Affordable Mobile Robotic Platforms for Teaching Computer Science at African Universities

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***Abstract*—Educational robotics can play a key role in addressing some of the challenges faced by higher education in Africa. One of the major obstacles preventing a wider adoption of initiatives involving educational robotics in this part of the world is lack of robots that would be affordable by African institutions. In this paper, we present a survey and analysis of currently available affordable mobile robots and their suitability for teaching computer science at African universities. To this end, we propose a set of assessment criteria and review a number of platforms costing an order of magnitude less than the existing popular educational robots. Our analysis identifies suitable candidates offering contrasting features and benefits. We also discuss potential issues and promising directions which can be considered by both educators in Africa but also designers and manufacturers of future robot platforms.**

I. Introduction

Higher education these days is considered one of the biggest challenges but also opportunities for developing countries. This is especially true for Sub-Saharan Africa which did not even experience the growth of wealth seen by other developing countries [1]. The challenges faced by African institutions are diverse, ranging from limited economic capabilities to old-fashioned pedagogic methodology failing to engage and teach students effectively. However, and in particular in computer science, the effectiveness of hands-on exercises and collaborative learning has been identified [2] and is promoted by many of the western higher education institutions.

There were some recent efforts made by selected African institutions to improve the quality of teaching and learning by the adoption of educational robotics. Such initiatives, usually joint ventures between western and African universities (e.g. [3], [4]), follow a belief that robots are an effective means to facilitate more engagement, higher motivation, and the development of practical skill sets, beyond the focus of robotics itself. In our own work [5], we have analysed the effectiveness of robotics as a subject to convey a larger skill sets to students. The positive effect, to a large extent is gained from the "embodiment" and physical presence of robots, which make the outcomes of programming very vivid and immediately accessible, providing a continual formative assessment of learning progress and encouragement to students. Following these ideas, robotics has begun to attract educators attention [6] and is being used as an educational tool. Teaching with robots will encourage learners to participate actively in the learning process and also assist them to appreciate the importance of existing knowledge, conceptions and varied learning styles. In robotics, learners are invited to work on experiments or problem solving with selective use of available resources, according to their own interests, search and learning strategies [7].

In this paper, we are looking at one of the key challenges for adopting robot programming in the curricula of African universities: identifying robotic platforms which are *suitable* for education purposes in computer science and at the same time are *affordable*. Affordability has to be seen differently than normally looked at in developed countries: for example, a minimal wage in Ghana is an order of magnitude (more than 15 times) lower than in the UK [8]. This specific challenge also gave rise to a number of initiatives discussed in Sec. II which focus on the design of particularly affordable platforms.

In this context, the key contributions of this paper are (i) the identification of *assessment criteria* for affordable robotic platform in education, weighing in the challenges and limitations imposed by the affordability constraint, and (ii) a unique assessment and comparison of ten different platforms that are generally deemed suitable for the tasks at hand. Hence, this paper is complementary to other existing surveys, such as [9] and [10], which provide an extensive review of educational robotic platforms suitable for tertiary education. These surveys target a rather broad spectrum of STEM subjects and therefore follow assessment criteria based on modularity, re-usability, versatility and affordability. Some of the platforms are relevant in our context (e.g. Microbot, Scribbler) but many are outside of our criteria: either their suitability for teaching computer science is limited or they are simply not affordable for educational institutions in developing countries (e.g. Khepera, NAO). Affordable robotic kits are very popular in Japan - a subject of a survey presented in [11]. However, many of the products are targeted at the Japanese market only and have limited support and distribution outside of the country. Researchers in swarm robotics focus on developing hardware and software platforms which are by necessity of limited functionality and very low cost (see for example a comparison of such platforms presented in [12]). The functionality provided by the hardware of these robots makes them perfect platforms for educational purposes, but with a few exceptions (e.g. E-Puck robot), the software and supporting materials are not focused on educational use.

II. Educational Robotics in Sub-Saharan Africa

In order to take advantage of the benefits provided by educational robotics, some institutions in Africa have started to use the robots for teaching activities. In Ghana, for example, Carnegie Mellon University, USA in partnership with Ashesi University in Accra, developed an undergraduate introductory robotics course teaching students how to design, build and program robotic systems [3]. The main purpose of this initiative was to encourage students to recognise the scope of computer science and to enhance their technical creativity and problem solving abilities. Despite the positive outcomes, the organisers mentioned lack of suitable, low-cost robot platform as one of the key limitations. In South Africa, University of Cape Town teamed up with Aachen University, Germany to design an inexpensive robotic platform for use in RoboCup Junior competitions and education [4]. The main motivation behind this development was lack of available commercial products within financial abilities of African institutions. The presented, promising initial design has not been followed up, however which prevented us from including this platform in our survey.

There are also initiatives outside of academia which involve building and using robots for educational purposes in Africa. The most prominent example, of pan-national relevance, is African Robotics Network (AFRON) [13]. AFRON brings together a number of organisations from the entire world interested in developing robotics-related education, research and industrial projects in Africa. One of the main activities organised by AFRON is the "Ultra Affordable Educational Robot" project featuring two robot design challenges to date. The scope of the competition is to design and build functional robotic platforms directed at engaging young pupils into STEM subjects and costing an order of magnitude less than commercial robotic products. The first "$10 Robot Challenge" from 2012, focused on very low cost robotic hardware platforms whilst the follow up competition, "Design Challenge: Robot Enhancements, Software, and Teaching Plans" brought the scope further by considering also accompanying software and educational material. This competition highlights the current trend in designing modern educational robotics platforms, which need to provide not only functional hardware components but also easy to use programming environment and supplementary teaching material. We include all these aspects in our assessment criteria presented in Section III. Selected contestants from both challenges were also included in our survey (see Section IV).

Educational robotic activities are also part of events organised by the iHub Research from Kenya - a community outreach innovation centre aiming to promote interest in technology, especially amongst young people. The activities include for example development and programming of robotic platforms based on Arduino boards during boot camps and hacking events [14].

III. Assessment Criteria

1) Affordability: Affordability is a very important factor to be considered which, due to economic inequalities between different parts of the world, has no global point of reference. There is a number of very popular and attractive robotic platforms used for education in developed countries which fall into the affordable category (e.g. [9]). Educational institutions in many African countries face regularly insufficient budgetary allocations, cuts in budgets and resource rationalisations [15] which make even reasonably priced robots such as LEGO Mindstorms beyond their reach. Some of the recent initiatives, such as the aforementioned AFRON robot design challenge address this issue by finding ways to overcome high prices that have put a hold on robotics education in the developing world [16]. The price target in a recent competition in that challenge was set at $20 whilst the limit of $100 was set for any contestants. In our survey, we assume a similar figure of $150 as the maximum price for an affordable robotic kit.

2) Kit Type: Following work of [9], [10], we restrict our survey mainly to a mobile robot category and disregard other platforms (e.g. electronic kits, manipulators) as not suitable for teaching computer science. In addition, we had to reject a number of popular flying platforms (e.g. Parrot drone) as their safe and convenient operation in a class environment is somehow difficult. Commercial mobile platforms are sold as a complete product and may be proprietary or open source. The proprietary platforms are difficult to adapt to suit the specific requirements. Open source commercial platforms on the other hand can be freely adopted and modified by users. The assembly kits are commercial products which come with parts, modules and accessories that need to be assembled and typically can be re-configured. The DIY kits which are available as open source projects need to be built from scratch but are usually cheaper than the commercial platforms and can be made from materials and components available locally.

3) Platform Features: An important aspect of any educational robotic platform is its hardware platform features such as processing power, sensory capabilities and software deployment. The majority of the affordable robots are equipped with on-board microcontrollers which, depending on specification, can process high-bandwidth sensors such as cameras, load and run programs autonomously, or be only limited to providing an interface between sensors/actuators and a PC. The popular sensors include tactile devices such as bumpers or whiskers, odometry, infrared or ultrasonic proximity sensors and video cameras. In addition, robots may feature LED indicators and displays which can be useful for debugging purposes. Deployment of the robot software is usually implemented by a tethered connection or a more favourable wireless connection, and may in addition require a special programming equipment and software tools. When scoring this criteria we looked at relative processing power of the built-in microcontrollers, variety and number of sensors and the convenience of software deployment.

4) Software Development: The software environment supporting popular programming languages with appropriate software libraries and development environment is essential to make the robotics platforms useful in education. For teaching computer science, high-level programming language support is crucial so that programming concepts like variables, loops, subroutines could be introduced. The software libraries provide helpful abstraction of low-level operations allowing at the same time access to all hardware resources of the robot. This feature is especially important for teaching computer science, so the students can focus more on programming techniques rather than on low-level technical details. Similarly, a well integrated development environment will assure more efficient and effective learning experience. When scoring this criterion, we looked favourably at platforms with a dedicated software environment, high-level language support and simulators.

5) Educational Material: The effective and widespread use of educational robots should be supported by the existence of educational material helping teachers to design subject curricula [17]. The importance of this feature was recently highlighted in the second AFRON robot design challenge which included not only hardware platforms but also accompanying software and supplementary teaching material. These additional features will allow educators in Africa for preparing lesson material for different study levels without having to change the platforms. Platforms which come equipped with detailed tutorials can support teachers with little or no previous experience in educational robotics which may encourage others to participate in such initiatives to make them sustainable. In our scoring, we looked at availability, quality and variety of provided tutorials and lesson plans.

6) Maintenance: In light of poor maintenance procedures, inadequate training and under-utilisation of equipment in Africa [18], the maintenance of the robots needs to be considered in order to assure their continuous functioning and sustainability. Even though many commercial platforms are available through on-line sales globally, in reality they are not easily accessible in Africa due to prevalent problems with poor credit rating of many institutions and unreliable shipping [4]. This situation makes it difficult to easily procure new platforms to replace or repair faulty ones or add to the existing pool as student number increases. Therefore platforms which are easier to maintain due to their reliability and easy to set up procedures will be preferred. When scoring this criterion, we looked at the presence of enclosure, quality of assembly, convenience of charging and requirements for any additional equipment.

IV. Review of Robotic Platforms

We have considered over 30 platforms which were identified by analysing related work [9], [10], [12], the results of the AFRON competitions and additional Internet search. Following the proposed criteria and discarding platforms that went out of production in recent years (e.g. Parallax Toddler, Wowee Rovio), we have narrowed our choice down to 10 platforms which we present in this section in more detail.

1) Thymio II: is an open source platform which is also available as a commercial product at the price of approximately $130. The robot uses a 16-bit PIC24FJ128GB106 microcontroller and includes a number of IR proximity sensors, odometry, temperature sensor, accelerometer and microphone. The robot can generate sounds and is equipped with an array of LEDs. The programs can be developed and uploaded from a PC through a USB port which is also used to charge an internal accumulator. The programming environment is based on Aseba, an open-source scripting language, which also includes a visual programming environment. There are some supplementary teaching materials provided with tutorials and project ideas. Thymio II has been used in teaching subjects such as physics [19] and computer science [20].

2) Scribbler 2: is a commercial robotic platform [21] with open-source hardware design available at a price of $130. The robot uses a custom-made, 8-core, 32-bit P8X32A microcontroller and is equipped with odometry sensors, photosensors, microphone and IR proximity sensors. The robot has also a speaker and status LEDs. The robot can run stand alone programs and be programmed through a serial interface using a USB dongle (provided with the kit) from a PC. The robot is powered by a set of replaceable batteries. The software environment is based on BASIC-like Spin language and comes also with a visual programming environment. Support for other high-level programming languages (e.g. C) is also provided. The robot comes with a rich set of educational materials both for students but also educators. Scribbler 2 (and its predecessor Scribbler) is supported by the Institute for Personal Robots in Education [22] which provides a large spectrum of teaching material for different groups and subjects.

3) Kilobot: was developed for swarm applications [23]. It is an open-source design but it is now produced and distributed as a commercial product at a price of $116. Kilobot is the winner of the first AFRON robot design challenge with parts costing only $14. The robot has an 8-bit ATmega328 microcontroller and is equipped with ambient light and IR sensors for proximity readings and communication. The robot has an alternative moving principle based on vibration motors which requires a fairly smooth surface and results in a relatively slow movement. The robot's microcontroller can be programmed through a serial interface requiring a dedicated programming device. The robot is powered by a rechargeable battery which requires a separate charger. Kilobot comes with a set of basic software libraries for sensor reading and motion control and requires a basic knowledge of microcontroller programming. High-level programming language support is provided by the microcontroller's development environment. The robot has simulation support through the V-REP simulator. Since the platform is directed at swarm robotics, there is no supplementary teaching material provided.

4) Jasmine: is a robot platform designed for swarm applications [24] available at approximate cost of $113. It is an open source hardware and software platform with simulation capabilities. The basic version of the robot comes with an 8-bit ATmega168 main microcontroller and uses a number of IR sensors for proximity sensing, communication with other robots and light measurements, and LEDs for status monitoring. The capabilities of the robot can be extended by a number of customised boards including improved sensing, connectivity, etc. The robot's microcontroller can be programmed from a PC by a dedicated programming interface. Jasmine comes with software libraries simplifying the use of sensors and controls and requires a basic knowledge of microcontroller programming. High-level programming language support is provided by the microcontroller's development environment.

5) AMiR: is a robot designed for swarm applications [25]. It is an open-source platform which costs about $100. The robot uses an 8-bit ATmega168 microcontroller and is equipped with a number of IR proximity and communication sensors and LEDs for status monitoring. The robot's microcontroller can be programmed from a PC by a dedicated programming interface. AMiR comes with a set of basic software libraries for sensor reading and motion control. The programming requires a basic knowledge of microcontroller programming. High-level programming language support is provided by the microcontroller's development environment. The robot has been simulated in Player/Stage and has been used for teaching computer science courses at University of Putra, Malaysia [25].

6) Microbot: is a platform which comes as an assembly kit at an approximate cost of $65 for the basic kit [26]. Although requiring prior assembly, no soldering is required. The basic set comes with an 8-bit PIC-based PICAXE-20X2 microcontroller, two bumpers, a line tracking sensor, LEDs and a speaker. Robot sensing and communication capabilities can be further expanded by a range of additional modules. The robot can be programmed through a serial port requiring dedicated USB cable. The software programming language is based on BASIC but there is also a graphical programming tool called Logicator. Microbot is specifically designed for education but no supplementary teaching material is provided.

7) Colias: is a robotic platform developed at the University of Lincoln, UK for swarm robotic applications [12]. It is an open source platform and costs about $40. Colias is based on an 8-bit ATmega168 microcontroller and comes with IR sensors which provide proximity measurements and communication means with other robots, and there is an extra light sensor and LEDs. The robot's microcontroller can be programmed from a PC by a dedicated programming interface. Colias comes with a set of basic software libraries for sensor reading and motion control. The programming requires a basic knowledge of microcontroller programming. High-level programming language support is provided by the microcontroller's development environment. There are ongoing plans to develop Colias as an educational platform, but so far no supplementary material has been released.

8) SEG: is a winner of the second AFRON robot design challenge. It is an open source platform, with mechanical parts fabricated by 3D printing and assembled into a complete robot for an approximate cost of $20. The main hardware contains an Arduino Pro Mini board, which uses an 8-bit ATmega328 microcontroller. The basic set is equipped with a single photo sensor and LED only. The basic capabilities can be expanded by additional sensors, actuators, and communications modules which can be added for an additional cost. The robot's microcontroller can be programmed by a dedicated programming interface. The robot can be programmed using a graphical drag-and-drop interface through ArduBlock graphical environment which also automatically generates C++ code. SEG comes equipped with teaching materials in the form of curriculum that has been developed into worksheets, video lectures and labs for students to learn basic robotics and programming concepts.

9) AERobot: is a modified version of the Kilobot robot designed specifically for educational purposes [27]. The reduced cost and enhanced educational capacity was achieved by removing the Kilobot's swarm capabilities. It is available as an open-source project at a price of $11. AERobot was also one of the winning contestants of the second AFRON robot design challenge. It uses similar hardware platform as Kilobot but additional IR sensors and an colour LED have been added. The robot has been also enhanced by an addition of a built-in USB port allowing for direct programming from a PC without a need of special programmers, and for charging its battery. The robot comes with a modified miniBloqs software suite which is an open source graphical programming environment for Arduino boards. It comes with teaching materials made up of a set of lessons helping students to learn the basics of robotics and programming.

10) Lollybot: is an open-source platform with an approximate price for components of $9. The robot is a winner in the tethered robot category in the first AFRON robot design competition. The robot's main body and drive system are essentially built from a recycled PlayStation controller. Lollybot has bump sensors, LEDs and photoresistors which act as line detectors and are accessible through the controller's built-in USB interface [28]. This makes the robot directly controllable by a tethered PC which provides the robot's processing power. The robot software environment supports high-level programming languages such as Delphi, HTML and JavaScript. There are some suggestions provided for teaching different concepts and the robot was used in teaching activities which were part of the second AFRON robot design challenge.

V. Analysis and Discussions

Table I presents a comparison of the affordable robotic platforms based on our assessment criteria. The provided scoring is ordinal and each criterion is considered independently. The following analysis justifies the scores given for individual criteria, extracts general trends, highlights prominent examples and discusses the relevance for our teaching context.

Almost all platforms (excluding Microbot) have open hardware and software designs allowing for easy expansions and modifications. A general trend that can be observed is that cheaper options are available only as DIY kits, requiring a prior assembly, and that the price for commercial robots is above $100. It seems that affordable robots still pose a business challenge even in mass production, which should in principle result in more compelling prices.

The processing capabilities of all considered platforms are provided by inexpensive microcontrollers. One exception is

			Platform Features					
Robot	Kit Type	Price	Processing	Sensors	Deployment	Development	Edu. Material	Maintenance
Thymio II	commercial/DIY	$130	***	***	***	***	**	***
Scribbler 2	commercial	$130	***	***	**	**	***	**
Kilobot	commercial/DIY	$116	**	**	**	**	–	*
Jasmine	DIY	$113	**	**	**	**	–	*
AMiR	DIY	$100	**	**	**	**	–	*
Microbot	assembly	$65	**	*	**	**	–	*
Colias	DIY	$40	**	**	**	*	–	*
SEG	DIY	$20	**	*	**	**	***	*
AERobot	DIY	$11	**	**	***	**	***	*
Lollybot	DIY	$9	–	*	*	**	**	**

TABLE I
AFFORDABLE MOBILE ROBOTIC PLATFORMS (RELATIVE SCORING: *** = VERY GOOD, ** = GOOD, * = BASIC, – = MISSING).

the cheapest option, Lollybot which has virtually no on-board processing power and serves only as an interface for sensors and actuators and a PC. The most popular are 8-bit platforms from leading microcontroller manufactures (Atmel, Microchip) with two platforms (Thymio II and Scribbler 2) offering slightly higher specifications. Although all these devices provide sufficient resources for handling rather limited sensory capabilities of the robots, more powerful platforms could support more complex behaviours and richer functionality. It is likely, that future educational robots will see the adoption of recent developments in affordable computing platforms such as Raspberry Pi or Intel Edison.

All presented robots feature relatively simple sensors such as bumpers or light detectors. Odometry is present only in a couple of more expensive platforms (Thymio, Scribbler 2). A very popular sensing principle (not present in Microbot, SEG and Lollybot) is based on IR sensors which can be used as proximity sensors, light detectors but also for remote communication. The simplest and also the cheapest solutions (Microbot, SEG, Lollybot) support only a couple of simple sensors. More sophisticated sensors such as cameras and sonars are usually available as extension modules which unavoidably affect the final price of such a setup.

All considered robotic platforms are programmable through a serial interface. Some platforms such as Thymio II, AERobot and Lollybot feature a standard USB port, but all other robots require a dedicated programming interface which is not always provided. Lollybot is a unique example of a robot that needs to be tethered to a PC all the time. Platforms designed for swarm robotics (Kilobot, AMiR, Jasmine, Colias and AERobot) have short-distance wireless communication which is used for communication between individual robots but unfortunately none of these solutions is used for remote programming or control. Other wireless communication solutions such as Wi-Fi are only available as expansion modules in selected models. The remote deployment is essential in teaching environments and can simplify the ease of use and flexibility of the platforms.

All presented platforms come with some form of software libraries abstracting robot's low-level functionality. Platforms such as Kilobot, Jasmine, AMiR and Colias rely solely on microcontroller programming environments (e.g. AVR Studio by Atmel). In addition, Kilobot and AMiR provide simulation capabilities which is an important education feature enabling for example teaching of large classes or individual learning outside teaching activities. Jasmine supports also higher-level commands written in Motion Description Language. The remaining six platforms provide some dedicated programming environments based either on the existing open source projects (Aseba, minibloqs, ArduBlock) or specifically designed for the robot (Sribbler's Spin, or Lollybot's Delphi libraries and GUI). These platforms also support graphical programming environments which may have some use for teaching students new to programming. It is surprising to see no explicit support for ROS in any of the presented platforms, with an exception of Thymio II, which can provide more sophisticated off-board functionality and be useful for teaching robotics and software engineering in later stages of university education. This can be explained however, by a general lack of wireless communication in the presented robots which is essential for interfacing with a networked system such as ROS.

Supplementary educational material is typically not provided with platforms designed for swarm applications (Kilobot, Jasmine, AMiR, Colias), even though there is some mention of their use in education (e.g. [25]). Commercial educational platforms such as Scribbler 2 come with a rich set of teaching material targeting different groups and skills but also educators. The three cheapest platforms in our ranking (SEG, AERobot, Lollybot) which were all participants of the AFRON robot design challenge have also excellent teaching support. This demonstrates importance of such initiatives and hopefully sets a precedent for future designers and manufacturers of affordable robotic platforms.

Several aspects affect the scoring of the maintenance criteria in our survey. Platforms such as Thymio II, Jasmine, Colias and AERobot support convenient charging directly through a USB port without the need for additional charging equipment or disassembling parts of the robot. Platforms such as Scribbler 2 and Microbot require replaceable battery packs whilst Kilobot, SEG and AMiR need additional chargers. Commercial platforms (excluding Microbot and Kilobot) come with suitable enclosure which protects the circuitry and improve robustness of the design. The three cheapest robots also provide some form of shielding. Robots available as assembly or DIY kits require prior assembly and therefore their robustness will depend much on the skills of a person building the robot. In selected cases (SEG, AERobot), assembly will require access to specialised equipment (e.g. for mounting SMD components, 3D printer) which might not always be available at African institutions. This is less of a problem with a solderless assembly required by Microbot. Kilobot and AERobot feature alternative moving principle and may therefore require additional smooth surface for operation.

From the presented analysis, the most compelling platforms in our context represent the top and bottom cases in Table I. Commercial robots like Thymio II and Scribbler 2 score high in all considered criteria presenting rich platform features, good software support, available teaching material but also pose the least problems with maintenance. Therefore their use at African institutions would be recommended despite relatively high prices. One missing aspect which would help spreading the use of such robots in Africa is related to missing customer support, distribution and service centres locally. On the other end of the price spectrum are robots such as SEG and AERobot which are excellent educational platforms with somehow limited functionality and posing various maintenance issues. A compelling aspect of these platforms is that they can be sourced and made locally, but their wider adoption requires skilled technicians and also specialised equipment. It is disappointing to see that platforms in the middle price range which were designed for swarm applications have currently strong limitations in software development and educational material, which would prevent their straightforward adoption in Africa.

VI. Conclusions

In this paper, we have presented a survey and analysis of currently available affordable mobile robotics platforms suitable for teaching computer science at African universities. We have proposed a set of assessment criteria and reviewed a number of platforms costing under $150. Our analysis has identified suitable candidates from both commercial and DIY categories offering contrasting features and benefits. Potential issues and promising directions were also discussed which could be considered by both educators but also designers and manufacturers of future robot platforms. The presented survey can only be treated as a snapshot of current developments in affordable robotic platforms as there are ongoing initiatives taking place. There is a number of interesting projects currently seeking funding through crowd sourcing platforms such as Kickstarter with examples such as Tiddlybot, a Raspberry Pi based robot platform or RoboCORE, an inexpensive computing platform specifically designed for making own robots. Therefore we should expect more compelling and affordable robot platforms in near future. Educational robotics can play a key role in addressing some of the challenges faced by higher education in Africa and its successful implementation will partly depend on the issues discussed in this paper.

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