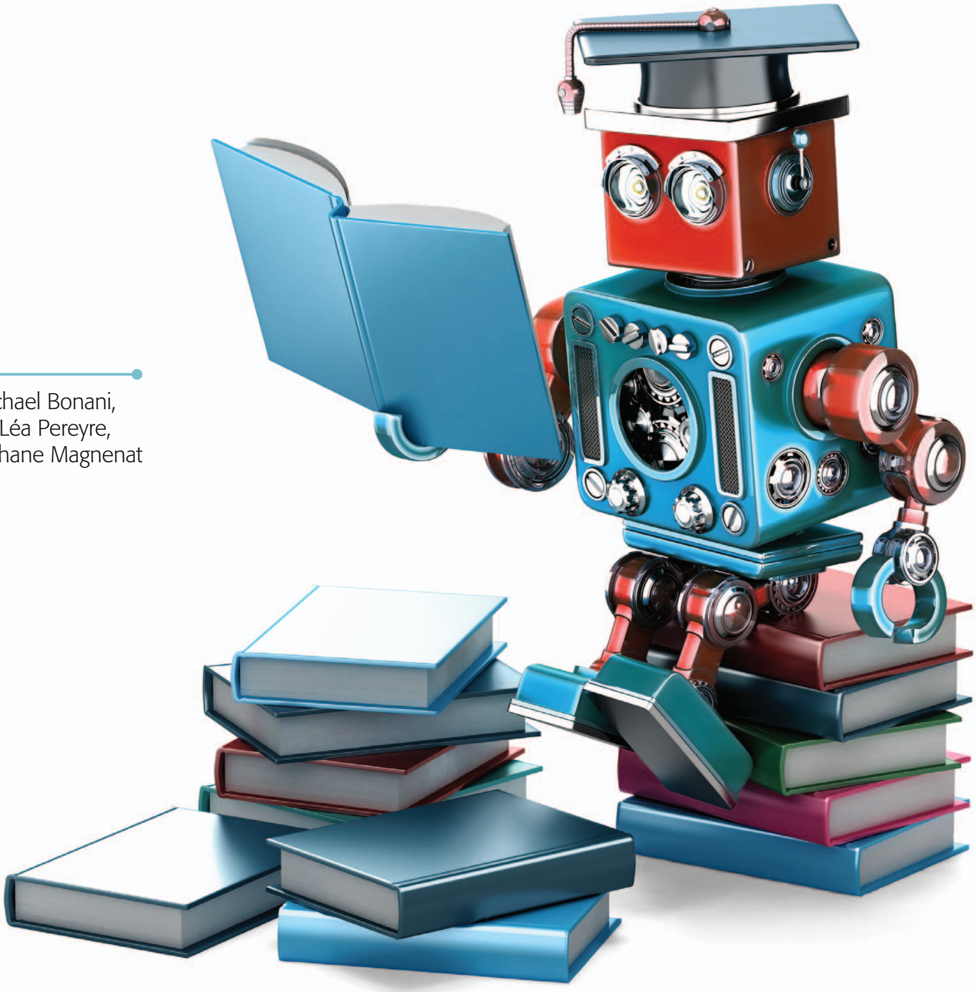
Bringing Robotics to Formal Education

The Thymio Open-Source Hardware Robot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Mobile robots are valuable tools for education because of both the enthusiasm they raise and the multidisciplinary nature of robotics technology. Mobile robots give access to a wide range of fields, such as complex mechanics, sensors, wireless transmission, mathematics, and computer science. However, despite their potential as educational tools, robots are still not as widespread in schools as they could be. In this article, we identify five key reasons: lack of diversity, high cost, noninclusive design, lack of educational material, and lack of stability over time. Then, we describe our answers to these problems, as we implemented them in the Thymio project: a mature mass-produced open-hardware robot, at a low price, with a multiage and gender-neutral feature set, and with a design promoting creativity, facilitating learning, and providing a wide range of interaction possibilities from built-in behaviors to text programming, passing through different visual programming environments. We highlight some neglected key issues that differentiate open-source hardware from open-source software, for instance the legal uncertainty of designing open hardware

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using professional computer-aided design (CAD) tools and the difficulty to distribute the development. Our solution to these being to increase the awareness of CAD editors to open-source hardware and to provide a two-layer development model for hardware.

Background

As mobile robots sense the environment and take actions based on their perception, they seem to display intentions of their own [1]. This impression of intelligence, the permeating presence of robots in science fiction, and their projected use in our society give a sense of touching the future. Among the possible reasons robots are not as widespread in schools as they could be, we believe that the following five play a key role:

1) Although many research projects are developing innovative and interesting educational robots, few reach sufficient maturity to become distributed and accessible to schools.
2) A versatile robot performing interesting behaviors is a complex piece of technology and, therefore, expensive. This prevents most schools, which have a limited budget for equipment, from acquiring educational robots.
3) Introducing robotic tools into teaching activities requires investment in time and training for the teachers [2]. Therefore, to be accepted by teachers, robots must be both accessible with minimal effort and accompanied by well-prepared educational material shared among colleagues.
4) Robot construction, use, and programming are often perceived as boyish activities in Western society [3], [4]. This strongly limits the potential of robots as general-purpose educational tools, especially in schools.
5) Finally, many teachers are reluctant to follow volatile trends, especially if these are based on purely commercial arguments. Teachers prefer to invest in stable tools, in contrast to trends in current consumer technology.

Open-source hardware projects can address several of these issues in a different way than closed-source, purely commercial products. By open-source hardware, we mean, following the definition of the Open Source Hardware Association (http://www.oshwa.org/definition/), "hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design." In this article, we show that this concept, implemented in the Thymio project through a community of users, developers, and manufacturers, brings a strong added value to the robot and to the educational methods. In addition, we compare our experience with other robotics open-source hardware projects not focused on education and highlight challenges and opportunities specific to education.

Related Work

Many publications present educational robots, from low-cost systems targeting Africa [5], [6] to extremely sophisticated humanoids [7], [8]. Among those, only a handful are commercially available, limiting their validation by educational scientists, who are typically not roboticists. As a result, 90% of publications about validation of educational results have been based on LEGO Mindstorms [9], a widely available commercial product. The latest version, EV3 (http://mindstorms.lego.com), is expensive ($\approx$ US$400) but offers a wide range of possibilities, especially at the mechanical level, using LEGO bricks, and at the software level with its graphical programming environment. Among the recent new players on the market is the Edison robot (https://meetedison.com/), which is extremely low cost (US$49), robust, and compatible with LEGO bricks. The low price has pushed drastic design choices: very few sensors, three buttons, two light-emitting diodes (LEDs) as the user interface, and a unidirectional communication with the computer by audio jack. These choices strongly limit its possible usage.

Among the robots available on the market, only a few are open source and used in schools: Scribbler2, produced and sold by Parallax (http://www.parallax.com) ($\approx$ US$180), is a large 188-mm robot, designed to move around on the ground and equipped with a few light sensors, one distance sensor, two ground sensors, and few LED displays. It runs on standard AA batteries and has a hacker port for interfacing electronic extensions. It is programmable with a graphical or a textual code interface. The main weakness of Scribbler2 is its limited number of sensors and compatibility with other systems. Moreover, there seems to be no active community around its development. The e-puck [10] robot targets university-level education. Well equipped with sensors and actuators, modular, and compact, it can be programmed with industry-standard environments. Several simulators allow running highly complex experiments. Its main weakness is its high price ($\approx$ US$870). Finch (http://www.finchrobot.com/) ($\approx$ US$99) is a very simple robot that has been designed around a wired connection to the computer. This connection reduces electronics requirements, such as batteries or wireless communication, and allows control to be implemented entirely on the computer. This results in availability of a very broad set of possible programming languages, which is the real strength of this robot. However, the cable does not allow real autonomy and mobility. Finally, the mBot (http://www.makeblock.cc/mbot/) is a mobile platform based on an Arduino board. Its electronics are simple and inexpensive, and the robot features only a couple of sensors, which allows drastic reduction in its price ($\approx$ US$75) but also limits the perception possibilities and therefore the span of use.

With respect to these robots, Thymio has a compact size (110 mm), many interaction possibilities, an affordable price (US$130), and a large set of sensors. To the best of our knowledge, beside Thymio, there are no educational products providing a similar integration of sensors and actuators at a lower price.

Teachers, from primary school up to high school, are a primary target user group of the Thymio project. They decide which tools are used in their class and are key people in the education ecosystem. For teachers, the motivation to use robotic tools depends on many factors [11]. Among them, the availability of materials and training plays a key role. The development of educational material and courses to train teachers requires a huge effort, based on a good mix between robotics and educational skills. Moreover, educational material varies from school to school, as requirements are very dependent on local educational programs and languages. A crowd-sourcing approach may solve this problem; an active community of users can contribute to the development of the material in a distributed manner, adapting the material to the local situation. LEGO itself is moving in this direction by promoting communities of users [12] with a user–producer interaction similar to that of open hardware projects. An open-source community regrouping developers, manufacturers, and end users is therefore a very interesting model to address the distributed development and sharing of educational material and the diffusion of training sessions. In this article, we study a case of implementation of this model.

Design Choices

We designed the Thymio robot along seven main axes: a low price to address a larger number of users; a feature set that suits both genders and multiple ages from young children to adults; a mechanical design that promotes creativity; a combination of sensors, actuators, and programming features that facilitates learning; a set of ready-to-use programs to quickly access robotic behaviors; an accessible programming environment; and an open-source community contributing to design and dissemination. The result is a miniature differential-wheeled robot suited for use on a desktop [Figure 1(a)]. The robot is robust enough to be mishandled by children; it can fall from a table without breaking. It features a translucent white hull and a wide range of sensors and actuators [Figure 1(b)]. The robot has an embedded battery, rechargeable by a universal serial bus (USB), that provides 3–5 h of power. More details on the robot and the previous research results can be found in [13], [14].

A Low Price

Price is key in the adoption of robots by schools [15]. Thus, the design of Thymio targeted low production costs while including a broad range of functionalities enabling flexibility. Because in this type of robot the main cost comes from electronics and sensors [16], we focused on low-cost sensors that allow rich interactions with both the environment and the user.

The resulting Thymio robot possesses a large number of simple sensors: seven horizontal proximity sensors, two infrared sensors pointing to the ground, a three-axis accelerometer, a thermistor, and a microphone. Five capacitive touch buttons organized as a direction pad form an intuitive user interface. Compared to physical buttons, these simplify the plastic hull of the robot and make it more robust. A remote control receiver provides additional distant buttons. Most of these devices cost less than US$0.20, the most expensive being the accelerometer with a cost of about US$0.80, which is an acceptable price given the possibilities it brings to the robot. We also chose low-cost toy motors and control them in speed (maximum of 13 cm/s) measuring the back-electromotive force.

We evaluated several microcontrollers and chose the PIC24F from Microchip because it integrates a USB interface and can drive capacitive touch buttons directly, saving additional components. This microcontroller controls all sensors

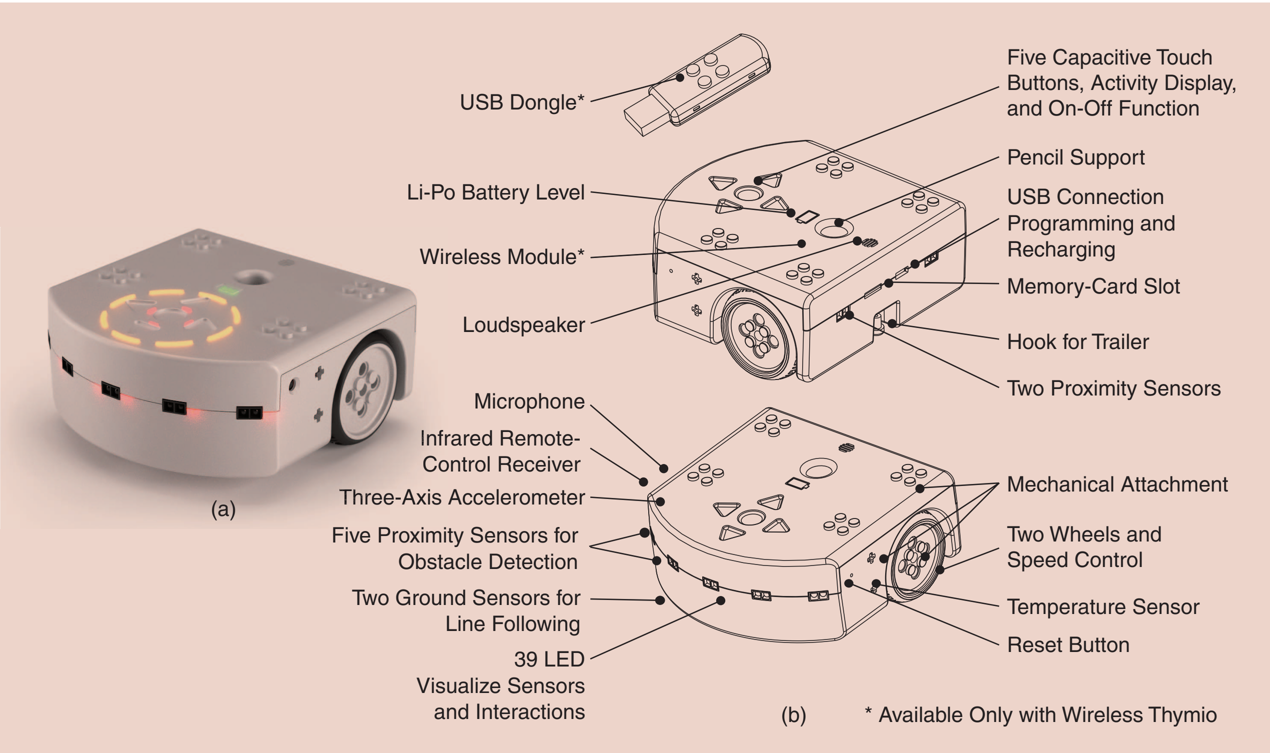

Figure 1. The Thymio robot and its main components for the wireless- and the USB-connected versions: (a) a rendering of the Thymio robot (courtesy of Ecole Cantonale d'Art de Lausanne) and (b) a list of key features of the robot. Li-Po: lithium polymer.

and actuators, with the exception of the internal lithium-polymer battery recharging logic, which uses a specific chip for safety reasons.

For our specific design, we needed custom-made mechanical parts. To reduce the price, all mechanical parts are injected plastic, for a total production cost of fewer than US$4.

Our choice of electronic components implies different degrees of automatization in the production. Full assembly is required for the robots to be certified for use by children. As full automatization requires investments that are beyond the possibilities of this project, the current production combines automatization for most components of the printed circuit board (PCB) and manual operations for the final assembly and is performed in China due to the low cost of manual work. We have thus far produced more than 16,000 robots in batches of 2,000 units, with a cost per robot of US$39. The strict quality control, the management of the production, the after-sales support, part of the development costs of the software, and the margins for distributors result in a final selling price of US$130.

Multiage and Gender-Neutral Feature Set

Several design choices, such as the variety of sensors, the multiple ways of interacting with the robot, the neutral hull design, the various programming environments, and the possible customization with accessories, contribute to make Thymio accessible to girls and boys of different age groups from kindergarten to university [17]. These design choices were made and implemented thanks to an important contribution by industrial designers of the University of Art and Design of Lausanne (http://www.ecal.ch). The white neutral hull is a key element in this set of choices, and it is the opposite of the technical look chosen for the LEGO robots. The look of Edison, designed after Thymio, is also technical due to its transparent cover. These latter two robots implicitly target a group of people interested in technical systems, mostly males, while Thymio is open to both genders and a larger target audience.

Promoting Creativity

The white neutral hull is also meant to represent a blank page that can be decorated and drawn upon, and the hull's shape allows easy integration into a larger structure. The square format of the hull facilitates the use of the robot as a base for the user's own constructions. To that end, Thymio is compatible with LEGO bricks, both on the body and on the wheels. This last connection can be used to actuate elements elsewhere in the added structure [Figure 2(e)] or to lift the robot's own weight (Figure 2(f)]. Therefore, we chose more powerful motors than strictly necessary to move the robot around. Paper can also be used to change the body shape or add body movements, as illustrated in Figure 2(a) by the orca opening and closing its mouth while moving forward or by the bat [Figure 2(b)] moving its wings. But paper and cardboard can also radically change the locomotion principle, as illustrated in the Figure 2(c) by the zombie, where the wheels of the robot activate the legs. The paper structure can also be used to interact with the sensors, as illustrated in Figure 2(d) by the bear, which extends its paw in front of the sensors to drive its iceberg (the robot). The same fixation points can be used to attach three-dimensional (3-D) printed customized parts, as illustrated by the winder shown in the Figure 2(g) and (h). Moreover, one can use paper to create environments, either flat with patterns that can be used in association with the ground sensors [Figure 2(i)] or 3-D objects, such as the trees beside the zombie in Figure 2(c). Finally, it is also possible to link several Thymio by software, allowing the coordination of complex multi-Thymio robotic structures.

Facilitating Learning

When designing Thymio, we took care to provide many incentives for the users to learn new things throughout their direct interaction with the robot. This translates into specific hardware and software choices.

At the hardware level, we render visible the activity of the various robot components by adding an LED next to each of them, for a total of 39 LEDs. These LEDs locally color the hull and allow the user to see immediately where and when the robot perceives a change in its environment: proximity of objects, changes in the ground color, temperature, sound, or accelerations. Some LEDs display data exchanges from the infrared remote control receiver or with the micro-secure digital card. The capacitive buttons give both visual and acoustic feedback. The link between a sensor and its feedback can be turned off when programming the robot so that the LEDs and loudspeaker can be used for other purposes.

At the software level, we provide a set of programming environments (see the "Programming Environment" section) that enable beginners to discover programming progressively. First, we teach them the basic rules of programming using a purely visual interface, then they discover the construction of syntax trees by assembling graphical blocks, and finally, we provide a full text-based coding environment with advanced debugging tools, such as real-time inspection of the variables of the robot and plotting features, providing a visual way to understand time-related concepts.

Fast Access to Robotics Behaviors

Many existing robots need to be built or configured before showing any operational behavior. For instance, the Edison robot needs to read a bar code, and the mBot needs to be assembled. This can be a barrier for school activities, one we wanted to avoid; rather, we wanted a robot able to show interesting behaviors right out of the box. Therefore, Thymio has six different basic behaviors, stored in flash permanently, accessible as soon as the robot is started. These basic behaviors allow people starting Thymio to immediately interact with it, while illustrating the many possibilities of the robot. The user can begin creating constructions on top of these basic behaviors without the need for programming, such as in the paper creations shown in Figure 2(a)–(d).

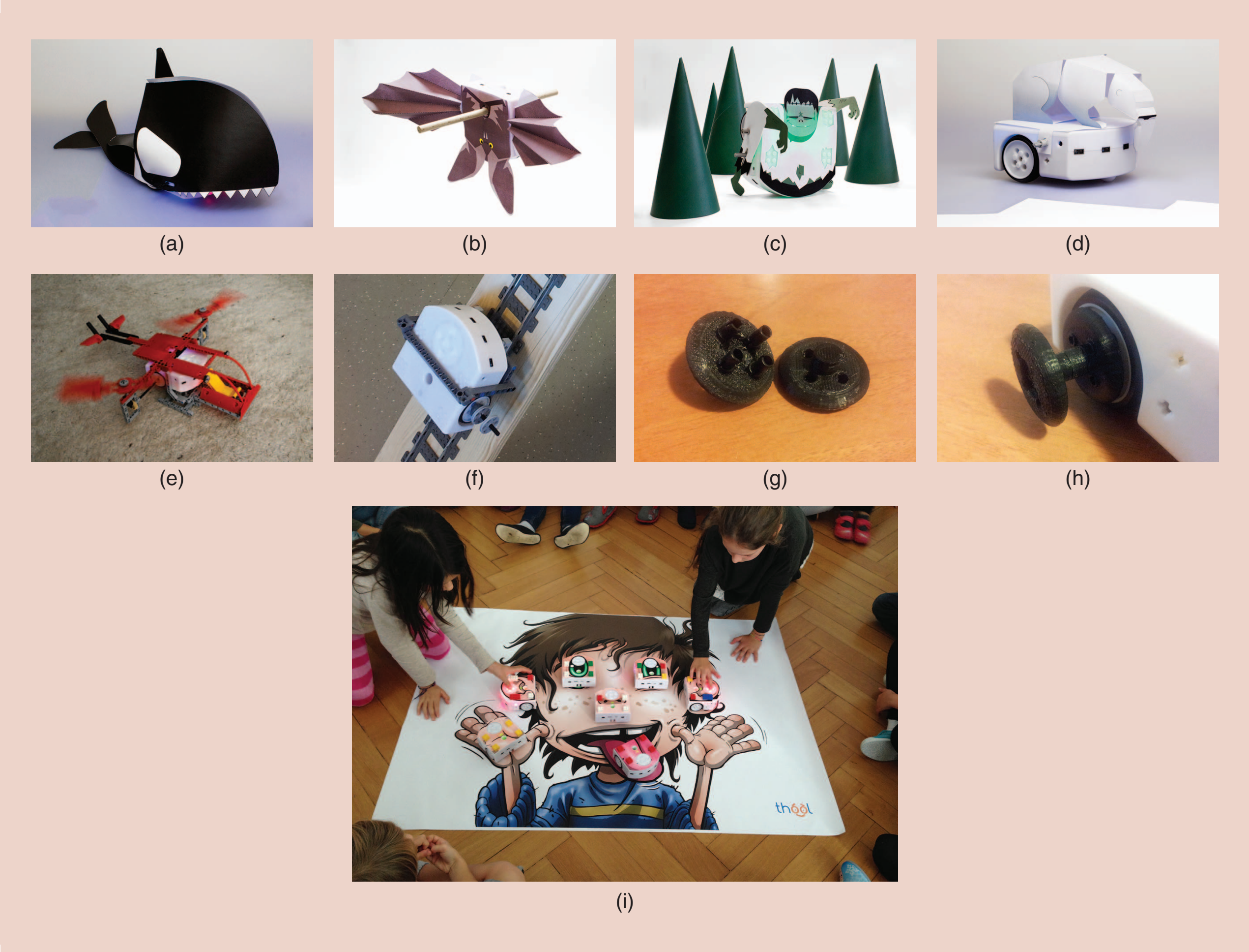

Figure 2. Examples of extensions of the Thymio basic robot (a)–(d) with paper or cardboard body extensions, (e) and (f) using LEGO structural extensions, (g) and (h) using 3-D printed extensions (courtesy of Ezio Somà), and (i) using a printed environment (courtesy of Thool project).

Programming Environments

Thymio runs the Aseba open-source programming environment [18]. Aseba is designed to enable novices to program robots easily. On the robot side, it provides a lightweight virtual machine that runs on microcontrollers such as the PIC24F inside Thymio. A virtual machine allows instantaneous upload and safe execution of programs. On the desktop side, Aseba provides an integrated development environment (IDE) featuring a visual programming language (VPL) (Figure 3); a scripting language (Figure 4); and a mixed language, Blockly (https://developers.google.com/blockly/), to assemble scripts graphically (Figure 5). These different languages cover the abilities of children of different ages and the progression of skills of learners.

The IDE supports real-time feedback on the status of program execution, as this feature was recognized as of critical importance to properly learn programming [19]. This capability is provided both with the VPL [20] and in the scripting environment by displaying the content of variables in real time through texts or plots.

Aseba integrates with the Robot Operating System (ROS) [21] through the asebaros (http://www.ros.org/wiki/asebaros) bridge. The ROS is one of the most widely used software frameworks in robotics research, and this integration allows running sophisticated algorithms, such as simultaneous localization and mapping, in conjunction with Thymio. This makes the robot suitable for university-level education.

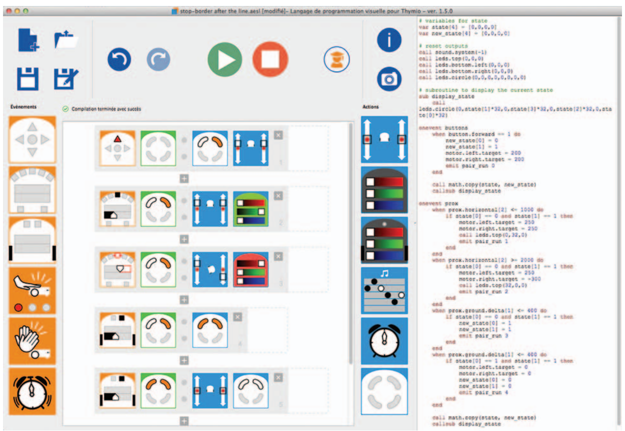

Figure 3. The VPL.

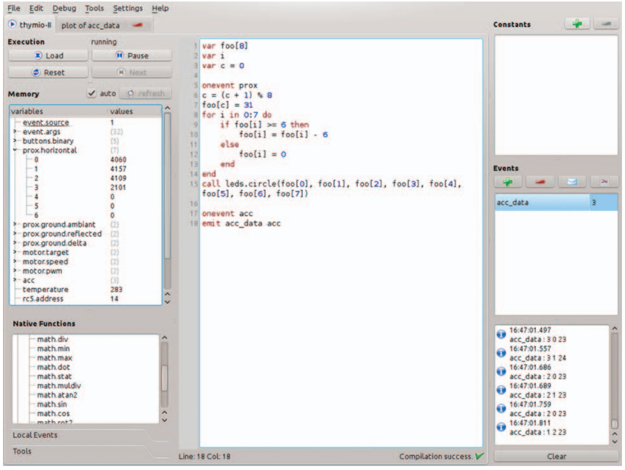

Figure 4. Aseba Studio, the IDE.

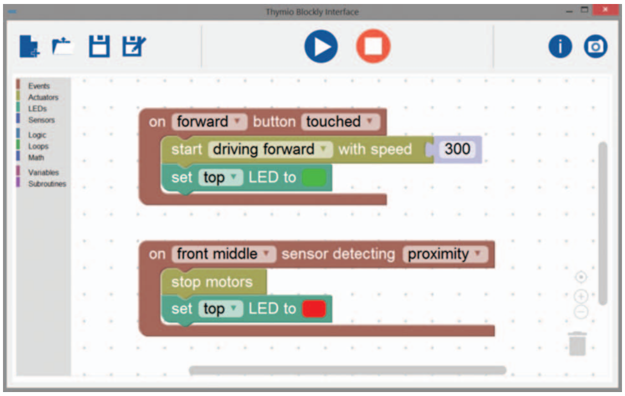

Figure 5. The Blockly programming environment.

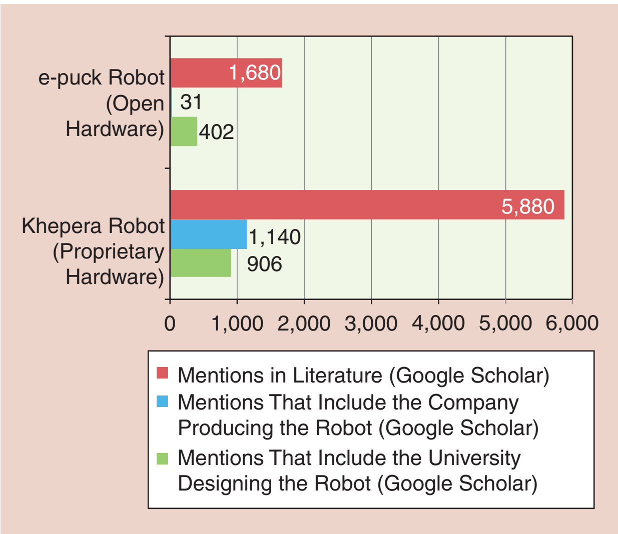

Figure 6. A comparison between e-puck and Khepera in terms of mentions in Google Scholar, either associated with the university or with the company producing them.

Open-Source Hardware: Choices and Impact

The final key design choice among the seven mentioned in the previous section is the open-source project. This choice

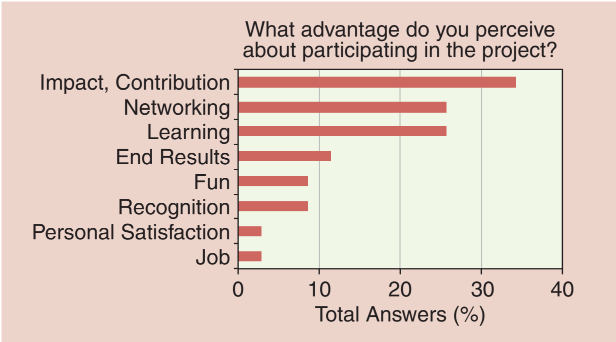

Figure 7. The advantages of contributing to open-source hardware.

has an impact on the robot design and the way this device is used in the community of users. In this section, we analyze in more detail the implications of this choice in the context of educational robotics. We compare these implications with the results of a survey we performed among several open-source hardware communities. We collected 35 answers from 11 project leaders, 13 core design team members, eight contributors, and three enthusiastic users of open hardware projects.

Motivation

Our group has good experience in disseminating robotic hardware with the Khepera [22] and e-puck [10] robots. Khepera was disseminated with a proprietary strategy, e-puck with an open-source hardware strategy. Both targeted similar users and have been sold in similar quantities. What we can observe after more than ten years is that Khepera generated royalties for the university, but the name of the robot was mostly associated with the name of the company producing it, not the university that developed it (see Figure 6). The e-puck robot, with open hardware and an image better linked to the university, generated no income for the university but much more relative visibility. In the case of Thymio, the institutional motivation was toward visibility more than money. Therefore, from an institutional point of view, the open-source hardware strategy seemed more adapted to the desired outcomes.

Along with the institutional motivation, each contributor has a personal motivation. When asked about their personal motivation, the people participating in the survey cited links to their professional activity and to the specific project. A few mentioned a more general goal like improving our society.

While most contributors participated in the Thymio project as part of their job, they showed a strong motivation to contribute to society, as developing a robot targeting education has an important societal component. Moreover, our project also has a strong scientific motivation; several studies are ongoing concerning the program's acceptance by teachers and the effect on children's learning. Sharing a strong fundamental motivation, such as education or scientific achievements, is a key element for building a solid community [23], especially if it is interdisciplinary like ours.

What benefits do people expect from participating in such a project? Figure 7 shows the answers from our survey. We can observe both a technological and a human-relations component, resulting from the community created around the project. Developers of the Thymio project had similar expectations. Working together with several partners was for everybody a win–win situation, and creating a community of users was the only solution that allowed the development of high-quality accessories and educational material. We established a wiki (http://www.thymio.org) as the meeting point for the learners, the robot developers, and the teachers. It is open for editing by anyone, and, although we initially provided most of the material, other members of the community have started to contribute. One of the important contributions from people outside the core design team was the translation of the wiki into four languages.

A last important motivation for having an open hardware project was the resulting image: we wanted a match between the nonprofit nature of the project and the nonprofit nature of education in general.

License of Project and License of Tools

When starting an open-source hardware project, one of the typical questions is which license to use when disseminating the project source files. All Thymio documentation and plans are distributed under the Creative Commons Attribution ShareAlike 3.0 license, and the software is distributed under the lesser general public license. We will not discuss this matter here, as it is a very common and well-covered issue.

There is another licensing issue that is less well known and that we discovered very late in our project: the constraints of the licensing of the mechanical and electronic CAD tools. When asked about this issue, 57% of the participants in our survey were not aware of the fact that CAD licenses can be very restrictive about the way source files can be published, and only one-third checked the license on this aspect. This issue is very serious, as most contributors to open-source hardware projects are academics and use educational licenses that do not allow commercial use of the resulting designs. As producing or selling the product is part of the definition of open hardware, these licenses simply forbid publication under the standard open-source hardware conditions.

To clarify this issue, we contacted twelve of the major editors of mechanical CAD and PCB routing software. We asked them if their educational license allows the publication of the source files. Figure 8 summarizes the results of this survey. Only three of the twelve editors have education licenses allowing this type of publication. Two others explicitly mentioned the possibility if permission were requested before publication. A large mechanical CAD editor was puzzled by our questions and, after realizing the impact of the license, introduced a special condition allowing publication of files in clearly labeled open-source hardware projects. In previous situations concerning open-source publication, the same editor asked the universities to purchase commercial licenses to permit

⚙ = Mechanics ⚡ = PCB Design	Software	Editor	Free Publication of Source Files from Educational License	Explicit Mention of Possible Publication After Editor Approval	Price Increase Between the Educational License and One Allowing Publication
⚙	AUTOCAD or INVENTOR	AUTODESK	Yes		0%
⚡	Diptrace	Diptrace	Yes		0%
⚡	Eagle	CADsoftUSA	Yes*		0%
⚙	CREO	PTC	No	Yes**	0%
⚡	Allegro PCB Design	Europractice/Cadence	No	Yes	0%
⚡	Target3001	Ing.-Büro FRIEDRICH	No	Yes	0%
⚡	Altium Designer	Altium	No	No***	193%
⚙	VariCAD	VariCAD	No	No	658%
⚙	Cobalt	Ashlar	No	No	875%
⚙	Vectorworks Fundamentals	Vectorworks	Not Answered After Ten Months		
⚙	CATIA or SolidWorks	Dassault Systems	Final Answer Not Arrived in Ten Months		
⚙	NX or SolidEdge	Siemens	Too Busy Staff to Answer in Ten Months		

Reaction to this Survey (CREO, Allegro PCB Design, Target3001, Altium Designer)

* If explicit open source license.
** Approval automatically granted for open source and european research projects.
*** Academic package can include a commercial license allowing publication.

Figure 8. The publication possibilities as function of the CAD editors through of November 2016.

publication. This can multiply by factors of hundreds the price of the CAD license. This legal issue is totally underestimated by both people participating in such projects and by the CAD editors, and it is a potential threat for many projects.

Who Designs, Produces, and Supports the Hardware?

In the definition of open hardware given in the "Background" section, we stated that one should offer "hardware whose design is made publicly available so that anyone can … make … hardware." Should "anyone" mean every single person or only companies able to produce the product?

In our project, we decided to have two different types of hardware: the robot itself and the accessories. The robot is the expensive part and has a very neutral design, allowing adaptation to specific situations. This adaptation is achieved by custom accessories that increase the attractiveness of the robot in its specific role, enabling activities for different ages and genders.

For the robot itself, we opted to interpret "anyone" as professional structures able to mass-produce hardware based on the price and complexity of the product.

For the accessories, less technically challenging and stronger linked with creativity and educational value, we promoted techniques that are accessible to anyone in the broader sense: paper, cardboard, LEGO constructions, and 3-D printing. This allows a much broader spectrum of contributors, including teachers and lay people.

Another strong element of our vision of open hardware is that Thymio should be durable. As schools invest in long-term training of teachers, for instance, the lifetime of the products should also be as long as possible. The open hardware approach fits well to this requirement, as it gives to the user, or to a generic technician, better conditions to repair the system, having the specifications of all components. This is not the case of proprietary robots like Edison, for instance. Supporting this type of operation has an impact on the robot design; e.g., Thymio can be easily opened with four standard screws, and we introduced connectors between key elements such as motors, the speaker, the battery, and the main PCB. Another key element in supporting repairs by end users is the documentation of calibration methods. When choosing very low-cost components, one faces large dispersion of characteristics. For example, in the Thymio, the right and left wheel motors can differ in their electrical characteristics, resulting in the robot not going straight for similar speed commands to both wheels. To correct this problem, we introduced factory calibration. To allow the user to replace a broken motor, it is essential to also give him or her the possibility of recalibrating the robot and adjusting the parameters of the new motor. In Thymio, this results in the design and the documentation of calibration processes that can be performed by anyone, getting close to the original definition of open-source hardware.

Conclusions

The introduction of robots in formal education is a very challenging task, not only because of technical requirements such as low cost and interactivity but also because of factors depending on the school environment, such as the diversity of the educational programs, the dependence on local structures and languages, or the required training of teachers. Most of the current educational robotic activities capitalize upon one strong element, e.g., the technical innovation, but miss matching the formal education requirements.

The open-source hardware approach used in the Thymio project addresses this and several other issues found in educational robotics. The inclusion of education scientists, teachers, and designers is possible because of the open nature of the project and the split between the core technology, which is produced in a central way, and accessories, which are accessible with do-it-yourself approaches. This split also allowed ensuring a gender- and age-neutral basic robot. This large inclusion of users and contributors allowed the production, in parallel to the robot technology, of a large set of pedagogic scenarios.

The philosophy of open source and free access to information fits extremely well with the community of users in education and was reinforced by producing the robot in a nonprofit structure. This approach allowed broad distribution of the robot with minimal charges due to management of intellectual properties, royalties, financial support, etc. Moreover, the open-source approach allows provision of a durable robot, easy to maintain and repair, with a community of users providing educational material and mutual support.

By conducting a survey among contributors to open-source hardware projects, we could observe that our project shares some characteristics with the majority of the projects represented in the survey. We identified, for instance, an underestimated legal issue for open-source hardware projects in the licensing term of CAD software. Finally, we could show some elements, specific to educational robotics, that differentiate our project from other open-source hardware projects. In particular, our project takes advantage of an alignment between the principles underlying open source and the nature of education institutions. We also found a solution to the problem of production methods by splitting our hardware into two categories, enabling both advanced technology for the robot and a large variety of accessories. Hence, Thymio appeals to a broad community of end users in education, addressing durability and inclusion at several levels.

Acknowledgments

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