Introducing a K-12 Mechatronic NIME Kit

Kyriakos D. Tsoukalas
Human Centered Design
Virginia Tech
ktsoukalas@vt.edu

Ivica Ico Bukvic
SOPA, ICAT
Virginia Tech
ico@vt.edu

ABSTRACT
The following paper introduces a new mechatronic NIME kit that uses new additions to the Pd-L2Ork visual programing environment and its K-12 learning module. It is designed to facilitate the creation of simple mechatronics systems for physical sound production in K-12 and production scenarios. The new set of objects builds on the existing support for the Raspberry Pi platform to also include the use of electric actuators via the microcomputer's GPIO system. Moreover, we discuss implications of the newly introduced kit in the creative and K-12 education scenarios by sharing observations from a series of pilot workshops, with particular focus on using mechatronic NIMEs as a catalyst for the development of programing skills.

Author Keywords
Pd-L2Ork, microcomputer, K-12 education, robotic musicianship, mechatronics

ACM Classification
• Applied computing~Sound and music computing; • Applied computing~Computer-assisted instruction; • Hardware~Sensors and actuators.

1. INTRODUCTION
"Learner-led learning environments" [1] offer challenges to learners who are motivated by their own enquiring mind [2, 3] to develop both their technical and creative skills. The Making culture is premised on critical thinking for problem solving, and design thinking for making artifacts. Embedded systems when adapted for a particular purpose can be considered as a form of an artifact. Furthermore, their programmability offers opportunities to facilitate users in the development of programing skills. One of the potential learning scenarios for such embedded systems in K-12 (kindergarten through 12th grade) education includes new interfaces for musical expression or NIMEs [2, 4].

The research in new musical interfaces describes robotic systems, which are capable of expressing musicianship [5-8]. In "a survey of robotic musicianship," Bretan and Weinberg state that robotic musicianship consists of "musical mechatronics, which is the study and construction of physical systems that generate sound through mechanical means; and machine musicianship" [9]. Simple musical mechatronics for physical sound production can offer K-12 learners an opportunity to explore transdisciplinary learning environments.

Simple systems can serve as a foundation for more complex systems and visual programing environments, such as Pd-L2Ork's K-12 learning module [4] that can be used to introduce concepts of programing using simple building blocks. The cost and portability of such systems are critical factors for their use in K-12 educational workshops, as well as in artistic performances, and sound installations.

Learning environments focusing on the robotic musicianship can be based on mechatronics of low cost and high portability. In the K-12 context, the accuracy and reliability of mechatronics is not highly critical, because the main objective is education. Thus, lower accuracy and reliability may be seen as an acceptable cost-saving measure. Microcontroller boards, such as the ubiquitous Arduino boards [10], may provide more outputs with accurate hardware-controlled PWM signal than the microcomputer boards, such as the Raspberry Pi model 3B (RPi) [11]. On the other hand, the RPi offers comprehensive low-power embedded computing, capable of running more advanced digital signal processing software, while also providing ways of interfacing with various sensors and emitters, including one accurate hardware-controlled PWM output. The RPi's low cost, inherent communication capabilities, computational power, and hardware-software integration make it particularly valuable in designing embedded solutions with K-12 educational scenarios in mind.

1.1 Pd-L2Ork Maker Lineage
Today, programing is an essential skill nurtured in both formal and informal educational settings as early as elementary school. The Pd-L2Ork visual programing environment [12] offers the K-12 educational module that has been used extensively in the K-12 Maker workshops [1, 4]. Since its introduction in 2011, Pd-L2Ork and its K-12 module have been utilized internationally in dozens of clinics ranging in size and scope from a one-hour introductory workshop to week-long camps for middle school students. While the original infrastructure of choice in such workshops was the Arduino board [3], the focus has since shifted towards using the RPi embedded system and an add-on electronics board (a.k.a. shield) to extend RPi's capability with analog inputs [13, 14]. Thus, the design paradigm for the educational workshops has morphed into an embedded mechatronic and digital signal processing environment. As a result, the current Pd-L2Ork version provides comprehensive support for the RPi platform [13]. Following the 2014 inaugural RPi Orchestra two-day pilot workshop as part of the summer public school gifted program, in the summer 2016 the authors introduced the new RPi-centric approach as part of a weeklong annual Maker-camp that has been used as the primary platform since. To facilitate learning, these workshops included education techniques such as scaffolding using the Pd-L2Ork's K-12 module, and reflecting on group communication, as well as the making process (ideation, design, development) [1]. The lesson plans used in these workshops encouraged users to near seamlessy transition from the K-12 module to the fully functioning version of Pd-L2Ork [4], so as to address more complex designs, especially among older and more advanced participants, such as high school students, and school teachers, both of whom have engaged in select workshops.

2. PROBLEM STATEMENT
Through the aforesaid K-12 educational workshops, we have identified a need for low-cost embedded learning kits that offer: (1) mechatronic components for physical sound production, (2) predefined methods of sound/control signal processing, and (3) wireless controllers for musical expression. In this paper we describe one such prototype design solution for such a musical mechatronics kit that was used in several workshops.

NIME'18, June 3-6, 2018, Blacksburg, Virginia, USA.

2.1 Design Challenges

For the newfound kit to be usable, it required implementation of new Pd-L2Ork K-12 objects (a.k.a. abstractions) that could produce control signals for actuators. Further, it had to do so without requiring additional changes to the system, including low-level drivers that may limit the kit's turnkey deployability and maintainability. The objects had to be capable of automatically detecting the availability of the hardware pulse-width modulation (PWM) capability, which on the current RPi model is limited to GPIO 18, as well as fall back on the software PWM implementation on the rest of GPIOs. This design goal challenged us to assess and compensate for the stutter that the microcomputer introduces to the control signal when relying on the considerably less accurate software interrupts. As a result, we have expanded Pd-L2Ork's K-12 library to include additional objects designed to control electrical actuators. The software PWM implementation was ipmplemented using the *disis_gpio* external [13] that allows connectivity on all GPIOs.

Another constraint was ensuring minimal additional cost overhead, given the project's primary focus on K-12 education where technology budget is often limited. Hence, the ensuing kit only had two actuators—a solenoid and a DC servomotor. Furthermore, all components, including the actuators, the external power for actuators, the analog sensors, and the analog-to-digital conversion (ADC) board (RPi shield) were off-the-shelf items that could be easily acquired at minimal cost through online retailers.

The ensuing kit was designed to empower users to build a simple computer-based mechatronic music instrument. While the small number of actuators included in the kit may have limited variety in terms of the mechatronics implementation, the ensuing kit was coupled with the existing onboard DSP capability that offered a diverse array of possible interactions with the users and its environment. In addition, the RPi's Bluetooth connectivity permitted the use of Bluetooth-enabled devices for human-computer interaction, such as the Wii Remote and Nunchuk controllers that further expanded the possibilities for implementation and interaction.

3. IMPLEMENTATION

3.1 The Kit

Figure 1 shows parts of the newfound prototype mechatronic NIME kit. In addition to the preexisting components, namely the RPi, A/D shield, USB soundcard, photoresistor, LED, microphone, speakers, Wii Remote and Nunchuck controllers, it also includes an example mechatronic instrument called MechXylo, with a potentiometer, micro switch, and power supply for the servomotor and solenoid.

Figure 1 – The prototype mechatronics deployment kit

3.2 Physical Sound Production Component

Figure 2 – MechXylo, an Example Mechatronic NIME

MechXylo (Fig.2) is a glockenspiel-like instrument that uses a solenoid, a DC servomotor, and 8 pitched (C major scale) metal-bars. The servomotor rotates the arm to position the solenoid at its end above each metal bar, such that the solenoid can hit one bar at a time. The arm has a stand to stabilize the distance of the solenoid from the metal bars. While the said design offers limited opportunities for varying the use of the servomotor and the solenoid, its ostensibly rigid design was intended as a starting point and a means of quickly generating mechatronic sound. Further, it is carefully designed to limit potential injury. For instance, the solenoid is coated with thermal tape, due to its overheating during extensive use.

3.3 Sound-Control Signal Processing

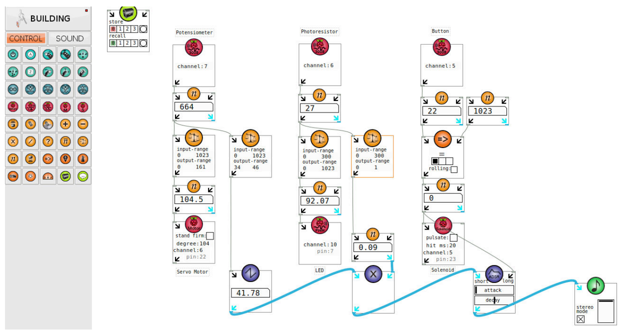

Figure 3 – Example Implementation of the Mechatronic Objects

Two new objects were added in the K-12 module to enable the control of servomotors, and solenoids from all GPIOs: *servomotor* and *solenoid*. An example of their implementation exploring cross-pollination of mechatronic and DSP-based interactions is shown in Figure 3. The example blends digital, and physical sound production and is split into three signal processing pathways that are vertically grouped. The leftmost column reads data from a potentiometer to sense the position of a knob that is then translated into a range of angle-degrees (1-161), and MIDI pitches (34-46). The angle controls the servomotor rotation, while MIDI values control the digitally produced sawtooth soundwave. The middle column uses a photo-resistor to sense brightness that is then translated into a voltage level (0-3V), and standardized loudness (0-1). The voltage level controls the brightness of an LED, while the loudness value controls the maximum possible amplitude of the sawtooth soundwave. The right column uses a digital GPIO input to sense when a micro switch is physically pressed that is then translated into a push-pull motion of the solenoid, while also triggering a simple attack-release envelope that outputs the sawtooth soundwave to the system's speakers.

3.4 Servomotor Control

In our effort to increase the reliability of the mechatronics system, we assessed the impact of improved kernel timers by testing two different kernels: a vanilla, "Raspbian Jessie" [15], and a custom real-time kernel [16]. In laboratory tests the RPi's software PWM implementation, based on the wiringPi library [17], offered inferior performance (stuttering) to that of a microcontroller, and RPi's hardware PWM. We tested the system for the number of servomotor rotation errors that occurred while changing 20 times between two specific positions. The estimated average reliability for correctly performing a move-command was estimated .93 for the software, and 1 for the hardware PWM setup. The mode of errors was 2 for the software, and 0 for the hardware PWM setup.

3.4.1 Pd-L2Ork Software PWM

The RPi's software PWM output (pin 18, applicable to all GPIOs) with a real-time kernel was measured using an oscilloscope to determine usability as a control signal for servomotors. Ten pulses were sufficient to trigger the servomotor's move-command. To minimize servomotor stuttering that was apparent when the arm was not moving, we programed the *servomotor* object to, by default, stop the control signal after sending ten pulses.

3.4.2 Pd-L2Ork Hardware PWM

The RPi's hardware PWM output (pin 18) with a real-time kernel was tested for reliability using a kernel overlay for PWM. The hardware PWM setup did not produce any rotation errors, thus it can be used in high-accuracy applications that require the servomotor to keep its position under load on its rotational axis.

3.5 Discussion

3.5.1 Demo Patches

To showcase simple mechatronic musicianship, we designed three demo patches showcasing three example modes of human-computer interaction:

1) *Arpeggio as a response to sound input.* The system listens for sound loudness and detects its pitch via the *fiddle~* object. The system is capable of producing 8 different sound pitches. Hence, it scales any detected pitch down to the diationic scale. If the estimated pitch is closest to that of C, then a predefined C- major arpeggio is performed. Else, a C-major scale ascend-descend is performed. After learners have experimented with this mode, we discuss about pitch, and harmony.

2) *Rhythmic pattern as a response to sound input.* The system listens for sudden sound onset via a microphone using the *bonk~* object. It creates a beat sequence by adding as sound event for each loud sound attack input within a period of looped 16 beats. After participants have experienced this mode, they were invited to discuss concepts of rhythm and time quantization.

3) *One-on-one response to sound input.* This mode is the most direct and engaging due to its simplicity and immediate response to humans-in-the-loop. The system listens for sound loudness and attack via the *bonk~* object and responds by striking and then moving to a random position. Moving to a position can be interrupted due to new sound-attack input. After experimenting with this mode, participants were given an opportunity to discuss concepts of polyphony and time quantization.

We envisioned these demo patches as a means of introducing newcomers to mechatronic musicianship by encouraging them to explore the mechatronic instrument, at first playing it and then by trying to alter its behavior and aural output.

3.5.2 Mechatronic System Design

The prototype mechatronics system was not designed with high-accuracy, efficiency, and reliability in mind. Rather, its focus was on low-cost, portability, and experimentation, while leaving room for more accurate, albeit also limited deployment using the hardware PWM microcontroller. When driving the servomotor using the software PWM signal, we observed the servomotor experience stuttering as long as it maintained charge. For this reason, by default the *servomotor* object in software PWM mode was set to put the servomotor to rest after issuing 10 periods of the new PWM signal. To offer greatest possible flexibility, the object also offers an option to keep the servo charged at all times. When testing the kit's *solenoid* object we observed it being capable of performing a push-pull motion in 20ms. This time was set as the *solenoid* object's default minimal possible push-pull period. As is the case with *servomotor* object, *solenoid* offers optional customization of the said period to accommodate other yet-to-be tested scenarios.

The MechXylo's mechanical constraints provided our workshop facilitators with possible topics of optimization, and efficiency to be discussed with learners during the design thinking process. For example, while scheduling a sequence of notes, should a solenoid strike a metal-bar before leaving from, or after moving to a position?

4. Real-World Testing

Based on the prototype deployment kit and its affordances, we organized three educational pilot workshops that varied in length and participant age. These workshops relied on the introductory lesson plan that aimed to enhance collaborative reasoning [18], and critical thinking [1] among learners. Participants explored one of the demo patches described in section 3.5 with the goal of creating a collaborative musical performance. They used their hands to manipulate MechXylo's mechanical parts and interact with the attached sensors, including a potentiometer, photoresistor, microphone, and a micro switch. Creative ideas for musical expression instigated an inquiry about the plausibility of different ideas to alter existing capabilities of predefined music instruments, or to introduce entirely new ones. Participants frequently expressed a desire to change the sound quality, and the rhythmic patterns of the predefined music instruments. As a result, they were encouraged to think about designing alternative mapping strategies. For example, instead of using the potentiometer to control the MechXylo's arm, one could consider using the photoresistor. The designing of alternative mapping strategies was scaffolded by allowing participants to manually control actuators using the aforesaid sensors. This enabled them to immediately mock-up their ideas, and easily communicate them to their teammates without having to delve into the code. The ensuing introductory lesson design was therefore propelled by a self-motivated inquiry and collaborative exchange of ideas, rather than pre-described lesson milestones. We refer to this lesson design as *sense-process-control*.

4.1 Introduction to Sense-Process-Control

Following the ideation session, participants were exposed to the programming environment and the ways they could make their envisioned interaction a reality. Figure 3 shows the Pd-L2Ork program that was used to introduce the *sense-process-control* paradigm. Figure 4 further elaborates on our approach towards facilitating the development of programing skills using the mechatronic NIME kit. Namely, it leverages human propensity for musical expression that motivates workshop participants to use and explore the mechatronic MechXylo instrument. Throughout this process the pilot-workshop facilitators offered scaffolding that motivated participants to learn through their interaction with their peers.

4.2 Possible Educational Workshops

In their work, Bretan and Weinberg use natural language processing "to support general music query" via their "Robotic Musical Companion" [19]. To showcase simple machine learning via simple Bayes classifiers, the mechatronic NIME kit could exemplify how to create voice commands for rotating its arm in predefined positions. The learner could specify a position and then record a voice command for it multiple times. Another possible workshop idea is to explore different sound qualities by using alternate ways of striking a metal bar. Long et al. propose to measure "latency, maximum loudness, dynamic consistency, and maximum repetition rate" to evaluate a striking mechanism's performance [20]. These properties can be explored to design perceptibly different ways of striking.

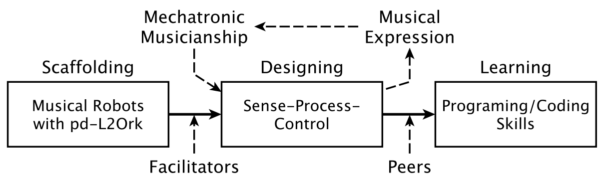

Figure 4 – Musical robots in K-12 education

5. CONCLUSIONS

A prototype mechatronic NIME kit was designed for K-12 educational workshops based on a programmable mechanical glockenspiel named MechXylo. It was complemented by the new *servomotor* and *solenoid* Pd-L2Ork K-12 objects to create control signals for actuators via hardware PWM on pin 18, and software PWM implementation on all the remaining RPi GPIOs. The kit was further coupled by a challenge-based a sensor-process-control lesson model that used musical expression as a catalyst for self-motivated exploration. Facilitators scaffolded the pilot-workshops with the ultimate goal of aiding workshop participants to develop programing, and coding skills using the Pd-L2Ork programming environment. The RPi-based mechatronic NIME kit presented here provides convenient hardware-software-lesson integration for the development of mechatronic NIMEs.

Although simple musical robots have limited capability for physical sound production, pairing them with the built-in DSP capability of the Pd-L2Ork software enables a broad array of sound-making and interaction opportunities between two or more co-located musical robots. Such an ecosystem can rapidly grow in its complexity through a perpetual cross triggering of different musical events within a single system or among multiple co-located systems. In their work, Long et al. discuss "musical information retrieval (MIR) techniques" [21] with a goal of creating more complex systems for sound production. Inspired by this idea we imagine exploring an ensemble of MechXylos and using their available musical information retrieval capacity to enhance expressivity and promote engagement. The ensuing kits were tested in three pilot workshops. Based on the pilot-workshop participant feedback, the mechatronics addition to the Pd-L2Ork K-12 module has proved a compelling and engaging introduction to the Maker-like NIME activities, serving as a potent catalyst for self-motivated discovery.

5.1 Future Work

To extend the prototype system's capacity for musicianship, we will further explore alternative Direct Memory Access approaches to timing pulses, and obtaining direct position feedback from the servomotor to enable closed-loop control. Additionally, we are designing lesson plans for teaching music theory and expanding our NIME activities with educational workshops targeting Kindergarten to College (K2C) learners.

6. ACKNOWLEDGMENTS

We would like to thank the Virginia Tech DISIS, L2Ork, and ICAT for their support during the development of this project.

7. REFERENCES

[1] Newbill, Phyllis Leary, Drape, Tiffany A., Schnittka, Christine Baum, Liesl, and Evans, Michael A. Learning Across Space Instead of Over Time. Retrieved Nov. 29, 2016, from: http://niost.org/images/pdf/afterschoolmatters/asm_2015_fall/asm_f2015_Learning_Across_Space.pdf

[2] Moriwaki, Katherine and Brucker-Cohen, Jonah. MIDI Scrapyard Challenge Workshops. *New Interfaces for Music Expression.* New York, NY, USA, 2007.

[3] B. Sawyer et al. Form, function and performances in a musical instrument MAKErs camp. 2013. DOI: 10.1145/2445196.2445392.

[4] Bukvic, I., Baum, L., Layman, B., and Woodard, K. Granular Learning Objects for Instrument Design and Collaborative Performance in K-12 Education. *New Interfaces for Music Expression,* pp. 344–346. Ann Arbor, Michigan, 2012.

[5] Weinberg, Gil, Brian Blosser, Trishul Mallikarjuna, and Aparna Raman. The Creation of a Multi-Human, Multi-Robot Interactive Jam Session. *New Interfaces for Musical Expression,* pp. 70-73. 2009.

[6] Singer, Eric, Jeff Feddersen, Chad Redmon, and Bil Bowen. LEMUR's musical robots. *New Interfaces for Musical Expression,* pp. 181-184. National University of Singapore, 2004.

[7] Kapur, Ajay, Michael Darling, Jim W. Murphy, Jordan Hochenbaum, Dimitri Diakopoulos, and T. Trimpin. The KarmetiK NotomotoN: A New Breed of Musical Robot for Teaching and Performance. *New Interfaces for Musical Expression,* pp. 228-231. 2011.

[8] Kapur, Ajay, Eric Singer, Manjinder S. Benning, and George Tzanetakis. Integrating hyperinstruments, musical robots & machine musicianship for North Indian classical music. *New Interfaces for Musical Expression,* pp. 238-241. ACM, 2007.

[9] M. Bretan and G. Weinberg. A survey of robotic musicianship. Communications of the ACM 59(5), pp. 100-109. 2016. . DOI: 10.1145/2818994.

[10] Arduino. Main products. Accessed Jan 6, 2017 via: https://www.arduino.cc/en/Main/Products.

[11] The Raspberry Pi Foundation. Products. Accessed Jan 6, 2017 via: https://www.raspberrypi.org/products/

[12] Pd-L2Ork software. Accessed Jan 6, 2017 via: http://l2ork.music.vt.edu/main/make-your-own-l2ork/software/

[13] Bukvic, I. Pd-L2Ork Raspberry Pi Toolkit as a Comprehensive Arduino Alternative in K-12 and Production Scenarios. *New Interfaces for Musical Expression*, pp. 163-6. London, UK, 2014.

[14] Modern Device. Lots of Pots (LOP) Board for Raspberry Pi. Accessed Jan 6, 2017, via: https://moderndevice.com/product/lots-of-pots-lop-board-for-raspberry-pi/

[15] Raspbian. Jessie Linux Kernel. Accessed Jan 6, 2017 via: https://www.raspberrypi.org/downloads/raspbian/

[16] emlid.com. Retrieved Jan 6, 2017 via: https://emlid.com/raspberry-pi-real-time-kernel/

[17] Wiring Pi, "GPIO Interface library for the Raspberry Pi." Accessed Jan 6, 2017 via: http://wiringpi.com/

[18] K. Kumpulainen and S. Kaartinen. The interpersonal dynamics of collaborative reasoning in peer interactive dyads. *The Journal of Experimental Education 71(4),* pp. 333-370. 2003. DOI: 10.1080/00220970309602069.

[19] Bretan, M., Weinberg, G. "Chronicles of a Robotic Musical Companion," submitted to Proceedings of the New Interfaces for Musical Expression Conference (NIME 2014), London, UK.

[20] J. Long, J. W. Murphy, D. A. Carnegie, and A. Kapur, "A Methodology for Evaluating Robotic Striking Mechanisms for Musical Contexts," Proceedings of the International Conference on New Interfaces for Musical Expression, Baton Rouge, Louisiana, June 2015.

[21] Long, Jason, Ajay Kapur and Dale Anthony Carnegie. "The Closed-Loop Robotic Glockenspiel: Improving Musical Robots Using Embedded Musical Information Retrieval." (NIME 2016), Brisbane, Australia.