Robot Theatre to Boost Excitement, Engagement, and Expression (E3) of STEM

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ABSTRACT

This paper presents a novel framework for advancing informal STEM learning in kids between the ages of 10 and 15, using robotics as a platform, enabler, as well as channel for STEM. Being a cross-disciplinary technology, Robotics not only connects theory and applications of science, mathematics, and engineering fundamentals, but also delivers instant gratification from the efforts put in, through active hands-on human-robot interaction. Supported by multiple real-world feasibility studies, the presented framework hypothesizes that if made easy to build, teach, interact, and play with robots, it can be a potent facilitator of STEM, especially in young children – an age group which is naturally curious and enthusiastic about new findings. The feasibility studies have been conducted in collaboration with regional libraries and museums to develop and evaluate the presented robot-orchestrated STEM learning framework. The framework operates on a twofold approach. First, active engagement with the target audience is established by leveraging proven techniques from theatre arts. Second, situationally relevant STEM content is seamlessly inserted in the active engagement with the target audience emphasizing on positive reinforcement learning. The preliminary feasibility studies have revealed overwhelming excitement and demand for this technology from kids, parents, and teachers.

Keywords: STEM education, Robot-orchestrated learning, Human-robot interaction, Social robotics, Intelligent Robots.

1. INTRODUCTION

STEM attrition is evidently one of the major contributors to the increasing worker gap in the United States. In the current geopolitical environment where the U.S. is striving to boost its onshore high-tech manufacturing and job growth, the demand for domestic STEM workforce, is paramount. STEM education not only offers the competency to become self-reliant but also to achieve social equality, especially in underserved communities. Using the number of STEM job postings in recent years as a real-time indicator of the demand for STEM-skilled workers, a recent report [1] on the worker gap in the U.S. suggests that "The median duration of advertising for a STEM vacancy is more than twice as long as for a non-STEM vacancy." This study also sheds light on the post-recession rapidly growing demand for STEM jobs and non-uniform regional supply of workers. Another study [2] using a similar data acquisition approach to examine job postings and unemployment data from 2010 to 2016 has corroborated the account of the United States' persistent and large shortage of STEM workers. There are many more recent surveys supporting the trend of growing demand for STEM workforce and diminishing job/college ready people. The U.S. Department of Commerce in its 2017 update [3] on STEM jobs has listed 56 specific occupation codes for STEM related jobs and 66 STEM undergraduate degree fields that span computer science and mathematics, engineering, and life and physical science. This suggests that there is more than enough STEM training available at the higher education level. In spite of this and the growing demand, the insufficiency in the number of STEM workers can thus majorly be accredited to the lack of a sound foundational preparation platform at the school levels. It is noteworthy that instructors at the college and university levels are specialists in their subject matter, while at the school levels, especially at the lower grades, instructors are more of generalists as they are expected to manage the overall curriculum in classrooms. This invariably results in oversimplification of STEM concepts, thereby, creating a step-wise knowledge building in children's STEM education, which ideally should have been a continuous process.

Cognitive neuroscience research on the correlation between performance in cognitive tasks and brain activation in specific regions, such as the prefrontal regions, reveals that the prefrontal regions develop rapidly during early childhood [4]- [5]. Studies in this area suggest that, in fact, the child's cognitive performance can be enhanced at an early age through experiential learning [6]. Additionally, the collaborative craft of theatre can emphasize genuine experiential learning and engages children multi-modally with technology platforms and the heuristic concepts of structured movement, speech and text, narrative, and affect recall. Logistical challenges, however, such as spatiotemporal limitations of the classroom setting, safety concerns in working with hardware and tools, and accessibility/affordability to appropriate content and guidance, often inhibit the implementation of experiential learning for science and engineering technologies. Recent remedial initiatives such as instructional experiences aligned in the psychologically based Learning Cycles, such as the 5E model that stands for Engage-Explore-Explain-Elaborate-Evaluate, is a much anticipated feature of future classrooms. As a supplement to formal education, informal STEM education can be a powerful method to boost the child's STEM concept understandings and, more importantly, ability to relate and apply STEM knowledge in real world scenarios, given the fact that children in K-12 grades spend a majority of their waking hours outside the classroom.

This aim of the work presented in this paper is to provide early childhood exposure to STEM education, especially through experiential learning in informal settings, for the development of the future generation of the workforce. This paper is organized as follows: section 2 reports some of the current state of the art technology utilizing robotics for STEM education. Section 3 introduces the target innovation space for the presented framework. Section 4 presents the unique implementation of interdisciplinary technologies to accomplish the targeted innovation. Section 5 presents the findings from the preliminary feasibility studies. Finally, section 6 concludes the discussion with the summary of work and future directions.

2. CURRENT STATE OF THE ART

Over the last two decades, robotic technologies have gained a great deal of popularity in formal and informal STEM education. Robotics has the potential to make significant impact towards improving formal classroom teaching as well as informal learning [7]. Even though there is no clear-cut definition for educational robotics, the use of robots in learning aligns with modern pedagogical theories [8] such as (*i*) principles of active learning [9] (*ii*) learning by design [10] (*iii*) constructionism theory [11] and (*iv*) social constructivism [12]. When used properly, robotic activities can be incorporated into teaching of various STEM topics effectively as it helps remove the abstractness [13] and allows better understanding. As robotics enables real-world applications of STEM concepts, it is an effective tool in STEM teaching [13]. Many schools have adopted robotics into their formal and/or informal curricula because of the excitement it brings into the learning environment [8]. Most of the use-cases, however, have been limited to the subjects that are close to programming, mechatronics, and robot building, which causes the robotics to stay a passive tool in the learning activity [7]. Other topics of robotic use for learning are mostly (almost 80%) related to mathematics and physics [7]. These topics include force, gravity, friction [14], speed and acceleration [15], work and energy [16], velocity, time and distance [17] from physics curriculum; angles [18], decimals [19], counting [20], fraction and ratios [21], and multiplication [22] from mathematics curriculum. When the skills that can be developed or improved by use of robotics are considered, we can list some examples from literature such as social communication skills [23], system understanding and thinking skills [24], problem solving skills [25], engineering design skills [26] and physics content knowledge skills [14]. Another aspect of robotics use in STEM education is the learning environment. Formal classroom activities are estimated to cover less than 18.5% time in K-12 learning which leads to a significant portion of student learning occurring outside of the classroom at informal learning settings [27]. That's why there are more than 1,100 informal science institutions in the United States, e.g. museums, zoos, aquariums, libraries, and youth organizations, which are serving students through workshops, demonstrations, camps, and field trips [28]. Use of robotics in informal STEM learning has been explored in the past through projects such as increasing museum visitors' experience with microbiology using Kinect [29], the project that involves "gesture-enabled, multi-touch spheres for teaching about ocean systems in science centers and museums" [30], the project to improve young children's inquiry-based science learning and engagement in museums using camera-based vision sensing [31], "Robotics and E-Textiles Backpacks for Family Learning" project [32], and "Bridging Earth and Mars (BEAM): Engineering Robots to Explore the Red Planet" [33].

Most of the aforementioned studies and projects use robotics as a passive tool, with minimal focus on Human-Robot Interaction (HRI), a key aspect in early childhood learning. Different people have different levels of attraction to robotic activities; some are interested in traditional ways, some are interested in some other creative ways (e.g. a mechanical puppet show) [7]. Social dynamics and interaction are as big a part of art as they are of science, and therefore, art based STEM learning is an interesting domain. Humans interact with each other through gaze, posture, gesture etc. and not through computer codes. Researchers have conducted studies [34] [35] [36] [37] on constructing virtual conversational agents, including how gaze, posture, movement, and other performance characteristics affect human participation. Based on the findings, multiple artificial intelligence modules [38] [39] have been proposed to make human-robot interaction more humanistic. ArticuLab at the Carnegie Mellon University has developed several virtual peers, called Embodied Conversational Agents (ECAs), to interact with humans through computer mediated contexts. These agents are designed to engage with a wide range of human subjects of different age groups in tutoring, socialization, gaming, and personal assistance roles [40]. A few other interesting projects that leverage enhanced human engagement strategy to teach STEM concepts are given in: Combining Craft and Performance to Teach Physical Computing [41], Orchestral Innovations in Science Education (OISE): An Experiment in Informal STEAM Learning [42], and EarSketch: An Authentic, Studio-Based STEAM Approach to High School Computing Education [43]. Jeon et al. in [44] and Barnes et al. in [45] presented their work with multiple humanoid and animal-like robots acting in a theatre production with elementary school-aged children in a variety of activities such as acting, dancing, and drawing. These studies, termed as robot theatre and robot opera, provide some insight to children's perception towards robots, especially from a social interaction stand-point. All students under the study expressed interest in learning about programming and building robots. While this program reported successful recruitment and extended engagement of the children, and also the long term impact of the learning with robots, it also reported substantial difficulty in managing the children and the robots at the same time. Although the result with the small sample size of this study is far from deriving any conclusive pattern about human-robot interaction in theatre settings, it does offer some valuable insight such as the need for autonomous and stable operations, advanced artificial intelligence for human-centric interaction, and combined use of theatre methods by the robots – the topics of this study. Interestingly, there are several instances of incorporation of robots in fine art. These include autonomous robots performing natural movements combined with character animation and control [46], biped androids with human-like face capable of facial expressions [47], and human-robot collaboration in drama [48].

Despite these initiatives, the U.S. Department of Education (DOED) reflects that significant challenges are still associated with STEM learning due to: student STEM enrollment and attrition, student perspectives on the value of STEM education, insufficient number of teachers skilled in STEM, quality of STEM education, and differences in accessibility to STEM education dependent on race, location, and economic status [49].

3. TARGET INNOVATION SPACE

The key innovation in the presented work lies in exploiting the subtle difference between knowledge and information. Most of the contemporary learning frameworks operate in a rule-based information-space, utilizing some form of analytical, experimental or statistical models to disseminate STEM contents, thereby bounding the free ideation and corresponding exploration. In the presented framework, a knowledge-based learning approach is adopted, which does not specify the content, rather lets its audience choose the content to explore. The built-in artificial intelligence (AI) of the framework then configures, in real-time, the appropriate discussion points, based on the ongoing interactions as well as past experiences. Figure 1 shows a hierarchical diagram of such knowledge-building process.

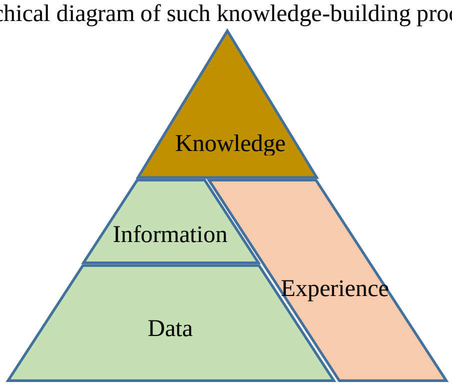

Figure 1: Knowledge-building process

The carefully choreographed theatrical interaction between humans and robots, as adopted in this framework, channels the child's efforts to go through the process of cognitive artifact creation through idea synthesis. Methods for delivery of the STEM topics, for example: dynamics of the solar system, robotic assembly and packaging, cooperative robots in the home and more, rely on better conceptualization and visualization instead of oversimplification, thereby allowing ample opportunities for critical thinking and problem solving.

Note that the artificial intelligence (AI) framework and robotic implementation brings in a synergistic capability of these two distinct technologies. Robots are programmable machines (or hardware) that can sense their environment and carry out a series of actions based on their specific operational modalities, which can be preprogrammed or tele-operated. On the other hand, artificial intelligence (AI) is a computer program (or software) that allows machine to have human-like intelligence to deals with tasks such as problem-solving, language/gesture/expression understanding, and logical reasoning. The robots used in the presented framework are artificially intelligence, in other words, they are autonomously controlled by AI software modules. The use of AI significantly alleviates the robots' limitations in performing complex tasks in human environments. Furthermore, this bridging between robotics and AI enables enhanced human robot interaction through theatre technologies that makes the "excite, engage, and express (E3)" model feasible.

4. THEATRE TECHNOLOGY FOR STEM LEARNING

Theatre arts methodology is a key enabler in the presented knowledge-based informal STEM learning framework as it offers the crucial freedom to the audience to explore their imaginations. Within the theatre canon, few performance techniques are as qualified to excite, engage, and express as the *Commedia dell'arte* performance technique. *Commedia dell'arte* is a 16th century performance technique founded by Italian folk artists based on improvisation, stock characters, and broad physicalization of comedic narratives [50]. Its influence on modern contemporary theatre and film/television through its seamless integration of comedy, physicalization and characterization [51], makes it a significant tool for the presented framework. In this framework, time-tested commedia theatre arts techniques are adapted and aligned with social robotics, technology, and STEM content to create a platform for excitement, engagement, and expression for children.

Additionally, theatre Arts is a collaborative discipline meshing the languages of many divergent fields; text, direction, design, and performance. It is learned and trained as a craft [52]. A human-robot interaction (HRI), specifically an interaction focusing on students utilizing a social robot as a platform for STEM technology, is essentially a performative event that can definitely inspire excitement and expression for the students. It is an event that needs the trust of an engaging social robot programmed with the complex social norms of interactions with humans. Recent studies have successfully used theatre as a model for research in social and emotional interaction. *Human-robot interactions as theatre* concludes, "Ultimately, all social interactions can be viewed as acting roles which the robot must perform" [53]. *On Stage: Robots as Performers*, develops the concept of performative arts alongside acting literature as a testbed and influencer of HRI [54].

The *Commedia dell'arte* is a particularly well-suited technique for informal STEM learning for the following reasons:
Improvisation: A comedic story is loosely based around a central theme, not directly scripted [55], critical for free thinking.
Characterization: Commedia stock comedy characters are varied, primary characters are defined as *Zanni* - a servant and/or trickster, *Pantalone* – a master and greedy egomaniac, *Dottore* - know-it-all old man, and *Innamorati* – young lovers, among many others. All commedia characters incorporate archetypal behaviors that students still see in their contemporary entertainment. *Mr. Burns* from *The Simpsons* is *Pantalone*, a greedy, miserly old man, while the *Spongebob* character from *Spongebob Squarepants* is a trusted servant, *Zanni* [56]. Time-honored stock characters originating from 16th century commedia are instantly recognizable to 21st century students who identify their commedia modern counterparts [57].
Physicality and movement games: Broad physicalizations and gesture is indicative of *commedia dell'arte*. Students who learn through the behavior, physicalization, and emotion of a stylized walk, pose, or rhythm learn STEM concepts through an innovative platform integrated with a robotic program.

For the discussed E3 framework, the defining characteristics of *commedia dell'arte*; i.e. improvisation, characterization, physical movement and audience participation are adapted for students interacting with a social robot teaching STEM concepts in an informal setting. The following methodology and structure frames how *commedia dell'arte* and its components of improvisation, characterization, and physicality and movement games are used to engage with students in an informal STEM learning narrative.

Steps to frame and structure commedia concepts to informal STEM learning concepts
Improvisation: An improvised script is essential for the students as scripted lines are neither easily accessible nor wanted as the

primary mode of communication in informal STEM. The framework does not produce a formal stage play with a robot, but rather utilizes all the exciting, engaging, and educational aspects of a stage play to infuse STEM concept for learners.

Characterization: The social robot will be the emcee/facilitator of the STEM content (*Zanni*) interacting with students first as the designator of character types, “Student A is *Pantalone*, Student B and C, *Innamorati*, etc.” The robot can also model and mirror the physical characteristics of each character for the students to learn in addition to facilitating STEM content that applies to the adapted commedia model. For example, for an astronomy lesson, The *Innamorati* may become the binary planet system, *Pluto* and *Charon*, described by the social robot as “the only binary planet in the solar system…likely formed…when the two objects collided” [58]. Commedia directives to the students would be the physical “orbit” around each other, not touching, but never far apart. Questions regarding proximity, retrograde orbit, mass, and surface temperature can be applied as students physically act their *Innamorati* parts of *Pluto* and *Charon*.

Physicality and movement games: The ability to learn kinesthetically, spatially, and interpersonally are educational theories that have been well-documented [59]. This framework utilizes the highly physical and creative theatre arts methodologies of commedia to not only excite and engage, but to establish an educational goal through the integration of a robot platform and STEM concepts. In summary, this effort identifies what specific types of interactions excite the target audience in order to design the HRI model.

Some of the suitable STEM topics that can leverage the E3 approach are: (i) Earth and Space Science, (ii) Electronics and Automation Engineering, (iii) Robot Programming, and (iv) Numerical Problem Solving. The presented framework uses game-oriented and reward-based STEM learning, encouraging kids to better their performances and share it in their community.

5. IMPLEMENTATION AND ANALYSIS

The authors are supporting a calendar of events at local public institutions such as libraries, museums, and Girl Scout events for informal STEM learning. The team’s participations in these events was to gather preliminary user response from a sample set of the target audience toward (a) pure instructor-based STEM education, (b) instructor-based STEM education aided by robot demos, and finally (c) social robot interacting with the audience to engage them in STEM topic discussions. Post-participation surveys gathered from a diverse audience pool suggests a strong preference for the presented “robot theatre for STEM” framework, further boosted by a large number of audience participation, in not only learning but also actively interacting/socializing with robots. A significant portion of the credit for these preliminary feasibility studies goes to the program development and outreach done in collaboration with the team’s informal STEM learning partners. Figure 2 shows a few snapshots from some of the different informal STEM learning sessions at these regional public institutions.

As indicated earlier, the presented informal STEM learning framework is implemented in two stages. First, engagement with the target audience is established by social robotic platforms such as humanoid robots, natural language processing artificial intelligence (AI) units, and other similar devices. These platforms utilize theatre art techniques including improved performance of a STEM content play, role play between the robot and the audience, characterization, and physicality for audience engagement via a personalized one to one or one to many conversation. Second, once the audience engagement is attained, the social robot’s AI gradually channels the interaction towards a selected STEM topic based on (i) a pre-defined hierarchical list of STEM topics, (ii) the detected audience interest area from the on-going interaction, and (iii) the standards for age and location appropriate content. During this stage, the presented framework uses other robotic platforms such as mobile robots, robotic manipulators, sensors etc., as needed to make the learning more experiential and entertaining for the target audience.

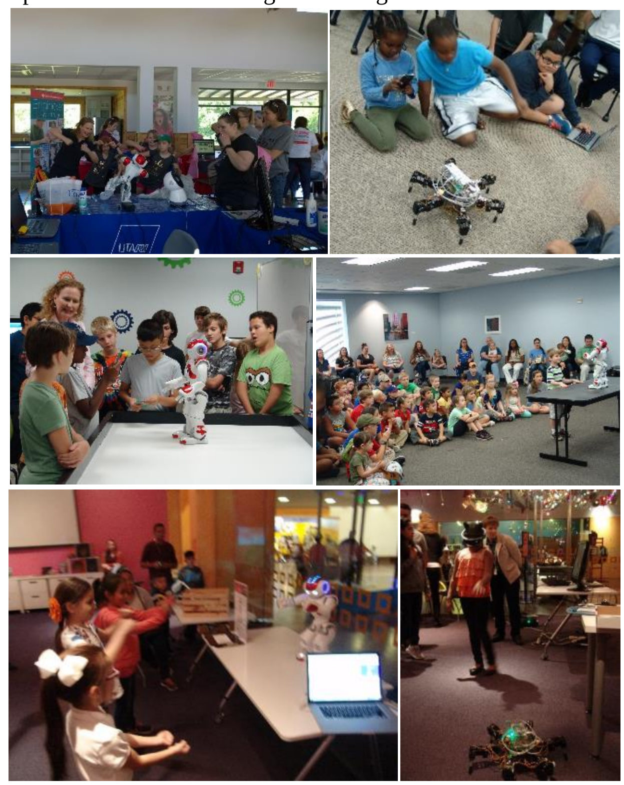

Figure 2: Robotic interaction with the audience at public events

6. CONCLUSIONS

STEM education is generally prohibitively expensive, especially for low income families, as it requires a combination of hardware and software tools to give the hands-on experience that the learners need to reinforce their conceptual knowledge. Through the presented framework, a large part of society can gain access to quality STEM education. The theatre art based robotic E3 STEM learning framework is envisioned to be easily and inexpensively made available to the target population, even in remote areas and at non-regular times. The presented E3 approach is a modified version of the well-known 5E Learning model used in science and mathematics education, which is grounded in research on the psychology of how children learn. The presented framework encourages audience participation, thus allowing the kids to not only learn by observing, listening, and building but also express themselves in this novel manned-unmanned teaming structure to share their ideas, queries, and accomplishments. The personalized and participatory nature of the discussed informal STEM learning framework offers encouragement to get actively engaged, something that is normally overlooked for underserved factions in the student population such as girls and minority groups in many STEM learning programs. The presented framework is envisioned to be an open platform, thereby allowing a wide range of innovators, programmers, engineers, educators and other interested contributors to customize, contribute, and focus on specific audience groups for new sessions on different STEM topics.

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9. REFERENCES

[1] J. Rothwell, "Still Searching: Job Vacancies and STEM Skills," The Brookings Institution, 1 July 2014.

[2] New American Economy, "Sizing Up the Gap in our Supply of STEM Workers: Examining Job Postings and Unemployment Data from 2010-2016," 29 March 2017.

[3] R. Noonan, "STEM Jobs: 2017 Update," U.S. Department of Commerce Economics and Statistics Administration, 30 March 2017.

[4] S. Tsujimoto, "The Prefrontal Cortex: Functional Neural Development During Early Childhood," *The Neuroscientist*, vol. 14, no. 4, pp. 345-358, 2008.

[5] N. Gogtay, J. N. Giedd, L. Lusk, K. M. Hayashi, D. Greenstein, A. C. Vaituzis, T. F. Nugent III, D. H. Herman, L. S. Clasen, A. W. Toga, J. L. Rapoport and P. M. Thompson, "Dynamic mapping of human cortical development during childhood through early adulthood," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 101, no. 21, pp. 8174-8179, 25 May 2004.

[6] J. H. Decker, F. S. Lourenco, B. B. Doll and C. A. Hartley, "Experiential reward learning outweighs instruction prior to adulthood," *Cognitive, Affective, & Behavioral Neurosci.*, vol. 15, pp. 310-320, June 2015.

[7] F. B. V. Benitti, "Exploring the educational potential of robotics in schools: A systematic review," *Computers & Education*, vol. 58, no. 3, pp. 978-988, April 2012.

[8] M. E. Karim, S. Lemaignan and F. Mondada, "A review: Can robots reshape K-12 STEM education?," in *2015 IEEE International Workshop on Advanced Robotics and is Social Impacts (ARSO)*, 2015.

[9] M. Harmin and M. Toth, Inspiring Active Learning: A Complete Handbook for Today's Teachers, ASCD, 2004.

[10] R. Goldman, A. Eguchi and E. Sklar, "Using Educational Robotics to Engage Inner-City Students with Technology," in *Proceedings of the 6th International Conference of the Learning Sciences*, Los Angeles, 2004.

[11] S. Papert, Mindstorms: Children, Computers, and Powerful Ideas, New York: Basic Books, Inc., 1980.

[12] L. S. Vygotsky, Mind in Society: The Development of Higher Psychological Processes, Harvard University Press, 1980.

[13] C. Kim, D. Kim, J. Yuan, R. B. Hill, P. Doshi and C. N. Thai, "Robotics to promote elementary education pre-service teachers' STEM engagement, learning, and teaching," *Computers & Education*, vol. 91, pp. 14-31, 15 December 2015.

[14] D. C. Williams, Y. Ma, L. Prejean, M. J. Ford and G. Lai, "Acquisition of Physics Content Knowledge and Scientific Inquiry Skills in a Robotics Summer Camp," *Journal of Research on Technology in Education*, vol. 40, no. 2, pp. 201-216, 2007.

[15] D. Alimisis and G. Boulougari, "Robotics in physics education: fostering graphing abilities in kinematics," in *Proceedings of 4th International Workshop Teaching Robotics, Teaching with Robotics & 5th International Conference Robotics in Education*, Padova (Italy), 2014.

[16] C. Saygin, T. T. Yuen, H. J. Shipley, H.-d. Wan and D. Akopian, "Design, Development, and Implementation of Educational Robotics Activities for K-12 Students," in *2012 ASEE Annual Conference & Exposition*, San Antonio, 2012.

[17] T. A. Mikropoulos and I. Bellou, "Educational Robotics as Mindtools," *Themes in Science and Technology Education*, vol. 6, no. 1, 2013.

[18] R. Mitnik, M. Nussbaurm and A. Soto, "An autonomous educational mobile robot mediator," *Autonomous Robots*, vol. 25, no. 4, pp. 367-382, November 2008.

[19] C. Rogers and M. Portsmore, "Bringing Engineering to Elementary School," *Journal of STEM Education: Innovations and Research*, vol. 5, no. 3-4, pp. 17-28, Jul-Dec 2004.

[20] A. Sullivan, E. R. Kazakoff and M. U. Bers, "The Wheels on the Bot Go Round and Round: Robotics Curriculum in Pre-Kindergarten," *Journal of Information Technology Education: Innovations in Practice*, vol. 12, pp. 203-219, 2013.

[21] B. S. Barker and J. Ansorge, "Robotics as Means to Increase Achievement Scores in an Informal Learning Environment," *Journal of Research on Technology in Education*, vol. 39, no. 3, pp. 229-243, 2007.

[22] C.-W. Wei, I.-C. Hung, L. Lee and N.-S. Chen, "A Joyful Classroom Learning System with Robot Learning Companion for Children to Learn Mathematics Multiplication," *Turkish Online Journal of Educational Technology*, vol. 10, no. 2, pp. 11-23, April 2011.

[23] G. Owens, Y. Granader, A. Humphrey and S. Baron-Cohen, "LEGO therapy and the social use of language programme: an evaluation of two social skills interventions for children with high functioning autism and Asperger Syndrome," *Journal of Autism and Developmental Disorders*, vol. 38, no. 10, pp. 1944-1957, 20 June 2008.

[24] F. R. Sullivan, "Robotics and Science Literacy: Thinking Skills, Science Process Skills and Systems Understanding," *Journal of Research in Science Teaching*, vol. 45, no. 3, pp. 373-394, 2008.

[25] S. Hussain, J. Lindh and G. Shukur, "The effect of LEGO Training on Pupils' School Performance in Mathematics, Problem Solving Ability and Attitude: Swedish Data," *Educational Technology & Society*, vol. 9, no. 3, pp. 182-194, 2006.

[26] D. B. Larkins, J. C. Moore, L. J. Rubbo and L. R. Covington, "Application of the cognitive apprenticeship framework to a middle school robotics camp," in

Proceeding of the 44th ACM Technical Symposium on Computer Science Education, Denver, 2013.

[27] D. Kotys-Schwartz, M. Besterfield-Sacre and L. Shuman, "Informal learning in engineering education: Where we are - Where we need to go," in *41st ASEE/IEEE Frontiers in Education Conference*, Rapid City, 2011.

[28] C. A. Haden, "Talking About Science in Museums," *Child Development Perspectives,* pp. 62-67, April 2010.

[29] National Science Foundation, "Award Abstract #1612831: Visitor Interactions in Microbiology: A New Genre of Science Museum Exhibits".

[30] National Science Foundation, "Award Abstract #1612485: Think Globally, Interact Locally: Advancing Science Learning using Interactive Spherical Displays to Model Global, Physical Systems".

[31] National Science Foundation, "Award Abstract #1612744: Intelligent Science Exhibits: Transforming Hands-on Exhibits into Mixed-Reality Learning Experiences".

[32] National Science Foundation, "Award Abstract #1516562: Robotics and E-Textiles Backpacks for Family Learning".

[33] C. f. A. o. I. S. Education, "Bridging Earth and Mars (BEAM): Engineering Robots to Explore the Red Planet," 2017.

[34] J. Allwood and L. Cerrato, "A Study of Gestural Feedback Expressions," in *Proceedings of the First Nordic Symposium on Multimodal Communication*, Copenhagen, 2003.

[35] T. Sinha, Z. Bai and J. Cassell, "A New Theoretical Framework for Curiosity for Learning in Social Contexts," in *Proceedings of 12th European Conference on Technology Enhanced Learning (EC-TEL '17J)*, 2017.

[36] H. Yu, L. Gui, M. Madaio, A. Ogan, J. Cassell and L.-P. Morency, "Temporally Selective Attention Model for Social and Affective State Recognition in Multimedia Content," in *Proceedings of the 2017 ACM on Multimedia Conference*, Mountain View, 2017.

[37] T. Sinha, Z. Bai and J. Cassell, "Curious Minds Wonder Alike: Studying Multimodal Behavioral Dynamics to Design Social Scaffolding of Curiosity," in *Proceedings of 12th European Conference on Technology Enhanced Learning (EC-TEL '17)*.

[38] O. J. Romero, R. Zhao and J. Cassell, "Cognitive-Inspired Conversational-Strategy Reasoner for Socially-Aware Agents," in *Proceedings of the Twenty-Sixth International Joint Conference on Artificial Intelligence (IJCAI '17)*, 2017.

[39] R. Zhao, T. Sinha, A. W. Black and J. Cassell, "Socially-Aware Virtual Agents: Automatically Assessing Dyadic Rapport from Temporal Patterns of Behavior," in *Proceedings of the 16th International Conference on Intelligent Virtual Agents (IVA '16)*, Los Angelis, 2016.

[40] Carnegie Mellon University, "ArticuLab: Projects".

[41] National Science Foundation, "Award Abstract #1612686: Combining Craft and Performance to Teach Physical Computing".

[42] National Science Foundation, "Award Abstract #1630154: Orchestral Innovations in Science Education (OISE): An Experiment in Informal STEAM Learning".

[43] National Science Foundation, "Award Abstract #1417835: EarSketch: An Authentic, Studio-Based STEAM Approach to High School Computing Edu.".

[44] M. Jeon, J. Barnes, M. FakhrHosseini, E. Vasey, Z. Duford, Z. Zheng and E. Dare, "Robot Opera: A Modularized Afterschool Program for STEAM Education at Local Elementary School," in *14th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*, Jeju, South Korea, 2017.

[45] J. Barnes, M. FakhrHosseini, E. Vasey, Z. Duford and M. Jeon, "Robot Theater with Children for STEAM Education," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 2017.

[46] C. Breazeal, A. Brooks, J. Gray, M. Hancher, C. Kidd, J. McBean, D. Stiehl and J. Strickon, "Interactive robot theatre," in *Proceedings 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Las Vegas, NV, 2003.

[47] C.-Y. Lin, C.-K. Tseng, W.-C. Teng, W.-C. Lee, C.-H. Kuo, H.-Y. Gu, K.-L. Chung and C.-S. Fahn, "The realization of robot theater: Humanoid robots and theatric performance," in *International Conference on Advanced Robotics (ICAR)*, Munich, Germany, 2009.

[48] G. Zeglin, A. Walsman, L. Herlant, Z. Zheng, Y. Guo, M. Koval, K. Lenzo, H. J. Tay, P. Velagapudi, K. Correll and S. Srinivasa, "HERB's Sure Thing: a rapid drama system for rehearsing and performing live robot theater," in *IEEE International Workshop on Advanced Robotics and its Social Impacts*, Evanston, IL, 2014.

[49] United States Department of Education, "Science, Technology, Engineering and Math: Education for Global Leadership".

[50] J. Rudlin, Commedia Dell'Arte: An Actor's Handbook, Taylor & Francis, 2002.

[51] theatreWashington, "John Aniello Award for Outstanding Emerging Theatre – Faction of Fools – 2012. Helen Hays Award (HHA) to heighten awareness of Washington Theatre".

[52] L. Strasberg, A Dream of Passion: The Development of the Method, Boston: Little Brown, 1987.

[53] D. V. Lu and W. D. Smart, "Human-robot interactions as theatre," in *IEEE RO-MAN*, 2011.

[54] G. Hoffman, "On stage: robots as performers," in *RSS 2011 Workshop on Human-Robot Interaction: Perspectives and Contributions to Robotics from the Human Sciences*, Los Angeles, CA, 2011.

[55] B. Grantham, Playing Commedia: A Training Guide to Commedia Techniques, London: Nick Hern, 2009.

[56] J. Rudlin, Commedia Dell'Arte An Actor's Handbook, London and New York: Ruutaledge, 1994.

[57] "How have the characters of the Simpson's been influenced by the stock characters of Commedia Dell'arte," 7 June 2014.

[58] N. T. Redd, "Charon: Pluto's Largest Moon," 23 February 2016.

[59] H. Gardner, Frames of Mind: The Theory of Multiple Intelligences, New York: Basic Books, 2011.