

Design and Evaluation of a DIY Construction System for Educational Robot Kits

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Abstract

Building a robot from scratch in an educational context can be a challenging prospect. While a multitude of projects exist that simplify the electronics and software aspects of a robot, the same cannot be said for construction systems for robotics. In this paper, we present our efforts to create a low-cost do-it-yourself construction system for small robots. We have created three different construction systems (laser-cut screw connectors, printed friction-fit connectors, and printed hybrid connectors) using small aluminium T-slot extrusions, based on prior work done by Industrial Design college students. Eighty-six secondary school students and 35 teachers tested these three systems during a five-day robotics contest where they had to build firefighting robots. Follow-up questionnaires and an expert evaluation were used to measure the usability, affective appraisal and functionality of the three systems in order to determine which system should serve as a basis for further design iterations. Overall, a clear preference was shown for the hybrid system, which relies on its interlocking shape as well as on a screw connection to create robot frames that are both quick to construct and very rigid once assembled. We believe our work represents a solid first step toward an inexpensive, "hackable" construction system for educational robotics.

Keywords

Educational Robotics, STEM, DIY, User Experience, Construction System, 3D printing

Introduction

In recent years, education has been characterized by a renewed focus on Science, Technology, Engineering and Math (STEM) skills. This interest is driven by a society in which technology takes an increasingly significant role in everyday life (Schmidt & Cohen 2013). This does not only result in a high demand for STEM skills on the job market (Sabadash 2012), it also means that technological literacy is increasingly becoming a necessary life skill for everyone (Bybee 2000).

Traditionally, STEM topics are often taught in an ex-cathedra format, where the teacher talks and the students listen. However, many argue that a constructionist learning approach, where students learn by doing instead of by listening, is advantageous because it leads to more motivated students and a deeper understanding of the subject at hand (Kafai & Resnick 1996; Papert 1980; Stager 2005). In fact, Hake (1998) shows that switching to any type of interactive teaching method, as opposed to traditional teaching, leads to an increase in learning outcomes in introductory physics courses by 108%.

In STEM fields, in particular, this method is gaining traction: examples include (Fortus & Krajcik 2005; Kolodner & Camp 2003; McPherson 2014; Rockland et al. 2010; Törnkvist 1998). Technology is evolving at an ever-increasing pace, and it is no longer sufficient to just be able to memorize and reproduce factual knowledge. Instead, a deeper understanding of knowledge and the ability to apply knowledge and skills in a real world context are becoming increasingly important. It is in these aspects, in particular, that the project-based learning (PBL) approach excels (Capraro et al. 2013).

Teachers frequently choose robotics as a subject for STEM-focused PBL. The reason for this is obvious: as Benitti et al. (2012) and Johnson (2003) show, teaching robotics is a very effective way of motivating and supporting many areas of the curriculum. Furthermore, it also stimulates students' social and teamwork skills. As a secondary aspect, robots are something that captures the imagination of many children.

One of the most common ways of implementing robotics in the school curriculum is through the use of commercial robot kits. LEGO Mindstorms, a system that combines common LEGO Technic bricks with sensors, motors, and a programmable logic brick, is a popular example of such a kit. LEGO Mindstorms is already being used in many classrooms, both at K-12 (Church et al. 2010; Williams et al. 2012) and at university level (Brandt & Colton 2008; Ranganathan 2008). Thanks to its ease of use and large user base, books, workshops, tutorials, and lesson preparations are readily available. Despite these advantages, we believe the main downside of these commercial robot kits lies in their fixed, closed nature. While commercial kits accelerate the process of getting up and running, they also limit the maximum potential of the robots. A simple example of this would be the number of motors in LEGO Mindstorms: the programmable brick can only drive three motors, but sometimes students want to use more, which is not possible. Users are also limited to the components offered by the kit, and interfacing with third-party components is hard, actively discouraged, or outright impossible.

The alternative to using a commercial robot kit is building a robot from scratch. In the past, this would have meant selecting microcontroller and motor driver chips, developing a printed circuit board, CNC milling a custom chassis for the robot, and finally programming the robot in low-level languages such as assembly or C. In recent years, however, a number of projects have come about that greatly simplify this

process: they provide flexible, yet user-friendly solutions to each of the sub-problems presented in robotics. A complete robotics platform can be seen as the combination of three distinct elements: (1) a set of electronics, (2) a programming environment (software), and (3) construction elements for a physical embodiment. Projects such as Arduino¹ and Raspberry Pi² (electronics), Scratch³ and Blockly⁴ (programming), and BitBeam⁵ and MakeBlock⁶ (construction) provide an intermediate solution between building from scratch and using a commercial kit (Vandeveldt et al. 2013). In doing so, they provide user-friendly tools for educational robotics that can potentially lead to a deeper learning experience. While this approach is already successful and widely used in software and electronics, common construction systems are still lacking. The choices for robot construction systems are not quite as diverse as those available for software and electronics. Consequently, the options that remain are either (1) to use one of the few purpose-built systems (e.g. MakeBlock, BitBeam), (2) to modify toy construction systems (e.g. LEGO, Meccano), or (3) to build a robot embodiment from scratch using raw materials. Often, cost and availability of parts are the main obstacles here. In our opinion, none of the approaches are analogous to what is offered in the other categories: platforms that allow novices to work with complex technologies in a user-friendly way, but that also allow advanced users to modify, extend, and hack the platform beyond its original capabilities. More research into the specifications of DIY robot construction systems is important here. In our work, we emphasize the role of user experience and user-friendliness precisely because we think those are decisive factors in the success of an open construction system.

The work presented in this paper is part of a larger effort to address this issue. Our goal is to create an extendable construction system that can be used in conjunction with electronics and software to build small robots from scratch. Influenced by the apparent flaws of existing approaches, we paid special attention to two key aspects. First of all, cost is often a barrier in the implementation of robotics in education (Gonzalez-Gomez et al. 2012; Johnson 2003; Mataric et al. 2007; Mondada et al. 2009; Riojas et al. 2012). As such, we have made a conscious effort to reduce cost without limiting functionality by repurposing standard components and by using affordable low-volume production methods. Secondly, we aim to make our system open (i.e. "hackable", suitable for DIY), meaning anyone should be able to modify and expand the system. In order to meet this requirement, we have restricted manufacturing techniques to those that can commonly be found in FabLabs (Walter-Herrmann & Büching 2013), e.g. 3D printers and laser cutters. While mass production techniques, such as injection moulding, can produce parts at a much lower cost, they would significantly hinder the ability for anyone to customize parts due to the costs associated with tooling and moulds.

Even if there are no FabLabs in the vicinity, online services (e.g. Shapeways, Ponoko, 3D Hubs) offer complete access to digital fabrication techniques. However, creating parts at a FabLab has the added benefit of bringing students and teachers in contact with a new environment that offers a plethora of STEM teaching opportunities

¹ <http://www.arduino.cc>

² <http://www.raspberrypi.org>

³ <http://scratch.mit.edu>

⁴ <http://code.google.com/p/blockly/>

⁵ <http://bitbeam.org>

⁶ <http://www.makeblock.cc>

(Blikstein 2013). It should also be noted that the two aspects mentioned above are, in fact, interrelated. By designing the system so that students can manufacture their own parts at a local FabLab, costs can be greatly reduced. Additionally, the students become familiar with the manufacturing process, lowering the barrier to modify existing designs into custom components and introducing them to the DIY culture.

The following sections will detail the design and evaluation of this construction system. The project has undergone two design iterations, resulting in three distinct construction systems. The three systems were given to students and teachers to be used in a robotics contest. Subsequently, the systems were evaluated on three aspects, usability, affective appraisal, and functionality, through (1) surveys filled out by the participants of the contest and (2) through an expert evaluation. Based on this information, we have chosen one system to be used as the basis for the next design iteration, incorporating feedback from both the user surveys and the expert evaluation.

Robots to motivate students into STEM

In the summer of 2013, Dwengo VZW⁷ launched the CERrobotics⁸ project in Argentina. Within this project, which was co-funded by the Google RISE 2013 program, students and teachers were trained to build robots. The idea is that by hands-on experience, students and teachers evolve from being consumers to technology producers. In total, 86 students (aged 11-18) and 35 teachers participated. The project took place in the Salta province in northern Argentina. Due to the geographical location and low budgets, these students had minimal access to the latest technologies. For these students, robotics and the combination of electronics, mechanics, and programming was a completely new experience.



Figure 1. Playfields used during the contest. The left playfield has a light-to-dark gradient on the floor to guide robots toward the flame. The right playfield has a bright spotlight above the flame to aid the robots in navigation.

At the end of the hands-on sessions, a robot contest was organized with the challenge of designing a firefighting robot. Participants were given five days to create a robot that can autonomously navigate around obstacles towards a fire – represented by a lit candle – and extinguish it. In order to persuade students to explore different solutions,

⁷ <http://www.dwengo.org> – A non-profit organisation that promotes science and technology.

⁸ <http://www.youtube.com/watch?v=jP-G1OrR5Ng> – CERrobotics project documentary.

two different playfields (fig. 1) were provided. The first (fig. 1 left) has a gradient floor, so grey scale sensors can be used to determine the distance of the robot to the candle. The second (fig. 1 right) has a spotlight above the candle pointed towards the robot, which can be detected using IR sensors.

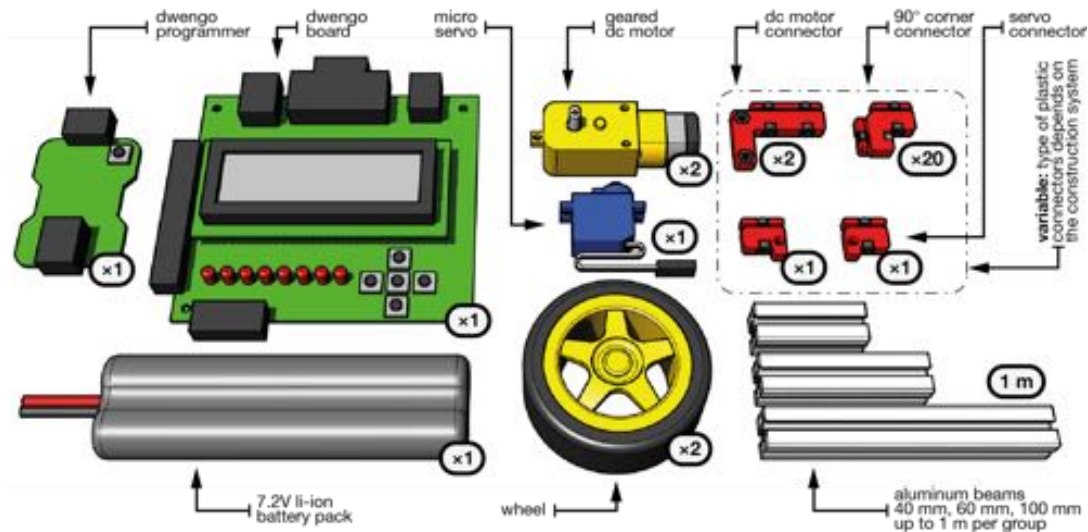


Figure 2. The robot kit used in the contest contains a microcontroller board and programmer, a battery, 2 geared DC motors, 1 RC servo, 2 wheels, 1 m of aluminium extrusions, and a set of plastic connectors. The type of connectors (shown in red) changes between the three systems.

In total, 86 students and 35 teachers participated in the project. They were divided into teams of two to three and were given a kit with building materials for their robots. Teams consisted solely of either teachers or students; there were no mixed teams. The kit (fig. 2) consisted of the following items:

- 1x Dwengo Board (Wyffels et al. 2010, 2012) (a microcontroller board with provisions to control 2 DC motors and 2 RC servos, along with multiple sensors).
- 1x programmer with USB cable.
- 1x battery pack.
- 2x geared DC motors with wheels.
- 2x IR sensors.
- 1x fan and balloons (either of which can be used to extinguish the candle).
- Aluminium beams: participants were free to select pre-cut pieces of 40mm, 60mm, and 100mm. A total length of 1m was provided per team. No team opted to cut beams of custom length.
- Plastic connectors, type depending on the system assigned to the team: 2 motor connectors, 1 pair of servo connectors and 20 90° corner connectors. More connectors were available, if needed.
- Miscellaneous items, such as nuts, screws and wires.

To successfully build a firefighting robot, it is important to master the basics of many STEM disciplines. Knowledge of materials, mechanisms and mechanical engineering principles are essential skills for building the physical embodiment of the robot, while

the electronics require insight into electricity and physics. Finally, to program the robot, subjects such as computer science, mathematics, and algorithmic thinking are required. As such, we believe robotics contests such as this one have great educational value because they teach the basic principles of engineering, programming and electronics in a fun and engaging context (Osborne et al. 2010; Pack & Avanzato 2004; Verner & Ahlgren 2004; Wyffels et al. 2010).

Design of the Building Systems

We have created our systems primarily to facilitate the design and construction of small educational robots. As such, the design decisions we have made resulted in systems that are much better suited for building small wheeled robots as opposed to flying drones, or even humanoid robots. At the start of the design process, we decided to build our construction system around standardized 15x15 mm aluminium T-slot extrusions. We based this decision on a number of factors:

- By relying on these aluminium extrusions, the only custom components required are small connector pieces. These can be quickly and easily manufactured using a laser cutter or a 3D printer. This strategy greatly improves the machine time required to produce a kit.
- Because of the T-slots, components can be fastened at any arbitrary spot along the length of the extrusion. Systems that rely on beams with regularly spaced holes (e.g. Lego Technic, BitBeam) do not offer this advantage.
- They are compatible with standard M3 fasteners, as opposed to larger size extrusions, which generally use proprietary nuts and bolts.
- Aluminium is stronger and more robust than common types of plastics (such as ABS or PP).
- They are inexpensive (€8.60 for a length of 2 m) and can be bought from multiple suppliers (e.g. Misumi, OpenBeam).

As mentioned earlier, one of the goals of this project is to create a system that is accessible and easy to (re)produce. As such, we have limited ourselves to tools and machines that are commonly found in FabLabs.

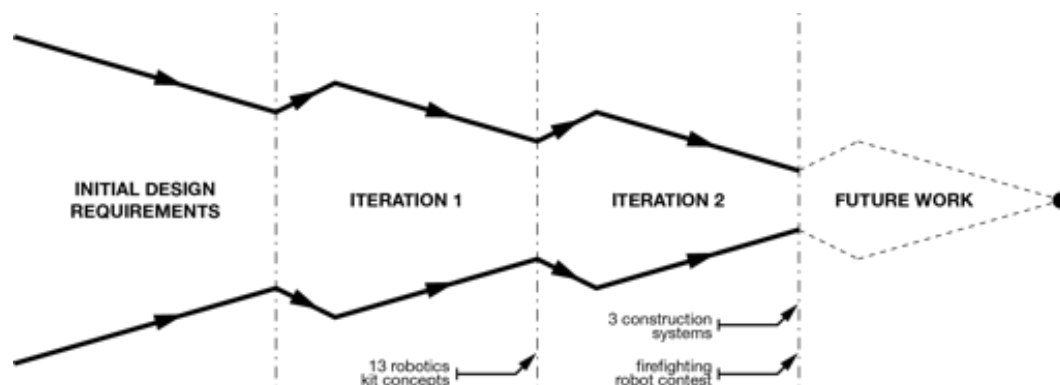


Figure 3. Design Funnel – schematic overview of our design process. Adapted from (Buxton 2010, p. 148; Pugh 1991, p. 75).

Our design approach (fig. 3) can be approximated by the Pugh's Design Funnel model (Pugh 1991), with two iterations of divergent and convergent ideation. The initial design requirements can be summarized as; (1) An open DIY construction system for

robot kits (2) producible with common facilities in FabLabs (e.g. hand tools, laser cutters and basic 3D printers) (3) using the standard 15 x 15 aluminium T-slot extrusions. An exploratory first iteration was done in conjunction with 2nd year Industrial Design students at Ghent University. As an assignment for one of the courses, they were required to design a kit, based on the aluminium beams that could be used to build 2 different robots. Altogether, the students designed 13 different robot kits. Figure 4 shows some of the robots they created.

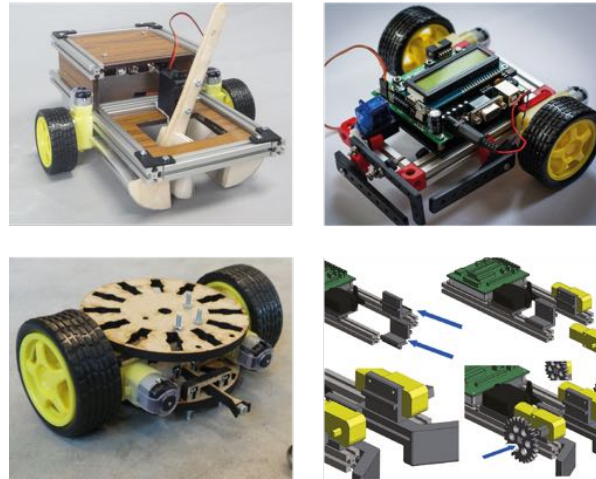


Figure 4. Student designs from iteration one.

A number of conclusions were drawn from the students' kits. None of the connection systems they designed were suitable for a larger scale experiment. Some of the connectors showed a lack of strength, some required too much manual labour to produce, and some were simply too limited. At a certain point in their design process, the students needed to come up with a type of reversible connector to guarantee the modularity of their kits. In retrospect, we think this step was the critical moment that determined the quality of the kits they designed. For this reason, we decided to focus solely on designing modular connectors in the second iteration. It is from this iteration that we generated the three systems that were used in the robotics contest. For each system, we designed a 90° corner connector (which allows for both corner- and T-connections), a servo connector, and a DC motor connector. The principle behind each system is highly adaptable, and new connectors, based on the same principle, can be easily designed to accommodate specific sensors, larger motors, etc. The adaptability of the connectors and the continuous mounting positions offered by the aluminium beams together result in a high degree of flexibility in the three construction systems. Figure 5 shows some of the divergent and convergent prototypes created in iteration two. Some of the "abandoned" prototypes are also shown in this picture. For instance, one concept relied on a lever mechanism to lock the connector into place. However, forces generated by the lever caused the printed part to delaminate, and no effective solution could be found for this problem.

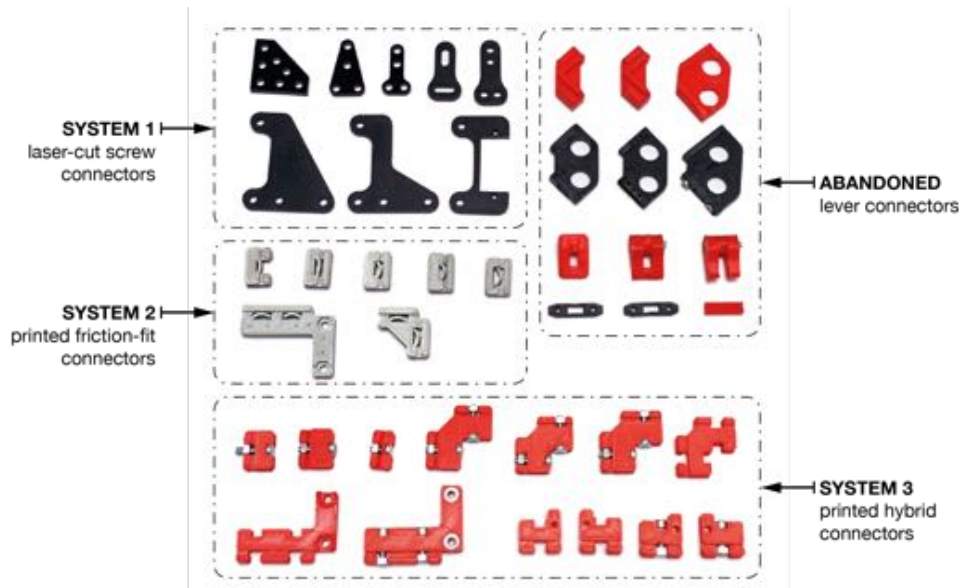


Figure 5. Prototypes from iteration two.

The final design files of the three systems can be found in our GitHub repository⁹. The parts for system 1 were laser-cut from 3mm sheets of ABS plastic. ABS was chosen because the material is strong, but not brittle and because it can be cut easily and cleanly using a 40W laser cutter. Systems 2 and 3, which were designed to be 3D printed, were printed on an Ultimaker 1 using PLA plastic with a layer height of 0.1mm and an infill density of 20%. PLA was chosen because of its ubiquity in low-end 3D printers and because the material can be printed without a heated bed. However, the pieces can also be printed in ABS, if desired. Systems 1 and 3 rely on M3 nuts and screws for their functionality. Either hex socket cap screws or cross-recessed pan screws can be used, though the former is preferred. Hex socket cap screws offer two advantages: (1) they are more durable (less prone to stripping), and (2) they can be tightened at an angle using a ball-end hex key. Since we had difficulty buying this type of screw in Argentina, cross-recessed screws were used during the contest. They work just as well, but are more cumbersome to work with in tight spaces.

System 1: Laser-cut Screw Connectors

System 1 relies on laser cutting as the sole production technique. In this context, the main advantage of laser cutting is its speed: all the parts required for 10 teams were produced in two hours, whereas the parts for the other systems took over a week, each using 3D printing. The main design limitation of laser cutting is that materials can only be cut from one direction, so only flat shapes can be produced.

The construction system we created using this technique relies on small T-shaped gusset plates to connect aluminium beams (fig. 6). The gusset plates contain four holes each, which are used to screw the plates to the aluminium extrusions. Two screws are used per beam to ensure that the beams cannot rotate in respect of one another. The aluminium extrusions we chose are well suited for this application as the T-slots of the extrusions can accommodate standard M3 nuts. Alternatively, the corner plates can also be used in conjunction with the threaded holes at the end of each beam to create a connection between beams.

⁹ <https://github.com/cesarvandevelde/RobotBlocks>

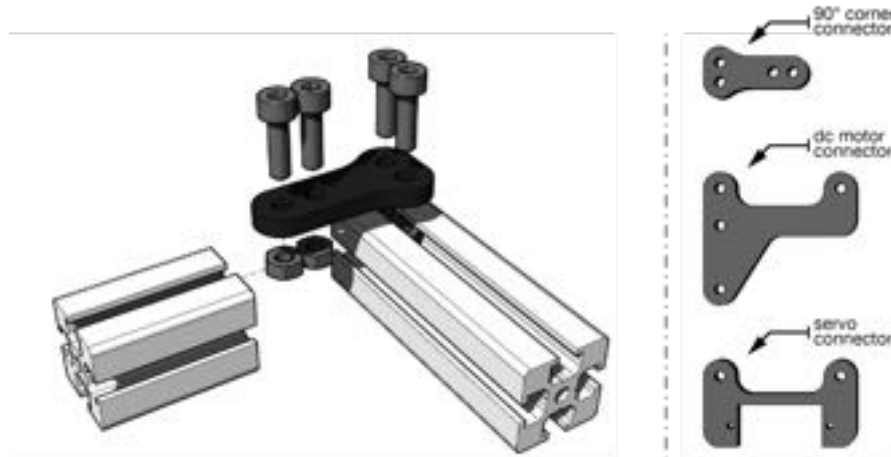


Figure 6. Laser-cut screw connector system.

To make a corner connection between two beams, two nuts need to be inserted into each beam first. Then, a gusset plate is positioned over the nuts, and screws are inserted in the four holes. Adjustment is possible by shifting the parts around in their T-slots. Finally, the connection is secured in place by tightening the screws.

This system relies on nuts and screws to create a rigid connection. While this method is reliable and low-cost, changing the construction takes some time and, therefore, limits the scope for rapid iterations of different designs.

System 2: Printed Friction-fit Connectors

For the second construction system, we wanted a type of connection that is very quick to use in order to encourage quick design iterations in the robotics contest. Consequently, our second connection system relies solely on friction to connect pieces together. The corner pieces of this system have two sets of grooves that match the profile of the T-slots in the aluminium beams (fig. 7). To create a connection, two beams are simply slotted into a corner piece with sufficient force. The drawback of this approach is that the friction force limits the amount of force that each corner can absorb.

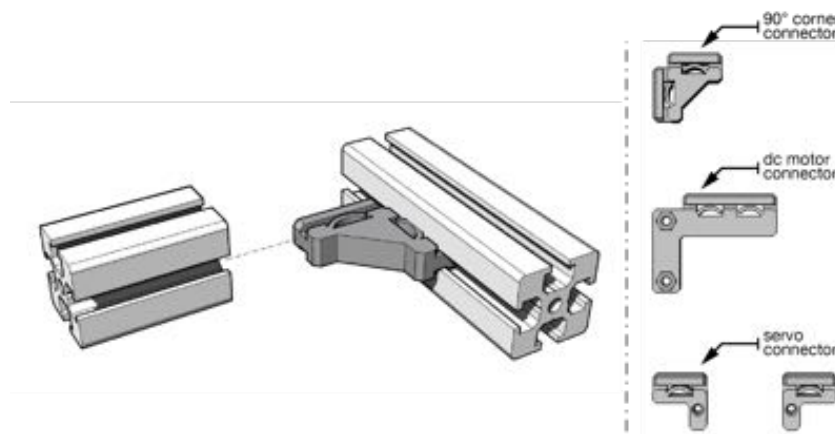


Figure 7. Printed friction-fit connector system.

The plastic pieces of this system were designed to be printable on a low-cost 3D printer (e.g. a RepRap, or in our case, an Ultimaker). Designing for this category of

3D printers poses several limitations from which professional 3D printers do not suffer. One of the main challenges is that low-end 3D printers typically do not have a second print head to deposit support material. This means that features such as undercuts need to be carefully designed so that they are self-supporting. Parts of this system can be printed with minimal overhangs by laying them flat on their side. The only overhangs – the bottom grooves – can be printed because both edges are supported.

The second challenge we encountered while designing this building system was to find a good way of reliably creating a friction-fit connection. The tolerances of parts produced on DIY 3D printers depend on many factors, including the construction and calibration of the machine, the quality of the plastic filament used, and even the ambient temperature. As such, a simple groove with correct sub-millimetre dimensions is not a feasible way to achieve a friction fit. Our solution was to incorporate a spring-like feature in the printed parts. The purpose of this spring is to create tension between the groove of the printed part and the surface of the aluminium beam. This design allows for much wider tolerances. The spring-like feature also takes advantage of the anisotropic nature of 3D printed objects: the springs flex in the horizontal plane, which is the strongest direction in Fused Deposition Modelled (FDM) parts because it does not depend on interlayer adhesion.

System 3: Printed "Hybrid" Connectors

In the design of third system, we wanted to strike a balance between the strength and robustness of the laser-cut screw connectors and the ease of assembly of the printed friction-fit connectors. This hybrid system combines the groove mounting system of system 2 with the nut and screw connection of system 1. In practice, this means that users can quickly try out new ideas by sliding connector pieces into the T-slots of the beams. Once they are securely in place, the connection can be fixed by tightening the two screws.

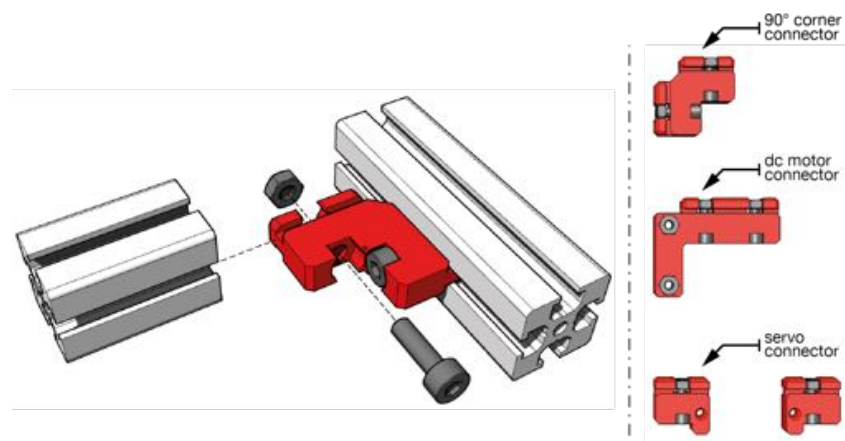


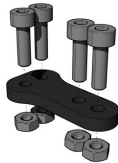

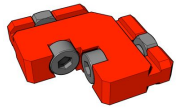
Figure 8. Printed "hybrid" connector system.

The connector itself consists of a printed plastic part, two nuts, and two screws. The basic shape of the corner connector is similar to the one from the friction-fit system, with grooves to accommodate the T-slot channels of the aluminium beams (fig. 8). Additionally, each side has a circular hole ending with a hexagonal cut-out, which holds a nut and screw in place. The nut sits in the hexagonal cut-out and is positioned in line with the ridge that slides into the T-slot channel of an aluminium beam. This

connector can be inserted into the extrusions with the fasteners already in place, resulting in a substantial speed gain over the laser-cut screw connectors.

As with the previous building system, a number of properties of low-end 3D printing are utilized: the parts can be printed without the use of support material, they are designed with wide tolerances in mind, and they can be oriented so that inter-layer forces are reduced to a minimum. Table 1 shows a summary of the properties of the three systems.

Table 1. Comparison of the three building systems

	<i>System 1</i>	<i>System 2</i>	<i>System 3</i>
			
Production technique	Laser cutting	3D printing	3D printing
Material	3mm ABS sheet	PLA	PLA
Production time per piece	< 1 min.	15 min.	15 min.
Connection method	screw	friction	friction + screw
Extra hardware per connector	4 M3x6 screws 4 M3 nuts	none	2 M3x10 screws 2 M3 nuts

Measuring Usability, Affective Appraisal, and Functionality

The main objective of our evaluation is twofold. Firstly, we wanted to determine which of the three systems is most appropriate for use in educational robotics. Secondly, we wanted to establish the next steps to further improve that system. To this end, we focused on three key aspects during our evaluation process. These aspects are (1) the usability (i.e. are the blocks easy to use?), (2) the affective appraisal (i.e. what is the perceived emotional value for users?), and (3) the functionality (i.e. how versatile are they, how well do they perform?).

The tools we selected to measure the above-mentioned aspects were subject to a number of constraints. We chose tools that are short and quick to fill out, that are unambiguous, and that can be completed through an online survey tool. Consequently, we chose the following three tools:

1. The System Usability Scale questionnaire (Brooke 1996). This questionnaire consists of 10 questions with 5 response options. Using a scoring key, the responses to these questions can be compiled into a single number between 0 and 100, which corresponds to the usability of a product or system.
2. The Pick-A-Mood tool (Desmet et al. 2012; Vastenburg et al. 2011). This is a set of nine cartoon drawings of different facial expressions. Users are asked to choose the drawing that best represents their mood during the course of the project. This tool is used to measure the affective appraisal of the different building systems.
3. The AttrakDiff tool (Hassenzahl et al. 2003). This questionnaire consists of a list of 28 antonym pairs (e.g. unimaginative – creative). Respondents are asked to pick a position on a seven-point scale to indicate where they believe the product is positioned between the two antonyms. Using these word pairs, four product dimensions are calculated: pragmatic quality (corresponds to usability,

how easily can a user complete their goals with the product?), hedonic stimulation (to what extent does the product stimulate the user's personal growth?), hedonic identification (to what extent do users identify with a product in a social context?), and attractiveness (a global measure of appeal to the user). Pragmatic and hedonic qualities are independent from each other and contribute equally to a product's attractiveness.

Additionally, we also asked respondents to indicate their age, gender, and the colour (which corresponds to the type) of the building blocks they used. Finally, we provided two open text areas where we asked what they liked, and disliked, about the system.

The questionnaire was given at the end of the event, after the final contest. We asked that only the persons who actively participated in the mechanical construction process complete the survey, as the survey relates to the robot building blocks. In most teams, one person was responsible for building the physical embodiment, while the others focused on the electronics and the programming. Consequently, in those cases, only one questionnaire was completed per team. In rare cases where multiple participants worked on the mechanics, they each filled in a separate survey.

While our questionnaire certainly measures usability and affective appraisal, functionality is not measured as explicitly. For that reason, we also conducted an expert evaluation. We asked six experts – teachers and coaches who are frequently involved in educational robotics – to participate in a two-part study. The experts were chosen for both their experience in teaching and their knowledge regarding the design of robotics. In the first part, they were asked to indicate which aspects they consider when evaluating robots. They were then shown short (less than 1 minute) video clips of 17 robots built during the CERobotics contest, and were asked to give each of them a score between 1 and 9. For the second part, the experts were given the opportunity to experiment with the three different systems. Subsequently, they were asked to rank the systems in their order of preference, and to write down any additional comments they had. While evaluation through video files certainly has its limitations, we feel that this approach, in combination with the responses from the open questions, do allow us to gain an insight into the functionality of each robot construction system.

Questionnaire Results

Of the 86 students and 35 teachers (121 participants total), 37 participants indicated they were actively involved in the mechanical building process and were asked to complete our questionnaire. This corresponds to a ratio of 30.6%. As mentioned above, one person per team completed the survey in most cases. At the start of the project, each group was assigned a building system in order to achieve an approximately even distribution (resp. 12, 12, 13) of the three systems. However, early on in the build process, several of the groups using the laser-cut screw system expressed their frustration with this system. They were, therefore, allowed to switch to a different building system of their choice, which resulted in a disproportionate distribution, where the laser-cut screw system was severely underrepresented as compared to the other systems. Four of the questionnaire respondents used the laser-cut screw system, 15 used the friction-fit system, and 18 used the hybrid system.

The average age of respondents is 18.5. However, this average is skewed because the groups consisted of a majority of secondary school students ($n = 32$) supplemented with a small group of teachers ($n = 5$). Average age of students was 16.1 ($\sigma = 1.65$); average age of teachers was 33.0 ($\sigma = 9.19$). Gender data show a male majority, with

27 male participants and 10 female participants. However, gender ratio skewness is not uncommon in robotics contests (Johnson 2003; Milto et al. 2002).

System Usability Scale

The results of the System Usability Survey showed an average SUS value of 80.8 ($\sigma = 14.6$) for all three systems combined. Bangor et al. (2008) calculated the average SUS value of 206 studies to be 69.69. A one-sided t-test at a significance value alpha of 0.05 indicates that the average value of 80.8 is statistically significantly different from the baseline value of 69.69, ($t = 4.621$, $p \ll 0.05$, 95% CI of the difference = [6.24, 16.001]).

To investigate differences in SUS scores among the three systems, a one-way ANOVA was performed. Inspection of the boxplots and the Kolmogorov's test ($p = 0.068 > 0.05$) suggests normality of the data. Moreover, the assumption of homogeneous variance was confirmed by Leven's test ($p = 0.261 > 0.05$). Based on the one-way ANOVA, with a significance level of 5%, ($F=0.007$, $p = 0.993 \gg 0.05$), we can state that there is not enough statistical evidence of difference in mean value of SUS among the three systems. We also performed a Kruskal-Wallis test, which confirms the result of the one-way ANOVA analysis ($p = 0.97 \gg 0.05$). This result is in contrast with our experiences early on in the project, where several groups switched from the laser-cut screw connector system to another system. A possible explanation is that only the users who were satisfied with the system remained, which would explain why no difference in usability is detected.

Indeed, two users of the laser-cut screw connector system indicated in the open questions that they had difficulty joining beams with this system. We think this is because the system is particularly sensitive to the order of assembly, because the nuts need to be inserted into the channels of the beams in advance. The main problems reported by users of the friction-fit system is that connection pieces require too much force the first time they are used, and that they are prone to loosening while in use. Users of the hybrid bricks reported only minor issues, such as the hexagonal openings for nuts being too small. In all three groups, users remarked that they would like a larger variety of different pieces. We suspect that the usability of systems 1 and 3 would have been slightly higher if hex socket cap screws were used instead of cross-recessed pan head screws, as described earlier.

Pictorial Mood Reporting Instrument

The second part of our survey uses the Pictorial Mood Reporting Instrument (Desmet et al. 2012; Vastenburg et al. 2011) to measure the overall mood participants experienced during the construction process of the robot. The facial expressions provided by this tool can be arranged on two axes, comparable to Russel's circumplex model of affect (Russel 1980). These axes are valence (pleasure - displeasure) and arousal (high energy - low energy). Figure 9 shows the moods reported by participants plotted on these two axes. Fisher's Exact Test (Fisher 1922) indicates that there is not enough statistical evidence ($p = 0.59 > 0.05$) to claim that there is a relationship between the type of building system used and the mood reported by the users. We think the low sample size is partially responsible for this. If we take the laser-cut connector pieces ($n = 4$) out of the equation, and cluster the moods in positive, neutral, and negative brackets (cfr. the valence axis in the circumplex model of affect (Russel 1980)), we do see a slight correlation ($p = 0.047 < 0.05$) between the building

system and the valence of the reported mood, with the hybrid connectors performing slightly better.

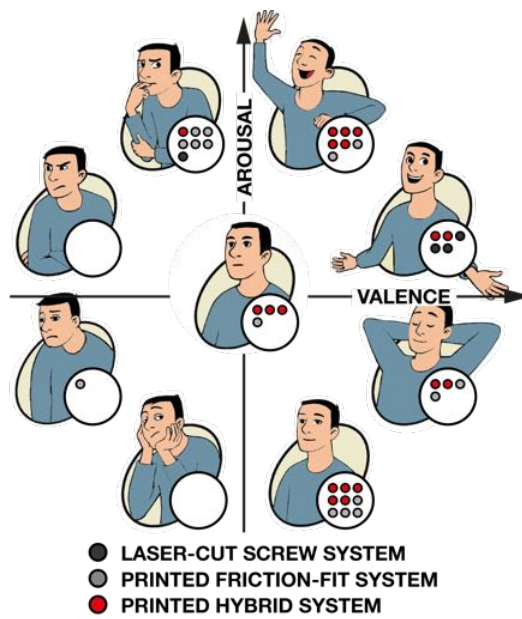


Figure 9. PMRI results, each dot represents the mood of one respondent.

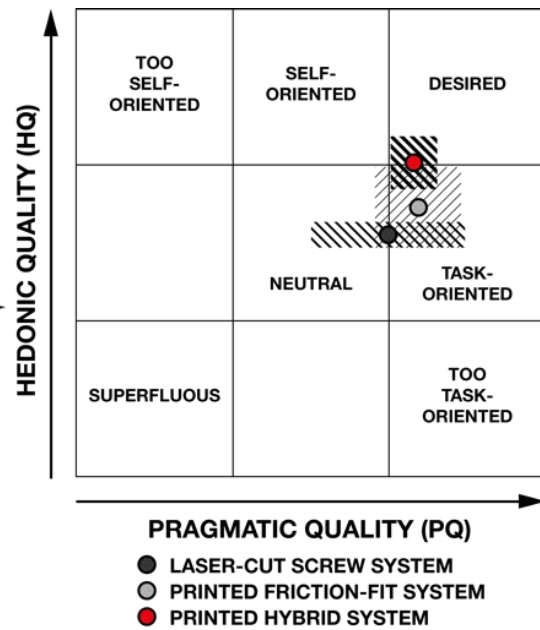


Figure 10. AttrakDiff results, the hatched area represents the confidence interval of each system.

AttrakDiff

The third part of our survey consists of the AttrakDiff questionnaire (Hassenzahl et al. 2003). The data was processed by means of the AttrakDiff online tool. Figure 10 shows the position and confidence rectangle of hedonic and pragmatic qualities of the three systems. Overall, we can say that the hybrid system scored better than the friction-fit system, which, in turn, scored better than the screw connector system. It should be noted that the large confidence interval of the laser-cut screw connectors is again a consequence of the low number of participants compared to the other two systems. The results from the AttrakDiff evaluation are in line with the feedback from the open questions and with our own subjective assessment. Although these results indicate that the hybrid system is the best of the three, there is still room for improvement.

Expert Evaluation

As a final part of our study, we performed an expert evaluation with six experts. In the first part of this evaluation, the experts were asked: "In your opinion, what criteria are important for grading mechatronics projects such as a robotics contest?" (Q1, fig. 11). The experts were then shown video clips of 17 different robots and were asked the following question: "Using the criteria and their importance you specified in the previous section (Q1), how would you rate the robots shown below?" Each robot could be rated individually using a 9-point scale, with 1 being the lowest and 9 being the highest rating. A 9-point scale was chosen to allow for more granular reporting than 5-point scales, while still offering a neutral position. Of the 17 robots, four were built using the laser-cut screw connector system, seven using the printed friction-fit

system, and six using the printed hybrid system. The results of Q2 (table 2) show an average score of 6.04 for robots built with the screw connector system, 4.52 for those built with the friction-fit system, and 6.75 for robots built using the hybrid system. While the sample size of this study is low, data does suggest that the use of the hybrid system tends to lead to better scoring robots.

In the last part of the expert evaluation (Q3), the experts were given samples of the three systems to experiment with. They were then asked to rank the systems in order of preference using three drop-down menus. Results of Q3 are shown in table 3. The hybrid system was ranked first the most (three times), followed by the friction-fit system (twice), and then the laser-cut system (only once). The experts frequently praised the ease of use of systems 2 and 3, but noted that the friction-fit system will probably loosen over time. In their comments, the experts also commended the laser-cut system for its simplicity and strength, remarking that it is a very cheap part to produce.

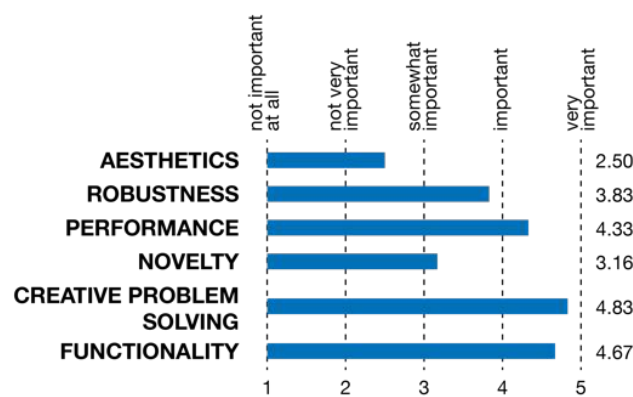


Figure 11. Q1 – Experts' criteria for grading robots.

Table 2. Q2 – Robot ratings

System	System 1: laser-cut screw connectors				System 2: printed friction-fit connectors						System 3: printed hybrid connectors						
Robot	H	M	O	P	A	B	C	E	F	J	K	D	G	I	L	N	Q
E ₁	9	2	9	2	8	2	6	2	2	2	2	6	2	8	6	9	8
E ₂	9	5	8	1	1	1	8	1	8	1	5	5	1	8	8	8	8
E ₃	8	5	8	5	2	2	7	3	6	4	6	5	3	7	7	8	8
E ₄	9	3	8	2	4	3	7	3	8	4	7	6	4	7	8	9	9
E ₅	8	5	8	3	4	4	6	4	7	5	6	6	6	9	8	8	9
E ₆	9	6	9	4	4	3	7	3	8	7	7	6	5	7	5	7	9
Avg.	8.67	4.33	8.33	2.83	3.83	2.5	6.83	2.67	6.5	3.83	5.5	5.67	3.5	7.67	7	8.17	8.5
	6.04				4.52						6.75						

Table 3. Q3 – Systems ranking by the experts

System	E ₁	E ₂	E ₃	E ₄	E ₅	E ₆
System 1: Laser-cut screw connectors	2 nd	2 nd	3 rd	2 nd	1 st	3 rd
System 2: Printed friction-fit connectors	3 rd	1 st	2 nd	3 rd	2 nd	1 st
System 3: Printed hybrid connectors	1 st	3 rd	1 st	1 st	3 rd	2 nd

Conclusion and Future Work

The results in this paper constitute a first step towards an open, Do-It-Yourself construction kit for small-scale robotics. We believe such a system has the potential of greatly complementing other efforts in educational robotics by providing a low-cost, "hackable" platform for building the physical embodiment of small robots.

We believe that the use of T-slotted aluminium beams helped us greatly toward this goal: they are low-cost, strong, and can be used to connect many different types of components. However, the downsides of this approach include the weight (the aluminium beams are heavier than their plastic counterparts) and their appearance (robots built with this system can be bulky and technical looking).

Of the three construction systems presented in this paper, we think the hybrid system is best suited to the context at hand. This conclusion is also supported by the results of our questionnaire. While feedback indicates that the friction-fit system is easy and pleasant to work with in the assembly phase, it does cause problems when the robot is used, due to failures of the connection under excessive force. On the other hand, the laser-cut screw system can be manufactured quickly and provides strong, firm connections. However, these connections are slow and difficult to use, resulting in frustrated users. The hybrid system strikes a balance between the strength and rigidity of a bolted connection and the ease of use of a friction-fit connection. Users can quickly try out different configurations by slotting the connectors in and out of the beams, and once they are happy, connectors can be locked into place by tensioning a single screw per side. We intend to move forward with the hybrid-construction system as a basis for our next design iteration.

A common point of criticism that applies to the three systems is that users want a larger variety of building blocks. We only provided three types of building blocks for this project: a 90° corner connector, a DC motor connector and a servo connector. While just these three types are adequate for building a firefighting robot, we recognize that this basic selection of blocks may have hindered the participants' creativity. Our first set of connectors provides only static connections, although we have every intention of creating components that allow for moving mechanisms, such as hinges, wheels and gears.

While on this subject, we would also like to involve the students in the manufacturing process of the building blocks. Due to logistical challenges, this was not possible for our robotics contest in Argentina. Instead, all components were manufactured and kitted beforehand. In future projects, we would like to give participants a starter kit, and provide them with the means (i.e. 3D printer, software, technical support) to print their own, custom building blocks that are compatible with the rest of the system. In addition to the potential for more advanced robot parts, Blikstein (2013) showed that FabLabs and digital fabrication offer many STEM-related teaching opportunities.

As a final point, we would like to continue improving our evaluation method. While we gained valuable insight through the use of questionnaires, we did still encounter some problems. We purposefully selected evaluation tools that are quick to fill out and avoided too many open questions, but we still noticed that some participants found the questionnaire too long. As an alternative, we would like to experiment with periodic evaluation forms, where we ask participants to fill out a very short survey at the end of each session.

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