeleton with a soft foam-padding layer, which is then covered with an outer layer made of stretchable fabric. However, big differences in the intended modes of interaction of the students' robots lead to different priorities for the skin design. To elaborate: Ono was originally intended as a huggable robot for children, much like Probo. A soft, huggable embodiment was therefore essential. On the opposite side of the spectrum are robots such as DriveMe (fig. 3G). They are not intended to be touched, so a hard plastic exterior is a valid solution. A third example is Professor Knowall (fig. 3C), which falls somewhere in between the two. The robot is intended for interaction with young children, thus a cold, hard exterior would not be appropriate. On the other hand, the robot does borrow the connotation of a professor to create a sense of distance between the child and the robot, so a soft foam exterior would also not have been an appropriate choice.

Within the class group, team I pioneered the use of EVA foam. This thermoplastic foam can be formed into three-dimensional shapes through thermoforming, a technique where thermoplastic sheet material is heated and pulled over a mold with the aid of a vacuum. This results in semi-flexible, thin parts that are soft to the touch. A number of groups also thermoformed polystyrene (PS) sheets, most of these groups combined the rigid PS parts with an outer layer of EVA foam. One notable exception is group G, which relied solely on thermoformed PS for the majority of the exterior. Group J experimented with the use of felt. This material can be formed into three-dimensional shapes with the aid of steam, but has a tendency to fray, resulting in a messy look.

C. *Questionnaire*

The goal of the questionnaire was to gain insight as to how the platform and the design process were perceived by the students. Whereas data on the modules and skinning techniques are represented in the robots themselves, it does not allow us to gauge the potential difficulties in the process. The first part of this questionnaire attempts to measure the general sentiment of the students toward the platform. This part comprises four 7-point Likert scale statement questions:

- *"The modules accelerate the design of new social robots..."* disagree / agree.
- *"The modules are..."* not useful at all / extremely useful.
- *The module system is..."* not adaptable / very adaptable.
- *"The snap connectors are..."* hard to use / easy to use.

Results of these questions are show in fig. 4. The nature of the experiment and of the platform itself makes it difficult to compare data to any baseline. However, in our opinion the data does show a generally positive trend, with the averages of each question being in the desirable end of each scale. For the second part of the questionnaire, we asked students to rate the level of difficulty of each phase of the design process. 7-point Likert scales were used, with a rating of 1 indicating that the phase was easy, and a 7 indicating that the phase was hard. Results are shown in fig. 5. As expected, the students perceive later phases as more difficult than the phases in the beginning of the design process. There is a twofold explanation for this phenomenon. Firstly, as part of their other courses, students are intimately familiar with general design phases such as concept generation, foam modeling, and cardboard prototyping. On the other hand, later phases of the design process simply pertain more engineering work and involve more specific knowledge.

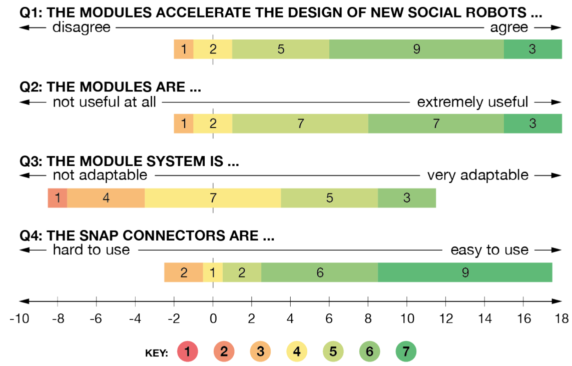

Fig. 4. Results of statement questions.

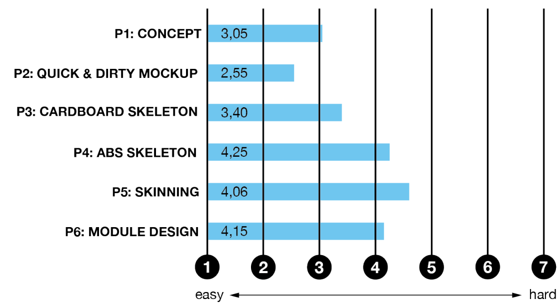

Fig. 5. Relative difficulty of each design phase.

V. Discussion and Future Work

One of the most noticeable shortcomings of our platform in this experiment is the adaptability of the modules themselves. Whereas the results indicate that the platform is flexible on a toolkit-level, this flexibility does not translate to the module-level. This observation is also supported by the result of Q3 of the questionnaire (fig. 5). We note a trend in the modifications that the students made to the modules: typically, these modifications were made to make the modules more compact at the expense of reduced functionality (e.g. eye-eyebrow module, eyebrow module as mouth). Consequently, future versions of the platform should include multiple alternatives for the same facial feature. Students also frequently changed the length of the levers of the mouth and eyebrow modules. It is evident why this modification is so common: the geometry of the robot's face directly influences how far the levers need to reach. Within this study, the lever design files were modified manually. However, future versions of the platform should anticipate this change. In general, future module versions should be less prescriptive in their intended use and should be easier to modify and hack.

Two groups (fig. 3 G & J) incorporated LEDs in the design of their robot. In previous experiments, we worked with autistic children. In this context, displays and LEDs are a hindrance to social interaction, hence why they were avoided in the design of the platform. However, the two student designs did show the merits of using LEDs to increase the expressive range of robots in their respective contexts. Consequently, support for addressable RGB LEDs (i.e. NeoPixels) has been added to the latest iteration of the platform's electronics.

The actuation of very large or very strong mechanisms (e.g. arm, neck) proved to be a third point of friction during the experiment. As discussed in section II, the OPSORO platform is built around low-cost hobby RC servos. While these servos are more than sufficient for the actuation of facial features, they are much less suitable for large or strong movements. Students used multiple strategies to work around this problem. Some groups (fig. 3 B, E, F) employed a 3D printed screw mechanism to gain enough mechanical advantage to move their neck. Others (fig. 3 D, I, J) attached lightweight, flexible arms to the end of joint modules. This way, if a user pushes down on an arm, the arm itself bends, and the servo is protected from excessive torque. A final case of note is Pillo (fig. 3 H). Originally, the robot was intended to have arms so it could embrace the user. In the end, the arms proved to be too troublesome, so instead the team opted to eliminate arms and instead focus on adapting the shape of the torso in order to insinuate and stimulate hugging behavior.

The experiment also revealed a number of noteworthy aspects concerning the methodology used in class. First of all, using a limited number of shared modules yielded interesting effects, both positive and negative. On the plus side, by limiting the available modules to two "full" toolkits, we forced the different student groups to collaborate. The result of this approach was that the students' module designs tend to be generic and much less bound to a single specific robot. Most of these new modules were used for multiple robots. A second advantage is that students had to take the (dis)assembly into account, seeing that they would have to add/remove the modules many times over the duration of the course. The main downside of this approach is that the limited number of modules ended up being a bottleneck in the design process, seeing that much time was lost by disassembling and reassembling robots. A better balance needs to be found between the number of groups and the number of available sets of modules; two complete sets for ten groups is simply too little.

We also noticed that our approach to alternate between low-fi (foam and cardboard mockups) and high-fi (laser cutting) prototyping worked out well. Our impression is that this encourages students to fail early and often. Potentially fatal problems are thus caught much sooner in the design process. The way students used their foam mockups to test the size and position of modules is an example of this. While the benefits of iterative design are well known within HCI, the complexity of robotics design makes it tempting to use a waterfall design approach, where a robot is designed, built, and tested in a single iteration, meaning that mistakes are only discovered at the end. We have observed that our method avoids this pitfall.

Thirdly, the questionnaire results indicate that the ABS skeleton phase, the skinning phase, and the module design phase are experienced as the most difficult parts of the design process (fig. 5). As mentioned earlier, the students' designs pointed out a number of shortcomings in the current selection of modules in the platform. We hope that an expanded set of modules will eliminate the need for custom designed modules in most cases. With respect to phases 4 and 5, we believe that a software tool, in the form of a specialized computer-aided design (CAD) program or plugin, could simplify these phases significantly. The design of a skeletal frame involves a large amount of work to draw up in CAD, but much of this work is completely formulaic in nature, requiring very little creativity, and would be an ideal candidate for automation. We envision this software as a more advanced version of 123D Make, where the user could load a 3D model of the outer shape, and then input the position of each required module. The software could then generate a skeleton for that specific embodiment, automatically adding features such as snap connectors, part numbering, and module mounting locations. Finally, dividing and flattening the outer shell, similar to UV mapping used in computer graphics, could easily generate skin and foam patterns.

In conclusion, we argue that the work presented in this paper represents an important step toward a modular design approach for custom social robots. As discussed, many of the opportunities for the field of social robotics rely upon inexpensive, yet highly customizable robots, tailored to niche applications. Within the scope of this study, we showed that our platform enables non-experts to design and construct new social robot embodiments. While our study has a number of limitations (e.g. limited number of participants, no control group), we feel that the results do adequately show that our platform enables and accelerates the design process of social robots. Furthermore, the students' designs show a widely varied ecosystem of robot types, all created from the same set of parts. The students' results demonstrated interesting additions to the platform, many of which we hope to incorporate in future iterations of the platform.

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