

Bringing robotics into formal education using the Thymio open source hardware robot

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I. INTRODUCTION

Mobile robots are valuable tools for education because of both the enthusiasm they raise and the multidisciplinary nature of robotic technology. Mobile robots give access to a wide range of fields, such as complex mechanics, sensors, wireless transmission, mathematics, and computer science, among others. 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.

Despite their potential as educational tools, robots are still not as widespread in schools as they could be. Among the possible reasons, 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 is often perceived as a boyish activity in our 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,¹ “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 paper, 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.

II. 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, EV3², 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 robot³, 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 and two LEDs as 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 are used in schools: Scribbler2, produced and sold by Parallax⁴ (\approx US\$180), is a 188 mm large robot, designed to run on the ground and equipped with a few

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¹<http://www.oshwa.org/definition/>

²<http://mindstorms.lego.com>

³<https://meetiedison.com/>

⁴<http://www.parallax.com>

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). Finch⁵ (\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 force of this robot. However, the cable does not allow real autonomy and mobility. Finally, the mBot⁶ is a mobile platform based on an Arduino board. Its electronics is simple and inexpensive and the robot only features 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 this direction by promoting communities of users [14] 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 paper, we study a case of implementation of this model.

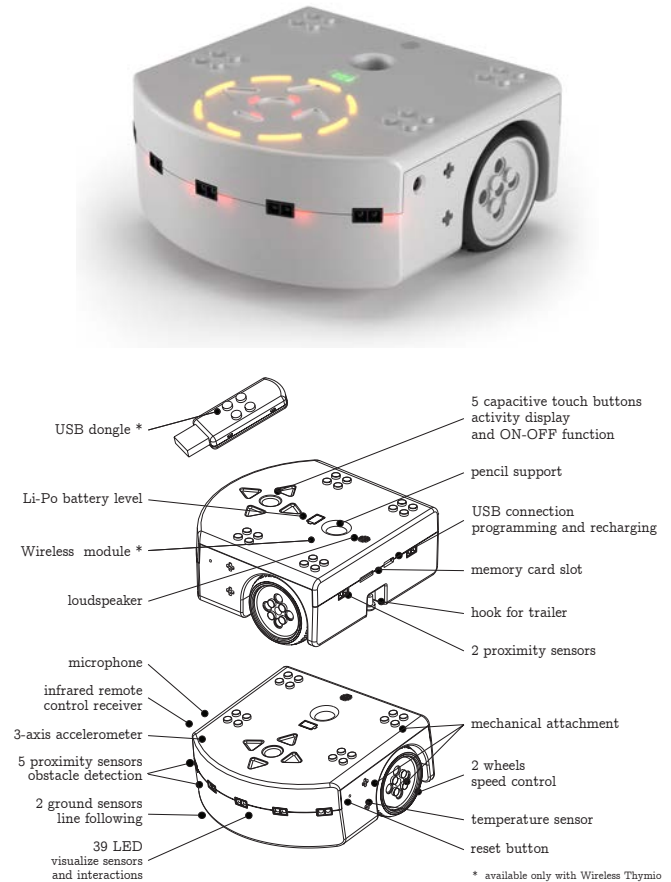


Fig. 1: The Thymio robot and its main components for the wireless- and the USB-connected versions.

III. 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 (Fig. 1, top). 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 (Fig. 1, bottom). The robot has an embedded battery, rechargeable by USB, that provides 3 to 5 hours of power. More details on the robot and the previous research results can be found in [16], [17].

A. Low Price

Price is key in the adoption of robots by schools [18]. Thus, the design of Thymio targeted low production costs while

⁵<http://www.finchrobot.com/>

⁶<http://www.makeblock.cc/mbot/>

including a broad range of functionalities enabling flexibility. As in this type of robot the main cost comes from electronics and sensors [19], 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 (max. 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 and actuators, with the exception of the internal Li-Po 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 less than US\$4.

Our choice of electronic components implies different degrees of automatization in the production. Full assembly is required in order for the robots to be certified for use by children. As a full automatization requires investments that are beyond the possibilities of this project, the current production combines automatization for most components of the PCB and manual operations for the final assembly, and is performed in China due to 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.

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B. Multi-Age 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 [20]. These design choices were made and implemented thanks to an important contribution by industrial designers of the University of Art and Design of Lausanne.⁷ The white neutral hull is a key

⁷<http://www.ecal.ch>

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.

C. 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 than on the wheels. This last connection can be used to actuate elements elsewhere in the added structure (Fig. 2, third row left) or to lift the robot's own weight (Fig. 2, third row right). 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 Fig. 2 by the orca, opening and closing its mouth while moving forward, or by the bat, moving its wings. But paper and cardboard can also radically change the locomotion principle, as illustrated in the second row of Fig. 2 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 the second row of Fig. 2 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 3D printed customized parts, as illustrated by the winder shown in the fourth row of Fig. 2. Moreover, one can use paper to create environments, either flat with patterns that can be used in association with the ground sensors (Fig. 2, bottom) or 3D objects, such as the trees beside the zombie in Fig. 2. Finally, it is also possible to link several Thymio by software, allowing the coordination of complex multi-Thymio robotic structures.

D. 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 microSD 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.

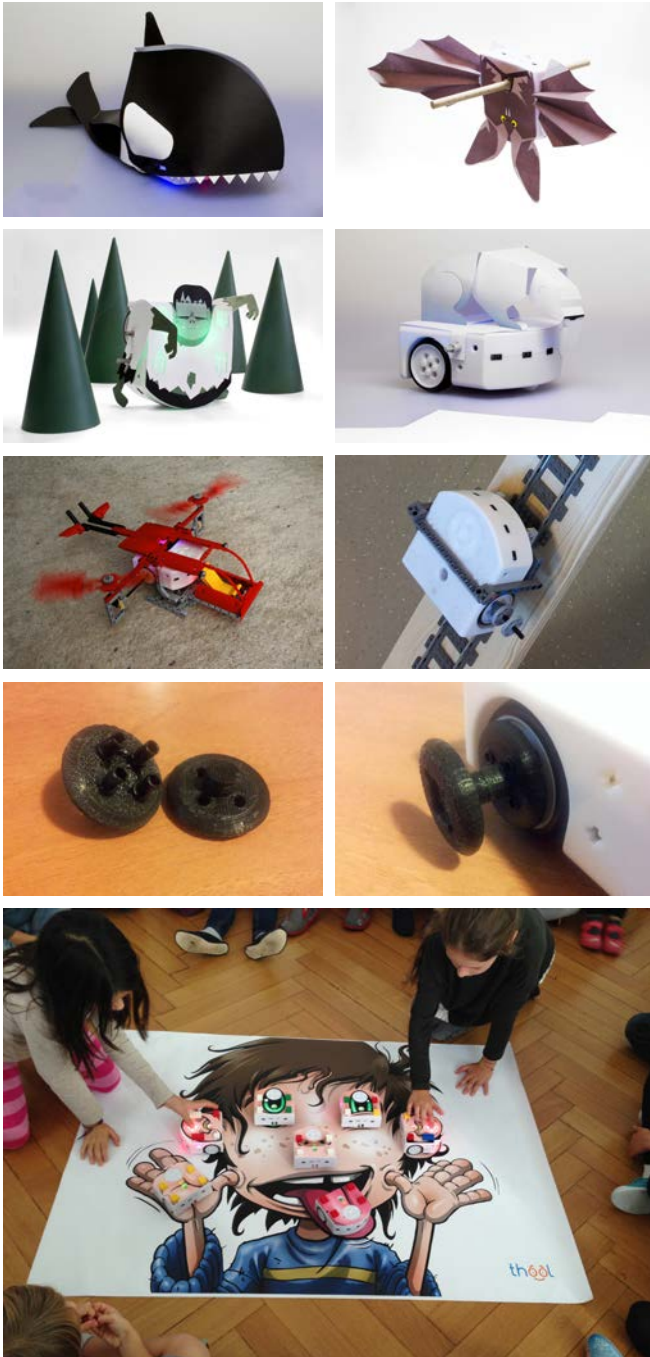


Fig. 2: Examples of extensions of the Thymio basic robot with paper or cardboard body extensions (top four images), using LEGO[®] structural extensions (third row), using 3D-printed extensions (fourth row) or using a printed environment (bottom).

At the software level, we provide a set of programming environments (see the Programming Environment section below) 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.

E. 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 the top four images of Fig. 2.

F. Programming Environments

Thymio runs the Aseba open source programming environment [22]. 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) (Fig. 3), a scripting language (Fig. 5), and a mixed language, Blockly,⁸ to assemble scripts graphically (Fig. 4). These different languages cover the abilities of children of different ages and the progression of skills of learners.

The IDE integrates real-time feedback on the status of program execution, as this feature was recognized as of critical importance to properly learn programming [23]. This capability is provided both with the VPL [24] and in the scripting environment, by displaying the content of variables in real time through texts or plots.

Aseba integrates with ROS [21] through the *asebaros*⁹ bridge. 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.

⁸<https://developers.google.com/blockly/>

⁹<http://www.ros.org/wiki/asebaros>

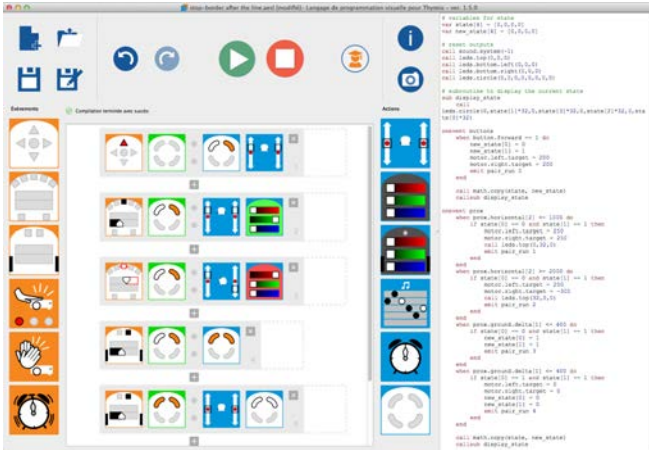


Fig. 3: The visual programming language.

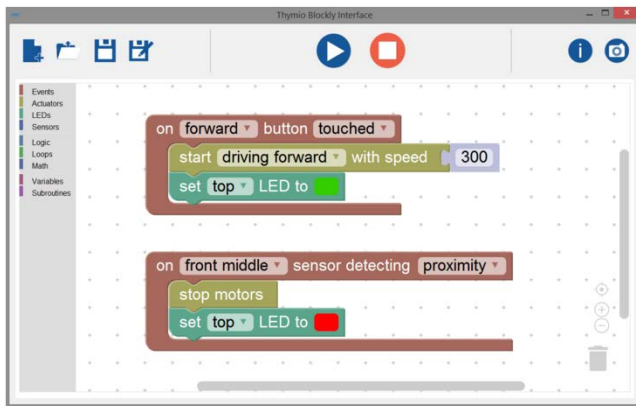


Fig. 4: The Blockly programming environment.

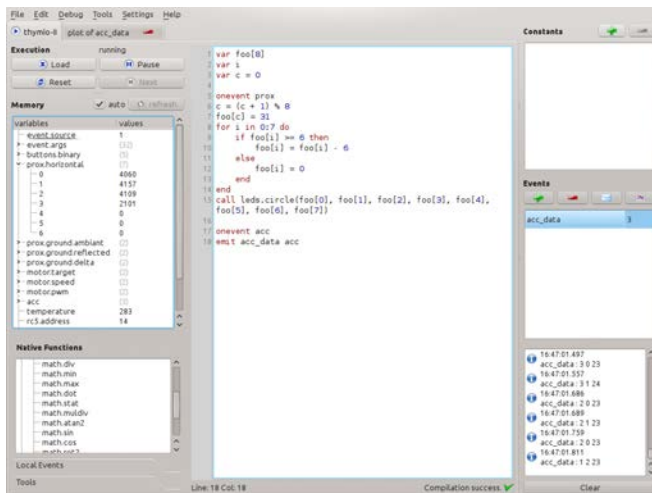


Fig. 5: Aseba Studio, the integrated development environment.

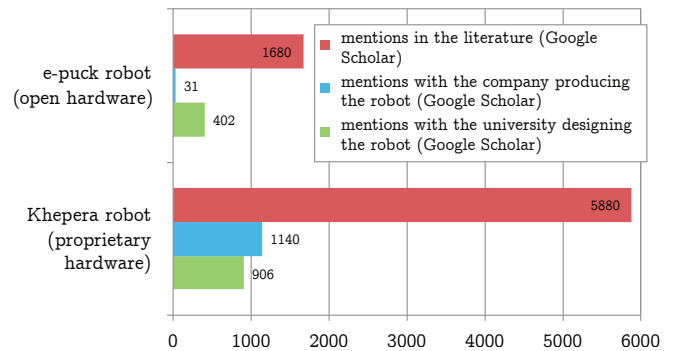


Fig. 6: Comparison between e-puck and Khepera in terms of mentions in Google Scholar, either associated with the university or with the company producing them.

IV. 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 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, 8 contributors, and 3 enthusiastic users of open hardware projects.

A. Motivation

Our group has good experience in disseminating robotic hardware with the Khepera [25] 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 10 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 Fig. 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

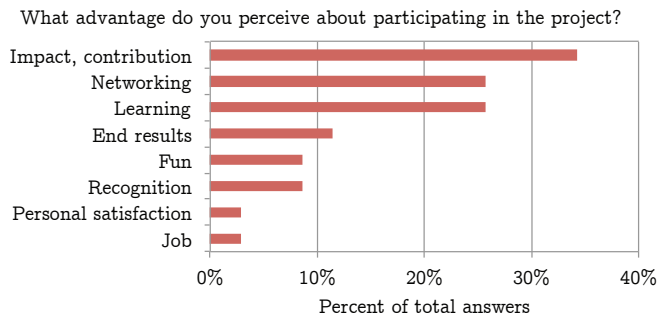


Fig. 7: Advantages of contributing to open source hardware.

motivation, such as education or scientific achievements, is a key element for building a solid community [26], especially if it is interdisciplinary like ours.

What benefits do people expect from participating in such a project? Fig. 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 wiki¹⁰ 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 because of the resulting image: we wanted a match between the non-profit nature of the project and the non-profit nature of education in general.

B. 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 CC-BY-SA 3.0 license and the software is distributed under the LGPL license. We will not discuss this matter here, as it is a very common and well-covered issue.

There is another licensing issue which 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. Indeed, 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.

¹⁰<http://www.thymio.org>

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 two months		
⊗	CATIA or SolidWorks	Dassault Systems	Final answer not arrived in two months		
⊗	NX or SolidEdge	Siemens	Too busy staff to answer in two months		

* if explicit open source license

** approval automatically granted for open source and European research projects

*** academic package can include a commercial license allowing publication

Reaction to this survey

Fig. 8: Publication possibilities as function of the CAD editors, as of the end of March 2016.

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. Fig. 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 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.

C. Who Designs, Produces, and Supports the Hardware

In the definition of open hardware given at the beginning of this paper, it is 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 only the 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 3D 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; for instance Thymio can be easily opened with four standard screws, and we introduced connectors between key elements such as motors, 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 give him also the possibility to re-calibrate the robot and adjust 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.

V. CONCLUSION

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, for instance the technical innovation, but miss to match 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 core technology, produced in a central way, and accessories, accessible with DIY approaches. This split allowed to ensure also 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 non-profit structure. This approach allowed to broadly distribute the robot with minimal changes due to management of intellectual properties, royalties, financial support and so on. Moreover, the open source approach allows to provide a durable robot, easy to maintain and repair, with at the same time a community of users providing educational material and mutual support.

By making 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 in 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.

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