How have robots supported STEM teaching?

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Abstract Context: Robotics has assisted teachers to combine technology and engineering topics to concretize science and mathematics concepts in real-world applications. As a result, benefits in different concepts and skills, as well as positive long-term effects have been observed. Objective: this work aims to identify state-of-the-art robotics applications to support STEM teaching. To do so, we intend to answer six research questions: (1) What concepts are considered and how are they explored? (2) What skills are expected to be developed? (3) How is educational robotics associated with school curriculum? (4) What types of robots are used? (5) What age groups/educational levels are considered? (6) How is educational robotics evaluated? Method: we carried out a systematic literature review to identify, assess and synthesize relevant papers published from 2013. A protocol developed by us guided the review conduction and enhanced its repeatability with reduced subjectivity. Results: 60 publications able to answer the research questions were summarized. We found that: (1) several STEM concepts have been explored in all educational levels; (2) educational robotics is still frequently associated with teamwork and problem solving development, extracurricular activities and LEGO robots; (3) only 25% of the 60 papers quantitatively and qualitatively evaluated learning. Conclusion: robots support for STEM education has been successful in different scenarios. The inherent flexibility, coupled with the experiences reported by a significant piece of the literature, can inspire new applications of educational robotics.

1 Introduction

New technological tools are introduced in our life very rapidly. “New iProducts are introduced into the market almost every six months. When watching the Jetsons television program in the 1960s and 1980s, very few people believed that a humanoid robot, such as Rosie, could become a reality in their lifetime. However, Robotics in education for school age children has been in existence since the late 1900s” (Eguchi (2014), p. 27).

Robotics, with its multi-disciplinary nature, provides constructive learning environments that are suitable for a better understanding of scientific and non-scientific subjects and it has a significant role on learning Science, Technology, Engineering and Mathematics (STEM) subjects (Khanlari, 2013). Robotics can be especially effective in teaching STEM, as it enables real-world applications of the concepts of engineering and technology and helps to remove the abstractness of Science and Mathematics. In fact, various Robotics activities led to improvements in Science, Technology, Engineering, and/or Mathematics learning (Kim et al, 2015).

Robots have the potential to be the next effective add-on to traditional education. The tangibility of robots and the excitements they bring into the classroom environment is considered conducive for learning (Karim et al, 2015). However, the actual contribution of robots in STEM education is not obvious. This brings us to the title of this chapter: how have robots supported STEM teaching?

Although several authors propose to explore the subject (Section 2), we did not find a recent and systematic study in order to identify state-of-the-art Robotics applications to support STEM teaching. Therefore, we carried out a systematic review to find relevant papers published from 2013 to answer six research questions:

1. What concepts are considered and how are they explored?
2. What skills are expected to be developed?
3. How is educational robotics associated with school curriculum?
4. What types of robots are used?
5. What age groups/educational levels are considered?
6. How is educational robotics evaluated?

To do so, we followed the Systematic Literature Review (SLR) protocol indicated in Section 3. Sections 4 and 5 discuss the results and describe the conclusions, respectively.

2 Background

Our students are digital natives who have grown up using technology. Home computers have been in existence since before they were born – Eguchi (2014) shared that some students thought “B.C.” means “before computer”! The world is rapidly changing and educational programs have to adapt to the changes. Thus, this section presents some review studies focused on Robotics use as an educational tool.

Potkonjak et al (2016) claim that the problems that still constrain the full realization of distance education in Science, Technology, and Engineering (STE) lie in the fact that these sciences inevitably require laboratory exercises as part of the skill acquisition process. Thus, the authors summarize the state of the art in virtual laboratories in the fields of STE. Two different points of view to the resolution have appeared. One is to try developing a physical (real) laboratory with distance access, while the other aims to develop a fully software-based virtual laboratory. They argue for the latter option. The paper intends to support wider application of virtual laboratories, and the criteria followed from one crucial requirement, which is: operating a virtual laboratory for a student must feel like they are working with real authentic devices in a real authentic space. The authors present a list with 20 virtual lab projects classified as:

- Two (2) projects in field of the general initiatives which have a wider focus and try to provide a framework for both virtual and remote-access-physical facilities.
- Two (2) projects in field of Science-physics.
- Two (2) projects in field of Process Technology.
- Five (5) projects in field of Engineering - non robotic.
- Nine (9) projects in field of Robotics.

Sullivan and Heffernan (2016) present a systematic review of research related to the use of robotics construction kits (RCKs) in P-12 learning in the STEM disciplines for typically developing children. The purpose of this review is answer the question: “How do robotic construction kits function as computational manipulatives in P-12 STEM education?” The synthesis of the literature has resulted in four key insights. First, RCKs have a unique double application: they may be used for direct instruction in robotics (first-order uses) or as analogical tools for learning in other domains (second-order uses). Second, RCKs make possible additional routes to learning through the provision of immediate feedback and the dual modes of unique representation to RCKs. Third, RCKs support a computational thinking learning progression beginning with a lower anchor of sequencing and finishing with a high anchor of systems thinking. And fourth, RCKs support evolving problem-solving abilities along a continuum, ranging from trial and error to heuristic methods associated with Robotics study. Furthermore, their synthesis provides insight into the second-order (analogical) uses of RCKs as computational manipulatives in the disciplines of Physics and Biology.

Can robots in classroom reshape K-12 STEM education, and foster new ways of learning? To sketch an answer, Karim et al (2015) review (no systematic review), side-by-side, existing literature on robot-based learning activities featuring Mathematics and Physics (see Table 1) and existing robot platforms and toolkits suited for classroom environment (36 robots / toolkits were identified). The survey suggests that the use of robots in classroom has indeed moved from purely technology to education, to encompass new didactic fields.

Toh et al (2016) carried out a systematic review to examine the use of robots in early childhood and lower level education. The paper synthesizes the findings of research studies carried out in the last ten years and looks at the influence of robots on children and education. Four major factors are examined – the type of studies conducted, the influence of robots on children’s behavior and development, the perception of stakeholders (parents, children and educators) on educational robots, and finally, the reaction of children on robot design or appearance. The authors point that:

- Robots influence on children’s skills development could be grouped into four major categories: cognitive, conceptual, language and social (collaborative) skills.

- Aside from the main users (children), parents and educators have to be on-board as well in order to increase the chances of success of this kind of programs. Lack of parental support would confine educational robots to applications only inside the classroom.
- Design is usually the last consideration when incorporating robots into an application. However, as studies showed, design could make a difference on robot perception and hence, how the children would interact with it. Unfortunately, little work has been done on this question.

Table 1 Summary of the topics covered in educational Robotics featuring Mathematics and Physics (Karim et al, 2015)**.**

Mathematics	Physics
Geometric primitives	Distance, time, and velocity
Counting	Constant speed, acceleration, and deceleration
Multiplication	Work and energy
Decimals	Force, gravity, and friction
Fractions and ratios	Doppler effect
Coordinate system	Fundamentals of electricity
Recognition of quantities	Weight scale and moment computation
Problems with operator	
Graph construction and interpretation	
Angles	

Mubin et al (2013) present a review on the field of robots in education (post-2000). The aspects reviewed include domain of the learning activity, location of the activity, the role of the robot, types of robots and types of robotic behavior. The overview shows that robots are primarily used to provide language, Science or technology education and that a robot can take on the role of a tutor, tool or peer in the learning activity.

Benitti (2012) reviews published scientific literature (until January 2010) on the use of robotics in schools, in order to answer the questions:

1. What topics (subjects) are taught through robotics in schools?
2. How is student learning evaluated?
3. Is robotics an effective tool for teaching? What do the studies show?

The papers reviewed suggest that educational Robotics usually acts as an element that enhances learning. However, this is not always the case, as there are studies that have reported situations in which there was no improvement in learning. Thus, Benitti (2012) indicates some factors considered important for an effective use of educational Robotics, summarized in what follows:

- The role of the teacher - the teacher plays an important role in stimulating pupils in their school work and giving them positive attitudes, because the teacher has considerable influence over the way in which these tools are received by the pupils.
- There are needs to have a larger space for the pupils to work.
- The working groups should not be too big (maximum 2-3 pupils/Kit).
- The task given to the pupils must be both relevant and realistic to solve.
- Short lessons, tutorials, and debriefings embedded in the problem-solving activities could help students to make the connection between experience and scientific concepts.
- It is important to provide an opportunity for students to explore the robotics kit before requiring them to work on a design challenge.
- Middle-school students, in particular, seem to need relatively specific guidance on how the robotics activities relate to Science and Engineering.
- The structure of the robotics environment combined with specific pedagogical approaches foster the thinking and Science process skills.

3 The systematic review process

A systematic literature review (often referred to as a systematic review) is a way of identifying, evaluating and interpreting all available studies relevant to a particular research question, or topic area. There are many reasons for undertaking a systematic literature review. The most common reasons are (Kitchenham and Charters, 2007):

1. To summarize the existence of evidence concerning a treatment or technology.
2. To identify any gaps in current research in order to suggest areas for further investigation.

3. To provide a background in order to appropriately positioning new research activities.

In this work, we applied this systematic approach to provide an overview about recent research in educational robotics, which can assist in the foundation of new researches.

In order to perform this review, we followed a defined process for conducting systematic reviews based on (Kitchenham and Charters, 2007), covering the stages and activities indicated in Figure 1.

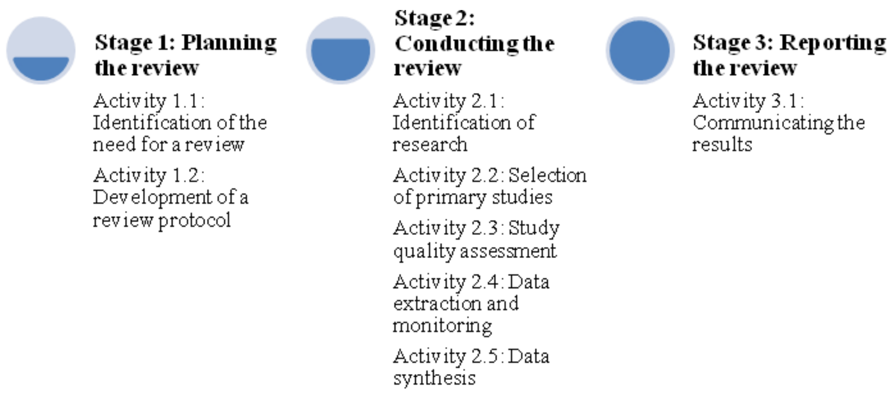

Fig. 1 Systematic review process: stages and activities.

3.1 Planning the review (Stage 1)

Initially, we have performed a search to identify the existence of systematic reviews involving robotics in STEM teaching. The main studies involving review in this issue are listed in Section 2. We then observed that they do not have a comprehensive and current review on the subject. Thus, we proposed to continue and expand the study carried out by Benitti (2012).

Within the context of this paper, we carried out a systematic literature review in order to examine the state of research in educational robotics, based on the following research questions:

1. What concepts are considered and how are they explored?
2. What skills are expected to be developed?
3. How is educational robotics associated with school curriculum?
4. What types of robots are used?
5. What age groups/educational levels are considered?
6. How is educational robotics evaluated?

To perform the SLR, the databases in which the search should be performed were defined. They were selected based on popularity on previous reviews in Education and related areas: ACM, EBSCO, ERIC, IEEE Xplore, Science Direct, Scopus, Springer Link, Web of Science and Wiley Interscience. Searches were restricted to peer-reviewed articles or conference papers, written in English, and published between 2013 and 2016 (research over the last four years). The search string used was: "robotics AND stem".

The selection criteria were used to evaluate each of the studies recovered from the search sources. Thus, the Inclusion Criterion (IC) applied to include relevant studies in our systematic review was:

- IC1: The primary study presents a description of robotics applications to support STEM teaching.

Moreover, the Exclusion Criteria (EC) were used to exclude studies that do not contribute to answer the research questions. In particular, the exclusion criteria considered in our SLR were:

- EC1: The publication does not consider robots application to support the development of STEM concepts or skills.
- EC2: The publication does not evaluate educational robotics in an elementary, middle and high school context.
- EC3: Duplicated publications by the same authors (Similar title, abstract, results or text). In this case, only one is kept.
- EC4: Publications composed of only one page (abstract papers), posters, presentations, proceedings, program of scientific events and tutorial slides.
- EC5: Publications hosted in web pages which are not accessed through the account of the Federal University of Santa Catarina, the Western Paraná State University or the University of São Paulo.

- EC6: Publications written in a language different than English.

The second author independently extracted the data – Table 2. Conflicts found during this process were resolved by discussion between the authors.

Table 2 Data extracted from each primary study selected.

Group	Information item
Group 1. Publication identification	IE1. Publication ID
	IE2. Publication title
	IE3. Year of publication
	IE4. Authors' name
	IE5. Students' age group/educational level
	IE6. Publication objective
	IE7. Publication source
	IE8. URL
Group 2. Activities reported in the publication	IE9. Duration of the educational robotics activities
	IE10. Motivation to use educational robotics
	IE11. Robot used
	IE12. Robot price
	IE13. Knowledge areas/subjects taught through robotics
	IE14. Skills taught through robotics
	IE15. Teachers' or tutors' training to deal with robots
	IE16. Learning theory used
	IE17. Educational robotics association with curriculum
Group 3. Evaluation described in the publication	IE18. Assessment approach (quantitative, qualitative or both)
	IE19. Sample size
	IE20. Reliability/validity analysis conducted during quantitative analysis
	IE21. Short description of the quantitative study
	IE22. Statistical test used
	IE23. Study type (non-experimental, quasi-experimental or experimental)
	IE24. Sample design/target selection conducted
	IE25. Sample composition and coverage
	IE26. Data collection procedure

3.2 Conducting the review (Stage 2)

The systematic review was conducted in April 2016 by executing the protocol. The process observed the steps shown in Figure 2, from which 60 out of 538 pieces of work were selected. The conduction of the studies was done in three steps:

1. Identification of candidate studies: pieces of work were collected by applying the search string in the databases selected. Table 3 outlines the specific search strings used for each source considered.
2. Selection of relevant studies: using a search string does not guarantee that all the material that was collected is relevant to the research context. Thus, after the identification of publications obtained through the search engines, the studies were analyzed according to the criteria established for exclusion.
3. Information extraction and synthesis: after setting the final list of relevant publications, the necessary information related to the research objective was extracted from them.

A quality strategy enables one to assess the selected studies in terms of methodological criteria. In Table 4, the 8 quality criteria considered by us are mentioned. Note that criteria QC3a, QC4a and QC5a are designed specifically for selected publications that quantitatively assess learning based on robots, while QC3b, QC4b and QC5b do the same for pieces of work regarding qualitative evaluations.

One can consider two approaches to deal with the assessment results: (1) supporting the synthesis of the selected publications or (2) specifying more detailed selection criteria. In this work, the first approach was adopted.

Based on the information items extracted and on the quality criteria applied, we conducted a synthesis to answer the research questions.

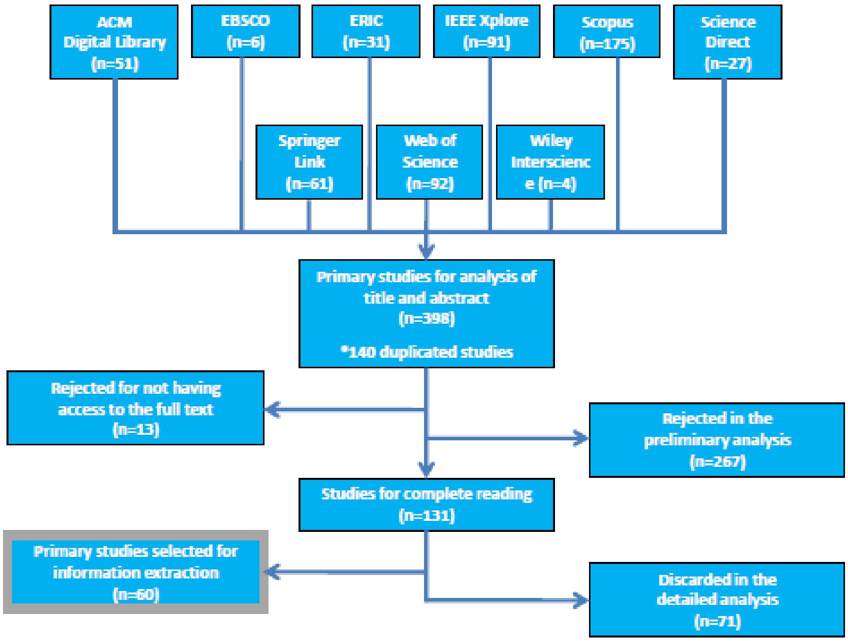

Fig. 2 Process of selecting primary studies.

Table 3 Digital libraries and associated search strings.

Database	Search String
ACM Digital Library	recordAbstract:(+robotics +STEM), published between the years 2013 and 2016
EBSCO (Teacher reference center)	title (robotics AND stem) OR subject terms (robotics AND stem) OR abstract (robotics AND stem), published between the years 2013 and 2016 peer reviewed only
ERIC	abstract:(robotics AND stem) pubyear: 2016-2013
IEEE Xplore	((“Abstract”:robotics) AND “Abstract”:STEM), published between the years 2013 and 2016
Science Direct	pub-date 2012 and TITLE-ABSTR-KEY(robotic) and TITLE-ABSTR-KEY(stem).

Scopus	TITLE-ABS-KEY (robotics AND stem) AND (LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013)) AND (EXCLUDE (DOCTYPE , “ch”) OR EXCLUDE (DOCTYPE , “ed”) OR EXCLUDE (DOCTYPE , “no”) OR EXCLUDE (DOCTYPE , “sh”)) AND (LIMIT-TO (SUBJAREA , “ENGI”) OR LIMIT-TO (SUBJAREA , “COMP”) OR LIMIT-TO (SUBJAREA , “SOCI”) OR LIMIT-TO (SUBJAREA , “EART”) OR LIMIT-TO (SUBJAREA , “MATH”) OR LIMIT-TO (SUBJAREA , “AGRI”) OR LIMIT-TO (SUBJAREA , “MATE”) OR LIMIT-TO (SUBJAREA , “CENG”) OR LIMIT-TO (SUBJAREA , “NEUR”) OR LIMIT-TO (SUBJAREA , “ENVI”) OR LIMIT-TO (SUBJAREA , “DECI”) OR LIMIT-TO (SUBJAREA , “MULT”) OR LIMIT-TO (SUBJAREA , “PSYC”))
Springer Link	(robotic AND stem), within Education & Language Social Sciences, published between the years 2013 and 2016 (robotic AND stem), within Education & Language Computer Science, published between the years 2013 and 2016
Web of Science	(robotics AND stem), years: 2013-2016 and type: article
Wiley Interscience	(robotics AND stem) in Article Titles OR (robotics AND stem) in Abstract OR (robotics AND stem) in Keywords between the years 2013 and 2016

Table 4 Criteria used to access the methodological quality of selected publications.

ID	Quality criterion
QC1	Have the teachers or the mentors been trained to use educational robotics?
QC2	Is educational robotics application based on any learning theory?
QC3a	Is there a comparison or control group? (Greenhalgh, 2000)
QC4a	Does the quantitative assessment described in the publication involve a statistical analysisof significance? (Crombie, 1996)
QC5a	Is any reliability or validity analysis carried out during the quantitative analysis?
QC3b	How well defined are the sample design/ target selection of cases/documents? (Petticrew and Roberts, 2005)
QC4b	How well is the eventual sample composition and coverage described? (Petticrew and Roberts, 2005)
QC5b	How well was qualitative data collectioncarried out? (Petticrew and Roberts, 2005)

3.3 Reporting the review (Stage 3)

Information extracted from each one of the 60 selected pieces of work (Figure 2) are published in a spreadsheet publicly available (https://goo.gl/AJcIyv). By assessing the methodological quality of these publications, it was possible to find 13 papers that accomplishes at least 3 quality criteria (Nugent et al, 2016; Sullivan and Bers, 2016; Christensen et al, 2015; Kaloti-Hallak et al, 2015a,b; McKay et al, 2015; Modekurty et al, 2014; Yuen et al, 2014; Abaid et al, 2013; Flannery and Bers, 2013; Nag et al, 2013; Sullivan and Bers, 2013; Kazakoff et al, 2013).

Section 4 focuses on these highlighted papers and on the synthesis conducted by us to answer the research questions.

4 Results and discussion

In what follows, the research questions are answered according to findings from the 60 papers selected by the systematic review. Table 5 specifies an identifier for each of these publications. Additional information regarding the papers are available in the supplementary material (https://goo.gl/AJcIyv).

Table 5 Identifiers of the 60 papers selected by the systematic review.

Identifier	Paper citation	Identifier	Paper citation
#1	(Abaid et al, 2013)	#31	(Laut et al, 2015)
#2	(Akiva et al, 2015)	#32	(Liu et al, 2013)
#3	(Ayar, 2015)	#33	(Martin et al, 2013)
#4	(Barger and Boyette, 2015)	#34	(McKay et al, 2015)
#5	(Brown and Howard, 2014)	#35	(McKay et al, 2013)
#6	(Bussi and Baccaglini-Frank, 2015)	#36	(Modekurty et al, 2014)
#7	(Catet´e et al, 2014)	#37	(Montironi et al, 2015)
#8	(Chen et al, 2015)	#38	(Nag et al, 2013)
#9	(Christensen et al, 2015)	#39	(Nemiro et al, 2015)
#10	(Chung et al, 2014b)	#40	(Nugent et al, 2016)
#11	(Chung, 2014)	#41	(Phamduy et al, 2015)
#12	(Chung et al, 2014a)	#42	(Pinzon and Huerta, 2014)
#13	(de Crist´oforis et al, 2013)	#43	(Prayaga et al, 2013)
#14	(Deken et al, 2013)	#44	(Qidwai et al, 2013)
#15	(Eguchi, 2016)	#45	(Rao, 2015)
#16	(Erickson-Ludwig, 2015)	#46	(Rubenstein et al, 2015)
#17	(Flannery and Bers, 2013)	#47	(Sahin et al, 2014)
#18	(Galley et al, 2015)	#48	(Sala et al, 2014)
#19	(Garcia et al, 2014)	#49	(Saleiro et al, 2013)
#20	(Gucwa and Cheng, 2014)	#50	(Sallee and Peek, 2014)
#21	(Hamner and Cross, 2013)	#51	(Senaratne et al, 2014)
#22	(He et al, 2015)	#52	(Suescun-Florez et al, 2013)
#23	(He et al, 2014)	#53	(Sullivan and Bers, 2013)
#24	(Jackson, 2013)	#54	(Sullivan and Bers, 2016)
#25	(Jeon et al, 2016)	#55	(Talley et al, 2013)
#26	(Kaloti-Hallak et al, 2015a)	#56	(Tewolde and Kwon, 2014)
#27	(Kaloti-Hallak et al, 2015b)	#57	(Tuluri, 2015)
#28	(Karp and Maloney, 2013)	#58	(Ucgul and Cagiltay, 2014)
#29	(Kazakoff et al, 2013)	#59	(van Delden and Yang, 2014)
#30	(Larkins et al, 2013)	#60	(Yuen et al, 2014)

4.1 What concepts are considered and how are they explored?

We tried to pull of the selected studies which contents were the focus of learning through robotics. After, we classify the content in STEM areas. This was an arduous task, since few publications clearly explain the contents that were addressed. For this reason, some contents are very specific and other contents were described more generally (such as robotics, for example). Tables 6 and 7 indicate subjects considered in the 60 publications collected from the literature.

Table 6 Subjects and related topics explored in the selected papers: Science and Technology.

Science	Technology
hypothesis formulation (#13)	robotics (#1, 2, 3, 4, 8, 10, 13, 14, 15, 16, 18, 21, 24, 27, 31,
astronomy (#42)	36, 38, 39, 44, 45, 46, 50, 53, 58, 60)
-terraforming (#30)	art platforms (#54)
-space exploration (#30)	computer aided engineering (#48)
-satellite control (#38)	computer science (#7)
body resistance (#57)	-cyber security (#18)
buoyancy (#34, 35)	-input-output (#26)
ecology	-interfacing with sensors (#26)
-recycling (#29, 49)	energy monitoring (#9)
-resource reuse (#49)	excel and matlab (#48)
-natural environment (#1, 31)	gear (#10, 34, 35, 37, 40)
-biodiversity (#31)	navigation (#44)
-marine pollution (#41)	programming (#2, 3, 6, 13, 16, 17, 18, 23, 24, 25, 30, 32, 33, 34,
electrical conductivity (#57)	35, 36, 37, 38, 39, 40, 44, 45, 46, 47, 52, 55,58, 59, 60)
inquiry (#40)	-visual programming (#29, 51, 53)
investigation (#28)	-control flow (#53, 54)
marine science (#1, 31)	-programming logic (#12, 54)
materials science (#48)	-Java programming (#12)
Newton's law of cooling (#57)	-programming action sequencing (#54)
photonics and lasers (#48)	-smart phone programming (#56)
physics concepts (#43)	-algorithmic thinking (#32)
thermal science (#48)	-general programming (#32)

	sensors (#4, 10, 13, 18, 30, 40, 44, 46, 53, 54, 58, 60)
	telemetry (#38)
	sturdy building (#54)

Table 7 Subjects and related topics explored in the selected papers: Engineering, Mathematics and Others.

Engineering	Mathematics	Others
advanced manufacturing (#48)	algebra (#4, 20)	"Me and My Community" (#54)
caudal fin building (#1, 31)	fractions (#40)	Theather and Poetry (#21)
computer engineering (#48)	functions (#10)	Arts (#25)
design (#4, 18, 30, 37, 38, 44, 55)	geometric progress (#12)	music (#12)
electrical engineering (#48)	geometry (#6, 10, 37)	boat structure and navigation (#8)
electromagnets (#59)	math education (#5)	
electronics (#3, 16, 18)	ratios (#40)	
engineering design (#21, 40)	reasoning (#49)	
engineering design process (#34)	Sequencing (#29)	
fluid power system (#19)	system of equations (#10)	
geotechnics (#52)	math education (#5)	
hydraulics (#19)		
industrial robotic principles (#59)		
manufacturing (#3, 4)		
mecatronics (#31)		
mechanics (#4, 24, 30, 37, 58)		
mechanics of materials (#48)		
mobile robotics (#56)		
pneumatics (#19)		
solar energy use (#55)		
some basic engineering (#59)		
robot modeling (#47)		

By focusing on the 13 papers highlighted on the previous quality assessment (Section 3), one can find examples of how the concepts are explored. Nugent et al (2016), for example, report positive results achieved by a comprehensive program for the youth conducted on informal (out of school) learning environments, such as robotics camps, clubs and competitions. This program requires from students Science, engineering, Mathematics and robotics concepts by including in each activity:

- Introductory material related to the focused concept and skills.
- A guided primary exercise with step-by-step instructions.
- An exercise that asks the youth to either research applications of the concepts or to record their efforts.
- A team exercise based on robots.
- A challenge that asks the youth to work as a team to solve a given problem with little facilitator guidance.

Their program is associated with a curriculum that consists of nearly 40 hours of instruction, in which each task typically needing one to four hours to be completed. Samples of tasks cover such skills such as writing simple programs, programming the movement of robot motors and the navigation based on sensors. Most of the robotics tasks are accomplished by pairs of students, while more advanced challenges are solved by groups of three or four students.

The reported results suggest that the program promotes gain in knowledge in some areas, such as Engineering and Robotics. This finding, based on non-experimental and quasi-experimental studies, may reflect the lack of an engineering course in middle school and the unique abilities required to program a robot.

Sullivan and Bers (2016) assess an 8-week robotics curriculum that supports teaching foundational robotics for children from pre-kindergarten to second grade classes. The program consists of the following lessons, which guide children to explore basic robots parts, sensors and robot navigation.

- What is a robot and what is programming?
- What is a sound sensor?
- What are repeat loops?
- What are distance and light sensors?
- What are conditional statements?
- Final project.

First, the children explored the basic parts of a robot and had the first contact with a programming environment based on wooden blocks with barcodes. After constructing the robot, organizing the blocks and using an embedded scanner, the students read the barcodes associate with commands to program the robot to dance. In the next lessons, the children made programs to allow the robot to interact with humans by the sound sensor and with the environment with the other sensors. Finally, the pupils made floor maps and programmed the robots to navigate on it.

As part of the study assessment, the children were asked to help the researcher identify different parts of the robot and their functions. As a result, it was noted that the students had a good understanding of the functions of each robot part. In addition, no significant difference was found among the classes, indicating that all children were able to master the robotics concepts similarly, regardless of what grade they were in.

It should be emphasized that each classroom moved at a pace that was comfortable for it. Thus, although all classes conducted robotics and programming activities during 8 weeks, not all grades followed all topics. In particular, pre-kindergarten children focused on the initial lessons, while the remaining classes were able to spend time experimenting with the different sensors and programming constructs.

McKay et al (2015) use WaterBotics, a challenge-based curriculum, to stimulate k-12 students to develop physical science concepts, such as buoyancy and stability. These concepts are explored in underwater robots, demanding a complexity level not found in many land-based robotics programs. To do so, a series of four challenges (missions) is managed to gradually lead to the production of a fully functional robot.

1. Rescue a drowning swimmer represented by ping pong balls by programming a single motor to follow a straight trajectory.
2. Clean a pollution spill (scattered balls) by programming two motors to enable steering and 2D movement.
3. Disable underwater mines by using a third motor to dive to the bottom of the pool in a 3D movement to achieve inverted plastic cups.
4. Collect objects (balls) from an imaginary sunken ship and deposit them in bins by using a fourth motor to grab and release the objects.

In particular, the youth focus on a group of robot capabilities in each mission, planning, designing, building, testing and iteratively improving a robot. This allows students to benefit from knowledge and experience gained in previous missions. Although the method evaluation did not show significant improvement in concept learning, students felt they had learned and their teachers agreed.

Flannery and Bers (2013) consider the CHERP programming language to support children to explore powerful ideas from technology-based domains that are often and unnecessarily reserved for older children or adults. In particular, their study is conducted as part of the TangibleK project, a program intended to detail what kindergarteners can understand about the robots programming concept. As part of the study, the participants are exposed to programming concepts and challenges, while the reasoning of each child is categorized into different developmental levels. In particular, the students attended a session for pre-assessments and introduction to the technologies. Afterwards, they participated in three sessions in which they built a robot vehicle, learned new programming concepts, attempted a challenge to program the robot to dance and reflected on their work.

By analyzing the programming achievement, the authors expect that children in different stages of cognitive development would benefit from learning goals, activities and scaffolding designed specifically for their characteristics.

It should be emphasized that educational robotics supported the exploration of different concepts in other papers found by the systematic review, as illustrated by (Akiva et al, 2015; Ayar, 2015; Barger and Boyette, 2015; Erickson-Ludwig, 2015; McKay et al, 2015; Montironi et al, 2015; Rubenstein et al, 2015; Brown and Howard, 2014; Chung et al, 2014b; Garcia et al, 2014; Laut et al, 2015; Karp and Maloney, 2013; Larkins et al, 2013; Liu et al, 2013; Martin et al, 2013; Suescun-Florez et al, 2013) – Tables 6 and 7.

4.2 What skills are expected to be developed?

The most usual skills found in the 60 reviewed papers are related to:

1. Teamwork.
2. Problem solving.

In addition, some selected publications report experiences on competition, mathematical skills, communication, brainstorming, presentation, creative thinking, critical thinking, strategy making and leadership.

Nag et al (2013) introduce the use of collaborative games as a bridge between space-based engineering and STEM and Computer Science education. To develop the teamwork, strategy making, leadership and communication skills, the authors assume as a tenet that collaboration and competition are not mutually exclusive. In particular, the potential to establish social interaction in some games is noted as an issue to support collaboration, even in a competition environment. As part of the evaluation of the learning quality, it was recorded that the k-12 participants found their leadership, teamwork and strategy making skills the most improved. For the leadership skill, this finding was similar to the one reported by the students' mentors.

Although Kazakoff et al (2013) applied the CHERP programming language for children, their focus was on developing sequencing. This important mathematical skill for early childhood is a component of planning and involves putting objects or actions in the correct order (Zelazo et al, 1997). As a result of using robots in this context, it was found a significant increase in terms of sequencing scores for both prekindergarten and kindergarten students.

4.3 How is educational robotics associated with school curriculum?

Figure 3 summarizes how educational robotics is associated with school curriculum. In particular, three categories are considered:

1. Curricular: papers using robots according to a curriculum in a school.
2. Extracurricular: robots applications unrelated to a school curriculum.
3. Hybrid: publications that either combine out-of-school or afterschool activities with a robotics curriculum, or report in-school and out-of-school activities grounded on a curriculum.

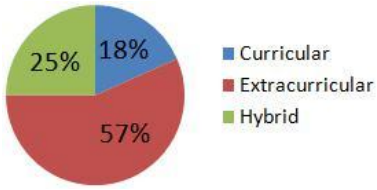

Fig. 3 Types of association between educational robotics and a curriculum.

The systematic review results suggest that most of the selected papers fall into the Extracurricular or Hybrid categories. In what follows, a few of the 13 publications highlighted in the previous assessment are considered.

Sullivan and Bers (2013) follow the TangibleK Robotics program, which consists of six lessons regarding topics related to Robotics, Physics and Programming. In particular, the lessons include introduction to a design process, robotics kits, control flow in a program and sensors. Furthermore, the curriculum is designed for a minimum of 20 h of classroom work and is implemented with the support of the CHERP language and the LEGO Mindstorms robot. The authors report an evaluation of TangibleK in 3 kindergarten classrooms, such that 53 students were exposed to the experience. It should be emphasized that the program was also considered in other publications, as exemplified in (Flannery and Bers, 2013; Kazakoff et al, 2013).

McKay et al (2015) exemplify the hybrid category. In particular, the WaterBotics curriculum was carried out in in-school and out-of-school environments. This program includes Science lessons embedded within missions with “achievements” that teams can earn. In this sense, the program is an alternative to competition-driven curricula, making it attractive to youth who may not yet have established STEM identities, interest and self-confidence. Moreover, WaterBotics focus on a few instructional design principles:

1. Design-based activities support Science learning.
2. Robotics learning represents a powerful learning opportunity for diverse youth.
3. Science content learning is scaffolded through mastery of a series of increasingly complex design challenges.

Abaid et al (2013) illustrate the extracurricular category with an outreach experience in the New York Aquarium. It was designed to ignite K-12 students' interest in STEM and attract them toward Engineering careers. As an educational tool, the authors considered a robotic fish easy to control by young participants. To act as a bridge between the knowledge of elementary and middle school students and the authors, two high school students were selected and trained. In this scenario, a student exposed to the experience typically participated in the following route:

1. Observing different fish species.
2. Making of caudal fins.
3. Mounting a fin on the robot and controlling its swimming.
4. Attending to a high school students' talk.
5. Observing robot pieces.
6. Answering a survey about the experience.

4.4 What types of robots are used?

The most usual robots found in the group of 60 chosen papers correspond to:

1. LEGO robotic kits (25 papers).
2. VEX robots (3 papers).
3. Robotic fish (3 papers).

LEGO robots consists in the most popular choice, as indicated in 25 out of the 60 papers. The potential to include varied sensors and the support for a few traditional programming languages are some reasons that explain this popularity. They are used to support the development of different concepts and skills, as illustrated by Nugent et al (2016); Kaloti-Hallak et al (2015b,a); McKay et al (2015); Yuen et al (2014); Flannery and Bers (2013); Kazakoff et al (2013); Sullivan and Bers (2013).

VEX robots, in turn, are selected for educational robotics in (He et al, 2015, 2014; Liu et al, 2013). These machines can be combined with remote control devices and microcontrollers associated with an environment that supports visual programming. Benefits for VEX users include robustness against shocks and good availability of sensors.

As can be seen in the literature, robotic fish is also considered in a few papers (Laut et al, 2015; Phamduy et al, 2015; Abaid et al, 2013). This bio-inspired robot contains an artificial flapping tail that approximates the locomotion of some animal species and can be managed remotely by an interface similar to a video game controller. The authors indicate that the entire system costs under US$ 100 on a limited production basis.

The following robot models are employed by only one or two publications: Kiwi (Sullivan and Bers, 2016), Linkbot (Montironi et al, 2015; Modekurty et al, 2014), Aerobot (Rubenstein et al, 2015), Hummingbird (Akiva et al, 2015), Proteus (Ayar, 2015), Bee-bot (Bussi and Baccaglini-Frank, 2015), a boat robot (Chen et al, 2015), Darwin-OP (Brown and Howard, 2014), SIFEB (Senaratne et al, 2014), Khepera (de Cristóforis et al, 2013) and Infante (Saleiro et al, 2013). One also can find alternatives in the literature, such the use of virtual robots (Gucwa and Cheng,2014; Martin et al, 2013) or telerobotics (Prayaga et al, 2013). The latter idea is particularly attracting when the cost per student must be reduced, while the participants are still able to control real robots by a Web interface.

4.5 What age groups/educational levels are considered?

It was found in the selected papers the use of robots to support teaching in different educational levels. Table 8 associates each level with the corresponding publications, which in turn are indicated by the identifiers specified in Table 5.

Christensen et al (2015) evaluate their program with three groups of participants:

1. Middle Schoolers Out to Save the World (MSOSW).
2. Communication, Science, Technology, Engineering and Mathematics (CSTEM) program.
3. Texas Academy of Mathematics and Science (TAMS) program.

Table 8 Educational levels found in the selected papers.

Learning theories	References
Authentic learning	#39
Cognition-based theories	#17, 30
Collaborative learning	#22, 47, 60
Constructivist/constructionism	#13, 16, 29, 53, 58
Elaboration theory	#58
Embodied theory	#33
Experiential learning	#2, 4, 40, 50
Interactive learning	#25
Meaningful learning	#26
Problem-based learning	#19, 34
Project-based learning	#8, 36, 52
Self-determination theory	#3, 27
Semiotic mediation	#6

The MSOSW project involved participants from 8 US states. Supervised by teachers, they monitor energy use in specific places and study natural environment topics. The CSTEM afterschool program, in turn, engages middle school students in multi-age groups to solve challenges by industry professionals and learning activities regarding geoscience, creative writing, sculpture, film and photography. Finally, the TAMS residential program is designed for high school juniors and seniors who are high achievers and interested in Mathematics and Science.

Sullivan and Bers (2016) report learning outcomes achieved in a US public school that serves children in Pre-kindergarten through 3rd grade. A similar school type was found in (Kazakoff et al, 2013). It should be emphasized that some authors also used alternative terms to refer to the considered educational levels, such as K-4, K-8 and K-12 (Yuen et al, 2014; Nag et al, 2013; Suescun-Florez et al, 2013).

4.6 How is educational robotics evaluated?

The following types of learning assessment were identified in the 60 papers: quantitative, qualitative or both. Figure 4 indicates the frequency of each type in the group of publications.

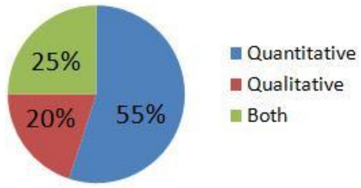

Fig. 4 Type of assessment conducted in a selected paper.

As can be seen, quantitative assessments are the most common choice (55%). McKay et al (2015) illustrate this category by taking surveys and students' achievements for further analysis. In particular, surveys intended to capture students' interest, enjoyment and learning, while the achievements attempted to identify learning outcomes in Physics. They also conducted the Mann-Whitney test to find if differences in specific results were significant. As an alternative to surveys, Yuen et al (2014) applied a group observation form to capture information related to students' observable behaviors and interactions that occur in collaboration during robotics projects.

Qualitative evaluations are found in 20% of the 60 references. To collect data from children, Ucgul and Cagiltay (2014) considered multiple strategies, such as semi-structured interviews, participant-observation, field notes and surveys. In addition, they applied intercoder agreement (Creswell, 2007), triangulation (Merriam, 2009) and other approaches to ensure the trustworthiness of the study. Nemiro et al (2015) also verified intercoder agreement in their evaluation in elementary schools.

Both quantitative and qualitative assessments were identified in some publications. Abaid et al (2013), for example, apply surveys with open-ended questions and with questions answered according to a Likert scale to participants of an outreach program associated with a US aquarium. Modekurty et al (2014) and Kaloti-Hallak et al (2015a) also illustrate this hybrid category.

Besides the assessment type, the research design was collected from the 60 pieces of work. Although the non-experimental setting is predominant (53 out of 60), there are a few illustrations of quasi-experimental settings. Nugent et al (2016), for example, compared outcomes found in robotics summer camp with the ones achieved by control group composed of students identified by some educational service units as youth with interest in technology and robotics. The experiment showed that the camp intervention led to a learning improvement, supplementing the non-experimental setting results.

4.7 Other findings

Besides the issues reported previously, we also collected additional information from the 60 references selected in April/2016. The publication year was one of the findings. As Figure 5 shows, a regular number of relevant papers have been published. In addition, it is expected that the number of pieces of work from 2016 increases as the year goes by.

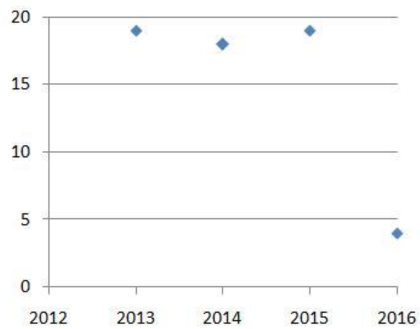

Fig. 5 Number of pieces of work published per year.

Another finding from the systematic review is that 26 educational robotics applications are clearly grounded in learning theories. Table 9 shows 27 study identifiers, as Ucgul and Cagiltay (2014) consider two theories in their work. The learning theory issue can be relevant, as represents a link between practice and theory in teaching supported by robots. Figure 6 shows that, from the theories used in more than 2 papers, the constructivist/constructionism theory (Papert, 1980; Piaget and Inhelder, 1967) is the most frequent one (5 occurrences), while experiential learning comes next (4 occurrences).

Table 9 Learning theories used in the literature.

Learning theories	References
Authentic learning	#39
Cognition-based theories	#17, 30
Collaborative learning	#22, 47, 60
Constructivist/constructionism	#13, 16, 29, 53, 58
Elaboration theory	#58
Embodied theory	#33
Experiential learning	#2, 4, 40, 50
Interactive learning	#25
Meaningful learning	#26
Problem-based learning	#19, 34
Project-based learning	#8, 36, 52
Self-determination theory	#3, 27
Semiotic mediation	#6

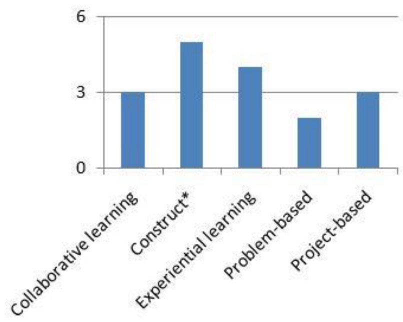

Fig. 6 Learning theory most used in the selected references.

5 Conclusions and perspectives

The present systematic review about robotics in STEM teaching was performed through the elaboration of a predefined protocol review that allowed us to identify and select our primary studies. From the 538 pieces of work initially identified, 60 studies were selected. Based on the synthesis conducted as part of the systematic review, we have observed that:

- By extracting information from 60 relevant publications, we noted that a large number of STEM concepts were considered in the literature. Although Technology and Engineering are more frequently associated with robots, Science and Mathematics also benefit from these powerful machines. These findings indicate the flexibility of robots as a supporting tool for learning. It also can inspire new applications of educational robotics on the same concepts or in related ones. Besides briefly describing a few highlighted examples of how these concepts were explored in classrooms, robotics camps and competitions, the current review reports information on this topic for all the 60 references by using a spreadsheet (https://goo.gl/AJcIyv).
- The mostly observed skills remain the same as reported in previous studies: teamwork and problem solving. We also can highlight the possibility of exploring the Engineering Design Process, illustrated by papers such as (McKay et al, 2015). When defining the problem, planning solutions, making a model, testing the model and reflecting and redesigning robots, students not only learn how technology works, but they also apply the skills and content knowledge learned in a meaningful way.
- The use of robotics as a predominantly extracurricular activity remains. It was not aim of this study to understand why – however, it can be a good topic for future research. Some hypotheses that can be considered are:

  - The schools do not have infrastructure to meet the amount of regular students.
  - Teachers have no knowledge to incorporate robotics into their practice.
  - It is not feasible due to the number of students and the need for follow-up.
  - Lack of methodological support.
  - Schools are not convinced that the result will be positive.

  Anyway, we need to understand the context, the needs and then propose solutions that integrate more robotics in the practice of the classroom.
- Karim et al (2015) identified 36 robots / toolkits suitable for use in the classroom. However, as noted in (Benitti, 2012) and (Karim et al, 2015), LEGO robots still consists in the most popular choice.
- We found robotics research at all educational levels. This is good news. However, kindergarten and pre-kindergarten concentrate the smallest

number of studies. We believe that there is much to research at this level.

- "Each primary type of qualitative data contributes unique and valuable perspectives about student learning to the outcomes-based assessment process. When used in combination, a more complete or holistic picture of student learning is created." (Bresciani et al (2009), p. 61). Similarly, we believe that the evaluation of research involving the application of robotics should include quantitative and qualitative analysis. At this point, only 25% of the considered studies used both approaches. Moreover, we highlight the need for more experimental studies in this area, once non-experimental settings are predominant. We agree with Karim et al (2015) and believe that it is necessary to standardize evaluation techniques used to quantify robot-based learning. In addition, statistical analysis, surveys and interviews could be merged to provide more complete findings.

It should be emphasized that this study was based on 60 articles located by using specific search criteria in 9 bibliographic databases. Other criteria and databases would, perhaps, have yielded more studies. The study should, therefore, be considered an attempt to explore the potential of educational robotics in STEM area, rather than a complete overview.

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