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Theoretical Quantum Modeling of Improvisation in Networked Music Performances to Regulate the Behaviour of Artificial Musicians

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***Abstract*—During collective musical performances over the network that are characterized by improvisation, a performer may face the problem of what connected musician to follow most in order to direct his/her own improvisation. This choice may be taken on the basis of different factors related to the state of the network and of the kind of the received musical signal. In this paper we investigate the possibility to adopt the mathematical formalism of Quantum Mechanics to describe some interaction phenomena occurring during improvised networked music performances. We propose a decision-making system, having a quantum circuit in its core, where the approximated decision by performers is modeled with state superposition and probability amplitudes used in quantum computing. The model considers the levels of signal clarity (i.e., audio quality related to packet losses), latency, and musical novelty (e.g., melodic or harmonic variation with respect to a previous musical sequence) as the factors that affect the decision of a performer to select another connected performer to follow. This model may be exploited to regulate the behaviour of an artificial intelligent agent playing the role of a virtual musician in the networked ensemble (via generative music techniques). This allows to create mixed human-artificial ensembles and even fully artificial ensembles in networked contexts.**

***Index Terms*—Quantum computing, networked music performances, generative music, artificial agents, Internet of Musical Things.**

I. Introduction

Networked Music Performance (NMP) is a field of research that investigates at the technological, artistic and perceptual level the act of playing music in distributed contexts, where musicians are connected by a wireless or wired link [1]–[3]. NMP systems are an essential component of the Internet of Musical Things [4], an extension of the Internet of Things paradigm to the musical domain. NMP systems (such as JackTrip [5], Elk LIVE [6], LOLA [7], and fast-music [8]) are hardware and software solutions that aim at recreating at each of the musicians' end realistic conditions as in on-site performance.

In a different vein, quantum computing refers to an emerging technology that is built on the principles of subatomic physics [9]. Such a technology promises to solve extremely complex problems beyond the capabilities of conventional supercomputers. Applications of quantum computing to the music domain is gaining momentum, as testified by the emergence of the new area of research and development on Quantum Computer Music [10], a growing number of publications on such a matter [11]–[14] and dedicated international gatherings[1]. However, thus far, there has been scarce interaction between the field of NMPs and that of quantum computing.

This paper investigates for the first time how NMPs can potentially benefit from quantum computing. In particular, we investigate the possibility to adopt the mathematical formalism of Quantum Mechanics to describe interaction phenomena occurring during NMPs. The main rationale underlying this quest lies in the fact that modeling the behaviour of human musicians interacting during an NMP could be exploited to regulate the behaviour of an artificial intelligent agent playing the role of a musician in the networked ensemble (via generative music techniques). This allows to create mixed human-artificial ensembles and even fully artificial ensembles.

The possible steps toward a quantum approach to improvised, collective, networked musical performances are the following:

- understanding and modeling what musicians are doing;
- formalizing it via quantum computing;
- considering the results as hints to code a real-time generative music system.

Creating such a quantum approach poses a set of questions. One of these is: How does a musician think and act during ensemble improvisation? While each human mind is original and, to a certain extent, unpredictable, certain mechanisms can be envisaged. In particular, during improvisation each performer balances information coming from their peers, for instance weighting their degree of novelty and synchronicity, and this information can be used to react and respond, making decisions along the way to produce dazzling music [15]–[19].

[1]https://iccmr-quantum.github.io/1st_isqcmc/

This is especially relevant in the context of remote collective performance, where additional problems arise, such as clarity of sound stream (due to packet losses), and sound delays (due to the latency introduced by the network) [20].

During an NMP, each performer can be seen as a node in a network, exchanging messages with its peers. The amount of indeterminacy in some parameters can be modeled in terms of probability amplitude superposition. Thus, with a slight conceptual abuse, we may recur to the quantum paradigm, to borrow quantum computing techniques to model our issue. An application of quantum computing might be helpful to direct decision making of an artificial agent generating music. Our approach may be used to support creativity, and create a dialogue between human musical intelligence and artificial intelligence. For instance, a single performer can use his/her sound as the input for the system, which is then sent to different synthesizers to create new music, selecting the "best elements" of the proposed sequences.

In this paper we make initial steps to apply the paradigm of quantum computing to the field of NMPs. In particular, we focus on the context of collective remote improvisation. In this context, each performer may choose to follow the hints from a group member or another one according to a qualitative choice, based on the originality of the musical content, the time of arrival of the musical stream, and the clarity with which it is heard. Such a "fuzzy" decision is almost instinctively made by performers during improvisations. The main steps of this rapid decision-making can be modeled taking into account probability amplitudes of these different components, such as the clarity of the signal (against the percentage of noise), the novelty of the musical content, and its latency.

A particularly efficient system for probability-based computing is quantum computing. For this reason, we can develop a theoretical approach to improvisation modeling via quantum computing. The result can help create a system with artificial intelligence to help musicians to automatically select the stream coming from a performer rather than from another one at certain time intervals, limiting the amount of information received by the other ones and possibly even improving the connection stability. A possible development of this approach may lead to a music generation system in an improvised context, where the intelligent system selects the "best stream" from the performers, according to novelty, clarity, and latency, and re-elaborates or generates new music according to its characteristics. Once such a model for improvisation in NMPs is implemented, it could be the starting point for a system encompassing an ensemble of sole artificial performers (e.g., robots or synthesizers) or a mix of human and artificial performers, sending and receiving signal and shaping their response according to the proposed decision model.

The structure of the article is the following. In Section II, we summarize key ideas of quantum computing and some recent research in the domain of quantum application to music and to networks. In Section III, we sketch a model of remote collective performances in terms of quantum computing, proposing a quantum circuit and performing some tests via an IBM quantum simulator. In Section IV, we summarize the results, discuss the limits of our ideal model, and consider some possible developments of the idea.

II. Related works

A. Quantum computing

Quantum computing [21], [22] is a branch of computer science derived by basic principles of quantum mechanics. The notion of classical *bit*, which can assume the values 0 or 1, becomes the *quantum bit*, called *qubit*, which can assume all values in the interval $[0, 1]$, that is, 0 and 1 with different probability amplitudes, according to the principle of state superposition in quantum mechanics. A quantum circuit is a set of transformations, through reversible gates, applied to a qubit or a set of qubits initializing the system. The output of the transformations is measured, and the result is stored into classical variables. The condition of reversibility is derived from the invertibility of quantum operators. The measurement is destructive, in the sense that it makes collapse the wavefunction of the overall state into a specific state, forcing all subsequent measurements to give the same output. To obtain new measures, the circuit is re-initialized.

Quantum computers and quantum simulators can nowadays be accessed remotely, and (up to a certain number of qubits and a waiting time) freely, such as IBM devices. When a circuit is transmitted to a simulator, 1024 run are performed, and the results show the frequency with which each state is obtained. The most likely state is the one presenting a higher frequency.

Quantum computing is more and more applied to artificial intelligence [23], [24], robotics [25]–[28], and swarm robotics [29]–[33]. The key reasons are the enhancement of algorithms efficiency, and the translation itself from classic codes to quantum codes. In fact, the translation from a classical algorithm to a quantum one is a non-trivial operation which is often the object of research in itself.

B. Generative music

In the past two decades there has been a skyrocketing interest towards algorithms able to artificially generate music [34]. A variety of generative music systems has been proposed [35], [36] along with methods to evaluate them [37]. Lately the attention of researchers has focused primarily on the use machine learning techniques to create artificial agents capable of generating music in an effective and artistically meaningful manner [38], [39].

The field of generative music has also been approached through the lenses of human-computer interaction [40]. Researchers have investigated how machine learning techniques can be applied to the design and generation of creative artefacts, or to support musicians in their creative practices [41]. This may occur in offline and real-time fashion. Of particular interest for the present study are the works that investigate a collaboration between human and virtual musicians, especially during improvisation contexts [42].

Recently, the field of generative music started exploiting the resources of quantum computing. In 2019, two quantum physicists from Yale University, Luke Burkhart and Kyle Serniak, in collaboration with the musician Spencer Topel generated music dynamics' of superconducting quantum devices. A performance recorded in 2021 in the Quantum Laboratories of Michel Devoret and Robert Schoelkopf can be accessed at https://www.youtube.com/watch?v=aOVW59VhaNk. This experiment shows how the concept of musical improvisation can be joined with the fluctuations typical of quantum devices. This characteristic intrinsically "improvisational" of quantum devices constitutes a resource yet to be explored not only for scientific purposes, but also for creative ones. In addition, the ontological, not only epistemic, indeterminacy of quantum systems, can be used as a formal and conceptual tool to represent the state superposition in the human mind [43]. Quantum formalism in music is also used to explain the extraction of pitches from the continuum of sounds [44] and the features of melodic perception [45]. These applications can be conceptually derived from an operation of "choice" as a measure. Thus, the interest of quantum applications in the domain of generative music is justified not only by quantum supremacy and potentialities yet to be explored, but also by conceptual reasons.

III. A QUANTUM APPROACH TO NETWORKED MUSICAL PERFORMANCES

A. The theoretical idea

We propose here a simple model of interaction between remote musical performers, based on three elements: the variety of the proposed musical sequence, the clarity of the stream, and its latency. Each one of these three elements is quantized, and thus the decision-making approach of each single performer will be modeled through quantum logic (see Section III-B). Let us analyze the details of the proposed elements.

- *[What]*. **Novelty:** quantifies the degree of variety/surprise/diversity/unfamiliarity of the musical information transmitted. A musical input is more likely to be considered by the other performers if it is novel with respect to the already-heard musical sequences [15]. In this context, novelty may be defined according to some musical metrics arbitrarily selected by the performers on the basis of artistic choices (e.g., rate of harmonic change, density of use expressive techniques, density of tempo variations, etc.). Logic 0 stands for a repetitive element with respect to the previous musical sequences, while 1 stands for the maximum level of novelty. This implies the use of a real-time system measuring the novelty during the NMP. This system may be based on a set of expressive metrics defining the concept of novelty, using music information retrieval methods [46].
- *[How]*. **Clarity:** this parameter characterizes the presence of noise (i.e., packet losses in the signal received from a connected performer that impact the quality of experience of a receiving performer). We can choose to assign the logic level 1 to a low level of noise, that is, to a high clarity of the audio stream, and the logic 0 to a high level of noise. The choice of a threshold for this parameter may be arbitrary, and should be set up by performers. This implies the use of a real-time signal quality measuring system during the NMP.
  In this article, we are considering novelty as a desired and generally positive aspect. However, in the framework of monotone and repetitive electronic dance music or modal jam sessions in a single key, the concept of novelty should be adapted and modified, in favor of a progressive variation strictly inside the proposed style. For an example, we can think of Philip Glass' music, with progressive and quasi-static variations.
- *[When]*. **Latency:** this parameter characterizes the delay with which the musical stream reaches the i-th performer. We can choose to assign the logic 1 to a low level of latency, that is, a signal with an end-to-end delay less than 30 ms (the commonly agreed upon threshold for realising a realistic interplay over the network [2]), and 0 to high level of latency (i.e., above 60 ms, where musicians are known to lose synchronicity). This implies the use of a real-time latency measuring system during the NMP.

In the following text and tables, we denote Novelty by N, Clarity by C, and Latency by L. The three parameters can be quantized. The network performance indicators are linked to clarity and latency. More aesthetic-focused elements can be represented by novelty. For the sake of simplicity, in this article we consider for novelty only melodic variety (i.e., the variation from a previous melodic sequence).

A single performer is seen as a node of the network, sending broadcast signals to all the other performers. Each performer is receiving signals from the other connected performers, and, to decide what to play next, he/she has to take into account *what* they are listening, *how*, and *when*. That is, which melody is performed, when it is heard, and with which clarity. For instance, a beautiful musical theme that is heard half-covered of noise (i.e., signal drop outs due to packet losses) and with a certain delay, will be probably neglected during the decision making process of following a performer, in favor of a less significant melody (from the novelty standpoint) that is heard clearly and with a smaller delay.

Figure 2 exemplifies the proposed concept. The whole process is run with a cadence which can be chosen by the performers (but depends on the computing availability and capability of the quantum computer at hand), and that can change according to the number of musicians involved. The considered quantum circuit is the quantum `AND`, discussed in Section III-B. We can consider it as a gate which is called remotely by each musician at a regular cadence (e.g., every 10 seconds). In this case each musician needs to have a quantum hardware. Or, in a slightly different approach, it can be treated as a centralized system called again at a regular cadence, but once for all performers – more precisely, we consider the same quantum computer, where the four circuits are run simultaneously.

B. Decision-making system

We can model the performance approach via a decision-making system, based on a quantum logic gate. Quantum logic gates are reversible and unitary. The reason is that they are replicating essential features of operators in quantum mechanics. In the present study, we consider an AND with three inputs. Ideally, the signal from a performer is considered by another one (yes, 1) if novelty (N), clarity (C), and latency (L) are all 1 (we consider latency $=$ 1 where there is a delay below the perceptual threshold of 30m). However, in real life, we have not only 0 and 1, but a range of possible values between them. This is one of the conceptual reasons to consider probability amplitudes and state superposition in this framework.

In the proposed system, the input is automatically written in terms of quantum superposition. Thus, the output of the quantum circuit is not given for granted, and thus, it can represent a schematic model of what happens in the short-time frame when musicians decide what to do in a collective, remote improvisation.

Table I shows the truth table of a quantum AND gate and Fig. 1 presents the quantum circuit implementing it. The quantum gate we propose is inspired by the quantum AND gate, to which we add another qubit representing the information got by the performer. It can be schematized as a Toffoli gate (CCCN). N stands for Novelty, C for Clarity, and L for Latency. R stands for the Result (good/not good) as received by the n-th performer. R is initially initialized as 0. In the output section, we indicate 0 as " bad" and 1 as "good." Here, we consider 1 as a low latency. The outcome is the likelihood to consider the stream as a good one: 1 stands for Yes, and 0 stands for No. To guarantee the reversibility, we also need to have the same number of inputs and outputs. Here, we need two *ancilla qubits*. They are supplementary qubits, introduced to make the gates reversible, and "store" information from a qubit to another one. The most simple choice is to introduce two more output qubits, repeating the information coming from two incoming qubits.

To move from the theoretical depiction to a practical implementation, this quantum logic gate can be embedded inside a software. The output (classical) is mapped to a quantum state and enters the quantum circuit. The output of the quantum circuit is the most probable state superpositions. These information are used as weights to indicate the likelihood of a stream to be considered or not. Such a strategy has been successfully undertaken for robots, where a quantum circuit, accessing remotely an IBM quantum simulator, has been embedded within a Jupyter Notebook, to compute the decision-making of a swarm of robots [33].

The quantum circuit, for an initialization with only Hadamard gates (mixed superposition of 0 and 1), and realized with IBM Quantum Composer, is presented in Fig. 1 [47].

Each performer receives the musical stream from the other remote performers. The system takes as input each stream,

TABLE I
THE TRUTH TABLE OF THE CONSIDERED QUANTUM CIRCUIT. N STANDS FOR NOVELTY, C FOR CLARITY, L FOR LATENCY, AND R STANDS FOR THE RESULT (GOOD/NOT GOOD) AS RECEIVED BY THE N-TH PERFORMER. R IS INITIALLY INITIALIZED AS 0.

N	C	L	R	N	C	L	R
0	0	0	0	0	0	0	0
1	0	0	0	1	0	0	0
1	1	0	0	1	1	0	0
1	1	1	0	1	1	1	1
0	1	0	0	0	1	0	0
0	0	1	0	0	0	1	0
1	0	1	0	1	0	1	0
0	1	1	0	0	1	1	0

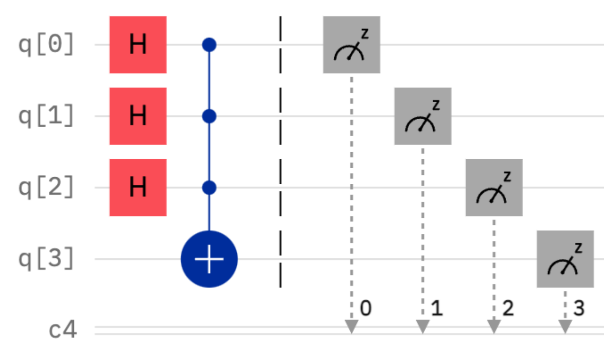

Fig. 1. Quantum circuit implementing an AND gate. Image obtained with IBM Quantum Composer, inspired by [48]. $q_0, ..., q_3$ are the qubits, corresponding here to N, C, L, and the outcome, respectively. c_4 is the classic variable used to store the result of the quantum measure.

automatically quantizing the values of novelty, delay, and clarity of the received stream. For each stream received, the quantum circuit is called. The measurements from the quantum circuit give us the frequency with which a specific state is obtained. The whole process of measurement is reiterated at given time frames, e.g., 3 seconds. The stream that, in the considered time frame, is more likely to lead to superposition of 1, is the one chosen by the performer as the example to follow. Thus, the *best stream* to follow is the one leading to 111 as the most likely output state after the quantum measurement.

At this point, different strategies are possible. The system can notify the performer, telling him/her to follow a specific stream, according to the results of the measurement. As another possible strategy, the system can automatically strengthen the signal of the unselected stream (especially those more problematic in terms of clarity and latency), increasing the network bandwidth dedicated to it (e.g., via adaptive network methods [49]). This strategy could be particularly helpful with a reduced Internet connectivity. The outcomes of the quantum circuit measurement provide also an information on how much the new musical stream should be inspired by the "winner" one. For example, if clarity and delay are good but novelty is medium, then the receiver should be inspired by the stream according to its degree of novelty. Or, if the winner stream presents a high degree of novelty but is partially unclear, then the receiver will follow it, but he/she will introduce new elements of novelty to compensate the partial lack of clarity. Fig. 2 shows the conceptual scheme of the proposed model.

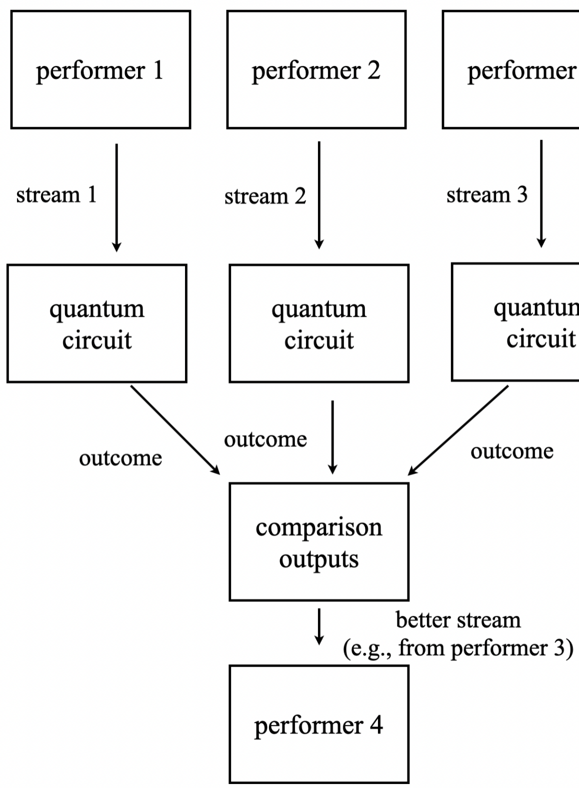

Fig. 2. The quantum circuit of Fig. 1 is embedded in the proposed conceptual scheme to select the "best stream" to be followed.

In the context of generative music by a virtual performer, the outputs of the quantum circuit can be used to shape a new stream, generated artificially, which may have the same or different characteristics of the "winning" stream to respond to it during the improvisation (e.g., using the same approximated degree of melodic novelty or a completely different one).

C. Test

We present here a simple test. The logic gate schematizes: one performer in input → an indication in output. Thus, clarity, novelty, and latency information refer to one performer at time. Ideally, the calculation is repeated for all performers sending signals to a given receiver, which compares the output of the logic gate, called from time to time for the various colleagues.

To give an idea of how the quantum circuit is working, we test it through the IBM quantum simulator. Table II shows the results we obtained. In our quantum circuit, we use the ancilla to "copy" the information on the current configuration of the main state. However, this is a slightly imprecise idea. In fact, because of the no-cloning theorem [50], it is not possible to "copy" a quantum state into another one. However, it is possible to change the state of the ancilla qubit according to the configuration of another one: for instance, if a qubit initialized as 1 is used as a control for a `NOT` gate (controlled NOT) of an ancilla, also the ancilla, if previously initialized to 0, will be switched to 1.

TABLE II
RESULTS FROM THE QUANTUM CIRCUIT ON IBM SIMULATOR, WITH A SMALL CHANGE. HERE, WE ONLY REPORT THE OUTCOME OF THE "LIKELINESS" OF THE STREAM, WHOSE PARAMETERS N, C, L ARE USED AS INPUTS, TO BE FOLLOWED. THUS, WE PERFORMED THE MEASURE ONLY ON THE CORRESPONDING QUBIT OF THE OUTPUT. FOR EACH INITIALIZATION OF THE CIRCUIT, THERE ARE 1024 SHOTS. R IS INITIALIZED AS 0.

initial state			frequencies of the output	
N	C	L	0 (not good)	1 (good)
0	0	0	1024	0
1	0	0	1024	0
1	0	1	1024	0
1	1	1	0	1024
0	1	0	1024	0
H	H	0	1024	0
0	H	H	1024	0
0	0	H	1024	0
1	1	H	508	516
H	H	H	145	879

Table III shows the results obtained with a quantum computer accessed remotely. The effect of quantum noise is visible. These results show how the considered quantum circuit works, and what are the outputs most likely to be obtained in a musical application of our code.

TABLE III
RESULTS FROM AN IBM QUANTUM COMPUTER, WHICH WAS REMOTELY ACCESSED. R IS INITIALIZED AS 0.

initial state			frequencies of the output	
N	C	L	0 (not good)	1 (good)
0	0	0	863	161
1	0	0	934	90
1	0	1	958	66
1	1	1	260	764
0	1	0	856	168
H	H	0	700	324
0	H	H	962	62
0	0	H	926	98
1	1	H	430	594
H	H	H	117	907

IV. DISCUSSION AND CONCLUSION

In this paper, we proposed to model the interaction occurring in networked, collective, remote musical improvisation in terms of quantum states: in presence of multiple performers streaming from different places and with diverse style, latency and sound quality, the n-th performer may decide to focalize the attention on the best stream, using it as a guide, or the basis for a dialogue, for the further immediate steps of the improvisation. We moved from the real-time, approximated reasoning of each musician to the definitions of states and probability amplitudes. In particular, we considered the decision-making problem of a performer receiving musical streams from the connected musicians, who decides which stream to focus on to direct his/her improvisation, according to the qualitative assessment of clarity of sound (dependent upon the degree of noise), latency of the signal (dependent upon the delay time with which the signal arrives), and novelty (which, in this context, is defined as the amount of variability with respect to the previous sequence, e.g., considering harmonic or melodic variation in a given time unit). Assuming that during an NMP a performer focuses more on the stream which presents the best values of clarity, latency, and novelty, we consider an `AND` gate as the idealization of the choice process. Thus, we formalized the whole problem in terms of a quantum circuit, and we proposed a solution where the quantum circuit can be embedded. The output of this circuit can then be exploited by an algorithm of generative music simulating a virtual performer that can interact with real performers in a mixed human-artificial NMP, or with other virtual musicians leading to a fully artificial NMP.

A limitation of the proposed approach is the needed speed for the quantum computation. With the quantum computation accessed via IBM, we need approximately 16 seconds. However, for a real implementation, a faster speed would be necessary – for instance, 5 seconds of less. With our study, we mainly investigated the theoretical framework and contextualized the problem in a quantum-computing framework.

The application of this technology during these kinds of NMPs will be assessed in future research. In particular, we plan to run tests with musical performers, to measure the limits of the ideal approach proposed in this study. Then, being inspired by the musical case, it is possible to extend the idea to the communication between devices, namely robots in a swarm, exchanging messages between them, whose collective behavior emerges from local pairwise interactions. In this sense, our music-based research can extend some first formalization of swarm robotics in terms of networks [51].

Regarding other future works, another possible strategy is using a perceptron, which is conceptually related with logic gates with the addition of weights and the activation function. The advantage of leveraging a perceptron is the use of the activation function, imitating the mechanism existing in natural neurons. In this case, the weights would correspond to the values of N, C, and L, and an activation function to let the receiving performer "approve" the musical indication or not. The perceptron would be here a metaphor for the rapid choice of musicians in taking (corresponding to neuron's firing) or not taking (not firing) the stream, and thus the musical proposal, coming from one of the performers. A perceptron can also be modeled via a quantum circuit. Future research can assess the usefulness of the neural networks approach for the considered problem.

Our study falls in the remits of the broader computer music field, which originated around the 1950s. Since then there has been extensive research into using computers for music creation. Today as quantum computing technology continues to develop, novel opportunities for computer music emerge. As a consequence, such a technology is expected to have a profound impact on the future of music. Our research is a little step in the vast domain of music-technology interactions. Once more, music can profit from technological development, and music can inspire new insights for technological advancement.

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