Institution: Queen Mary University of London		
Unit of Assessment: 11		
Title of case study: The Bela open-source hardware platform for music makers and artists		
Period when the underpinning research was undertaken: 2013-2017		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Dr Andrew McPherson (lead) Dr Victor Zappi	Reader in Digital Media Postdoctoral Research Assistant	2011-present 2013-2014
Period when the claimed impact occurred: 2016-31 Jul 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Bela is an open-source hardware platform for creating digital music, developed by Dr Andrew McPherson and his team at Queen Mary. It has ultra-low latency (input-output delay) processing of audio and sensor signals. Compared to existing tools, Bela offers superior technical performance and easy learnability. The technology enables a wide variety of users (over 2,500 artists, designers, students, researchers, the disabled) to develop new ways of producing music and sound. This may be through the modification of existing instruments, such as Strummi, a simplified guitar-like instrument, which can be adapted for single handed playing, or the creation of art installations involving sensors, sound and visual feedback.

Bela launched on Kickstarter in 2016, raising GBP54,000 (1100% of its goal), and thereafter spun out into the company Augmented Instruments Ltd in September 2016. Bela is being used for teaching in over 20 universities spanning Europe, North America and Australia and is a founding part of the core curriculum of a new cross-university Master's in "Music, Communication and Technology" (University of Oslo, NTNU Trondheim).

2. Underpinning research (indicative maximum 500 words)

There is demand from a wide variety of users for digital musical instruments to develop new ways of producing music and sound. However, musical instruments place stringent demands on digital systems in terms of reliability, responsiveness, resolution and dynamic range, and so digital musical instruments present unique challenges in comparison to most human-computer interfaces (HCI). There were several core challenges to overcome to establish new, effective ways to make music and sound:

- For musical instruments, the standards of success of a design are difficult to quantify since standard HCI metrics of accuracy and speed do not necessarily correlate with what musicians find expressive;
- There is a fluid and unpredictable relationship between designer and user as musicians have been appropriating and even subverting instrument designs to produce music in ways the designer never anticipated;
- Historically, many digital instruments have either been tethered to a computer or have suffered from low processing power, high audio latency (ie input-output delay), or low sensor resolution.

Therefore, the Queen Mary team sought to address the question: how can an interface be designed that embraces the user's willful subversion of its original goals [3.1]?

McPherson's interdisciplinary research has drawn on HCI, embedded hardware systems and arts practice to understand how musicians creatively (mis-)use technology. The team aimed to understand the design parameters that make a technology more open to creative use and develop a robust hardware and software platform for the creation of new digital musical instruments that would not be damaged by arbitrary wiring changes. To address the shortcomings

of existing tools, they built a custom platform capable of extremely low latency and sample-accurate alignment between audio and sensors, features not available on existing platforms. They developed a hard real-time audio processing environment based on the Xenomai Linux kernel extensions running on the BeagleBone Black single-board computer, which was novel in its use of asymmetric multiprocessing to achieve low-latency input/output [3.2]. This is a self-contained product without the need for an external computer. The measured latency is as low as 100µs (30-50x lower than similar platforms) with a high degree of timing precision (maximum 25µs jitter or timing deviation between successive events).

This technical infrastructure, completed in 2014, was originally focused on a single digital musical instrument. The Queen Mary team expanded it over the subsequent two years to become the platform they eventually branded 'Bela.' From late 2014, driven by Queen Mary's research, teaching and external collaborations with charities and other universities, the team developed new features, making it easier for people without an engineering background to create projects with Bela: a browser-based integrated development environment (IDE); novel in-browser visualisation tools such as a digital oscilloscope and support for several popular digital music programming languages [3.3].

Bela is used to create new musical instruments accessible to people with disabilities, including the physical adaptation of existing instruments for one-handed playing [3.4]. McPherson has recently been awarded a Senior Research Fellowship from the Royal Academy of Engineering, for a 5-year project starting March 2021. The project is jointly sponsored by Augmented Instruments Ltd.

3. References to the research (indicative maximum of six references)

[3.1] Zappi, V. & McPherson, A. (2018). Hackable instruments: Supporting appropriation and modification in digital musical interaction. *Frontiers in ICT 5(*26). https://doi.org/10.3389/fict.2018.00026

[3.2] McPherson, A. & Zappi, V. (2015). An environment for submillisecond-latency audio and sensor processing on BeagleBone Black. *Audio Engineering Society 138th Convention, Warsaw, Poland*. http://www.aes.org/e-lib/browse.cfm?elib=17755

[3.3] Morreale, F., Moro, G., Chamberlain, A., Benford, S. and McPherson, A. (2017). Building a maker community around an open hardware platform. *Proc. ACM SIGCHI Conference on Human Factors in Computing Systems (CHI)*. https://doi.org/10.1145/3025453.3026056

[3.4] Harrison, J. & McPherson, A. (2017). Adapting the bass guitar for one-handed playing. *Journal of New Music Research 46(*3). https://doi.org/10.1080/09298215.2017.1340485

Evidence of the quality of the research:

[EQR. 1] McPherson, A. [Principal Investigator]. (2013-2014). Hackable instruments: Musical interface design for appropriation, modification and creative destruction [EP/K032046/1]. *EPSRC*. First Grant. GBP100,000.

[EQR. 2] McPherson, A. [Principal Investigator]. (2016-2020). Design for virtuosity: Modelling and supporting expertise in digital musical interaction [EP/N005112/1]. *EPSRC*. Fellowship. GBP897,000.

4. Details of the impact (indicative maximum 750 words)

Research by McPherson at Queen Mary has led to the development of Bela, an open source [5.1] hardware platform for ultra-low latency processing of audio and sensor signals, designed for various creative uses. The technology enables a wide variety of users (artists, designers, students, researchers, the disabled) to develop new ways of producing music and sound.

At the end of 2015, Bela was in use by around 50 researchers and artists worldwide. The number of people using Bela has since exceeded 2,000. In 2016, the Queen Mary team launched Bela to the public on the crowdfunding site Kickstarter, attracting the backing of more than 500 people and raising over GBP54,000 (1100% of their goal) [5.2]. The technology was commercialised through the Queen Mary spin-out, Augmented Instruments Ltd (AIL).

Use of Bela by the music community and industry

There are an estimated 2,500 unique users on 6 continents that have bought their own Bela boards and a similar number have encountered it through classes or workshops. The Queen Mary team studied the characteristics of the Bela early adopter community in 2017 and found a diversity of profiles and interests: technology hobbyists and independent creators; musical performers; musical instrument designers; media artists; teachers; students and researchers in fields ranging from human-computer interaction to signal processing to neuroscience. Musical applications predominate with musical instruments and synthesisers being the most common. Art installations are another frequently mentioned application. Reasons that people used Bela, included "signature features": low latency (particularly important for percussive instruments as confirmed by a user); compact size; open-source design plans; ease of getting started and support for popular open-source software tools.

Dozens of instruments have been created by Bela users and are showcased on the project blog (86 posts to date) and their own sites. There is an online forum (over 830 registered users) with spontaneous (unsolicited) public promotion of the platform by its users, and volunteer ports to Bela of audio programming languages including SuperCollider, FAUST, Csound and Pyo.

Making music more accessible to the disabled community

The Accessible Music Hackathon

In February 2016, Bela was used in an Accessible Music Hackathon co-organised with Drake Music [5.3], with the support of the British Council, to develop prototypes of new accessible instruments. Tim Yates, Research & Development Programme Leader & Associate Musician at Drake Music said *"*we produce bespoke instruments for individuals; they have disabilities and can't use standard musical instruments in the standard way, so we help them to use the instruments in a way that is specific to each person. Bela is low cost and you don't need a Master's degree to build it. It opens up the opportunity to give access to music to people who didn't have that before; it's very powerful. It also opens up the possibilities to people from multiple different backgrounds to create projects and instruments that otherwise were not possible."

There was engagement with around 50 people on the day of the hackathon with an international audience. Two projects out of the 10 that were presented at the event used Bela. Leah Zakss, Programme Manager for the British Council's Music team in London, said that "It was amazing to see what entrants had produced in such a short period of time, and refreshing to be connected to a whole new network of people around the UK working in the field of AMT [assistive music technology]. I know that our international colleagues who visited were amazed at the innovation on display. We had a lot of fun and learned so much" [5.3].

The Haptic Baton

The Haptic Baton, created using Bela, helps visually impaired musicians to perform live within a group. Motion sensors inside the baton send data to a micro-controller, which wirelessly transmits the movement data as vibrations, felt by the musicians through wearable wristbands. Musicians can wear the wristbands and feel the baton movements as haptic vibrations rather than following the visual cues of the conductor's baton [5.3].

Strummi

In 2018, Jacob Harrison and Robert Jack (McPherson's PhD students) created Strummi, a simplified guitar-like instrument that uses Bela's low-latency audio processing to maintain the richness of strumming real physical strings while simplifying chord selection into a series of buttons. Strummi, shown in use in Figure 2, emerged from a collaboration with the OHMI Trust, a charity devoted to music-making for physically disabled individuals [5.6]. OHMI stands for 'one handed musical instruments.' Stephen Hetherington, founder of OHMI, writes "Our primary task is to adapt traditional instruments or create sophisticated emulators, such that the instrument itself is not a barrier to full inclusion and potential virtuosity. By making the guitar fully playable with one hand, Strummi offers the real opportunity for many thousands of disabled people in the UK to play music for the first time."

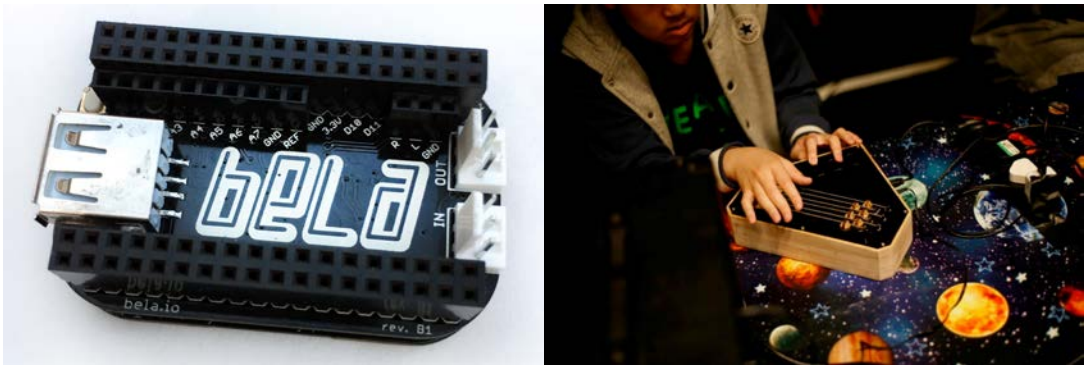

Figure 1: Left: Bela Mini unit; Right: Strummi in use.

Strummi is now in use in the OHMI national teaching programme, the OHMI Music-makers, which provides one-to-one music lessons and ensemble groups. It makes around 50 school visits per year. Lessons are given in school time so children learn alongside their peers. After launching in Birmingham in 2015, the project was rolled out in Surrey and Hampshire in 2016.

A new musical instrument for stroke patients in rehabilitation

A musical performance including Robyn Steward, who used Bela in a foot pedal called 'Barry' connected wirelessly to her trumpet, took place at the Barbican in 2019. This event was attended by 20-30 people. It was hosted by AIL and featured in an article in *The Guardian* (print readership: 3,600,000; circulation: 111,953; monthly browsers: 25,100,000) [5.7]. This led to a GBP25,000 grant to Queen Mary from the Chelsea and Westminster Hospital Foundation to create a new instrument for stroke patients "that could be used by patients at various stages of their rehabilitation, offering both accessibility and challenge, in a design small enough to potentially be used by patients in bed - and all this while adhering to hospital infection control protocols", according to Andrew Hall, Music and Sound Research Consultant at Chelsea and Westminster Hospital NHS Foundation Trust [5.8]. He wanted to use Bela, as it "was clearly the optimal starting point for the design of the instrument, due to its low latency and ease of implementation." He went on to say, "So far prototype trials with 4 patients, and interviews with 2 patients and 7 clinicians have illustrated the various ways of approaching the instrument, from picking out melodies to strumming the surface like a guitar, but they have also highlighted patients' appreciation of the instrument's aesthetic, describing it as ornamental or resembling an old board game."

Use of Bela as an educational resource

Bela has been adopted for teaching in over 20 universities spanning Europe, North America and Australia. It is a core part of the curriculum of a new cross-university Master's in Music, Communication and Technology (University of Oslo, NTNU Trondheim). According to Bernt Isak Wærstad, Academic Programme Director for the Live Electronics program at the Norwegian Academy of Music and co-founder of the COSMO Project (an open source project devoted to making a hardware and software framework for designing and building embedded standalone Csound instruments to use on stage), "the hardware solution was both more compact (one board sitting on top of a single board computer) and possible for anyone to order readymade (unlike our current custom designed hardware). The convenience of the browser based IDE made it possible for a much smoother and easier workflow making it easier for less advanced users who are not very comfortable operating a system through a terminal. Finally, the low latency and real-time kernel made this system both more snappy and much more stable in performance compared to the Raspberry Pi." [5.5].

The Bela team has also released a series of 14 free public YouTube videos on C++ audio programming with Bela, ranging from 22 to 53 minutes long, which as of 1 October 2020 have a combined total of 14,494 views and 699 likes [5.9]. Comments on the videos are very positive, including: "This entire course has been utterly fantastic, thank you so much for putting something so professional together and making it free. I really love what you and the entire Bela team are doing" and "Amazing material! I love how well the hardware and software has been designed. Can't wait to get one and get through the whole course."

5. Sources to corroborate the impact (indicative maximum of 10 references)

[5.1] *Create beautiful interaction with sensors and sound***.** Bela. http://bela.io. 26 October 2020

[5.2] *Bela: an Embedded Platform for Low-Latency Interactive Audio* (2019, 9 September). Kickstarter. http://kck.st/23pfLne. 26 October 2020.

[5.3] Fresh Perspectiv (2020). *Impact Case Study: Maker Platforms – 'Bela'.*

[5.4] Baalman, M. SuperCollider developer. *Freelancer* (testimonial letter, 11 July 2019). [Corroborator 1]

[5.5] Waerstad, B. I. Academic Programme Director. *Norweign Academy of Music* (testimonial letter, 5 August 2019). [Corroborator 2]

[5.6] Hetherington, S. Founder and Chairman. *OHMI Trust* (testimonial letter, 16 April 2019). [Corroborator 3]

[5.7] Davies, S. (2019, 10 July). *'We need to put inclusion at the start of the process': the disabled musicians making their own instruments*. *The Guardian*. https://www.theguardian.com/careers/2019/jul/10/we-need-to-put-inclusion-at-the-start-of-the-process-the-disabled-musicians-making-their-own-instruments. 26 October 2020.

[5.8] Hall, A. Music and Sound Research Consultant. *Chelsea and Westminster Hospital foundation* (testimonial letter, 23 April 2020). [Corroborator 4]

[5.9] Bela (2020). https://www.youtube.com/watch?v=aVLRUyPBBJk&list=PLCrgFeG6pwQmdbB6l3ehC8oBBZbatVoz3