Entangled Internet of Musical Things and People: A More-Than-Human Design Framework for Networked Musical Ecosystems

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***Abstract*—This paper proposes a paradigm shift from the current wave of Internet of Musical Things (IoMusT) research, which is mostly centered on technological development, towards the new wave of the Internet of Musical Things and People (IoMusTP). This wave focuses not only on musical stakeholders' values, needs, behaviors and diversity, but also on their mutual entanglement with networked musical devices, services and environment. In the IoMusTP, technology is not only aware of the users and their surrounding context, but is also compliant to ethical and sustainable principles that will make it possible more inclusive, personalized, and socially acceptable experiences for the 21st-century musical stakeholders and beyond. The move from the IoMusT to the IoMusTP is a move from a network of musical devices to a network of musical stakeholders, whose interactions with musical resources as well as other stakeholders are empowered by devices. To this end, we propose a framework that can concretely guide designers of IoMusT technologies in considering the human and non-human factors relevant in the IoMusTP vision. We illustrate our framework by analyzing a set of case studies, showing how existing systems are insufficient to comply with the IoMusTP vision. Finally, we reflect on the challenges ahead of us, identifying a set of promising future directions that can inform the development of the next generation of IoMusT technologies.**

***Index Terms*—More-than-human-centered design, entanglement HCI, Internet of Things, music technology, ethics, trustworthy AI.**

I. Introduction

THE INTERNET of Musical Things (IoMusT) is an emerging research area that investigates musical systems and musical activities in networked contexts [1]. In recent years, an increasing community of practitioners from the academic, industrial and artistic sectors has contributed to the development of this area, which is positioned at the confluence of various disciplines including Internet of Things (IoT) [2], Ubiquitous Music [3], New Interfaces for Musical Expression [4], Music Information Retrieval [5], as well as Artificial Intelligence [6] and Human-Computer Interaction (HCI) [7] applied in musical contexts. As part of the broader fields of the Internet of Things, the IoMusT relates to the network of devices serving a musical purpose. Specifically, these "Musical Things" are intelligent devices embedded in physical objects that are dedicated to the production and/or reception of musical content, and that are able to continuously collect, analyze, and repurpose data from users. Musical Things may support individual or collaborative musical activities.

Today, the IoMusT stands to revolutionize how music is created, experienced, and learned. The IoMusT paradigm has the potential to positively impact a large variety of musical stakeholders. These include musicians (such as composers, performers, students and teachers), audience members, live sound engineers, sound producers, recording labels and publishers. A definition of musical stakeholders and their role in the IoMusT is provided in [8]. One of the main goals underlying the IoMusT vision is that of simplifying the lives of musical stakeholders by having technology work for them seamlessly. However, the way IoMusT technologies are currently integrated with humans leaves much room for improvement. In a more desirable IoMusT scenario, technology would take user's context into account, learn from it, and accomplish proactive steps according to their situation, needs, and expectations, limiting to a great extent the user intervention while respecting the user's privacy and values. In addition, we do not know enough about the impact of IoMusT technologies on musical stakeholders. Notwithstanding the numerous societal, artistic, and economic benefits that the IoMusT promises, the ubiquitous nature and increased autonomy of Musical Things raise serious concerns about the ethical compliance of the associated services. This raises the urgent question on how to incorporate ethics in the IoMusT so that the services provided do not infringe on the ethical rights of its beneficiaries [9], [10].

Thus far, research in IoMusT has mostly focused on technological development. Much attention has been devoted by researchers to the implementation of Musical Things [11], [12], [13], [14], communication architectures and protocols [15], [16], [17], [18], [19], and synchronization mechanisms [20], [21]. These advancements now need to be further progressed by focusing on the individuals and communities involved in musical activities. While a number of studies have investigated the effect of IoMusT technologies in supporting musical activities [22], [23], [24] and some authors have provided reflections on IoMusT practices and potentialities especially in ubiquitous music contexts [10], [25], [26], [27] there is the need of a unifying vision

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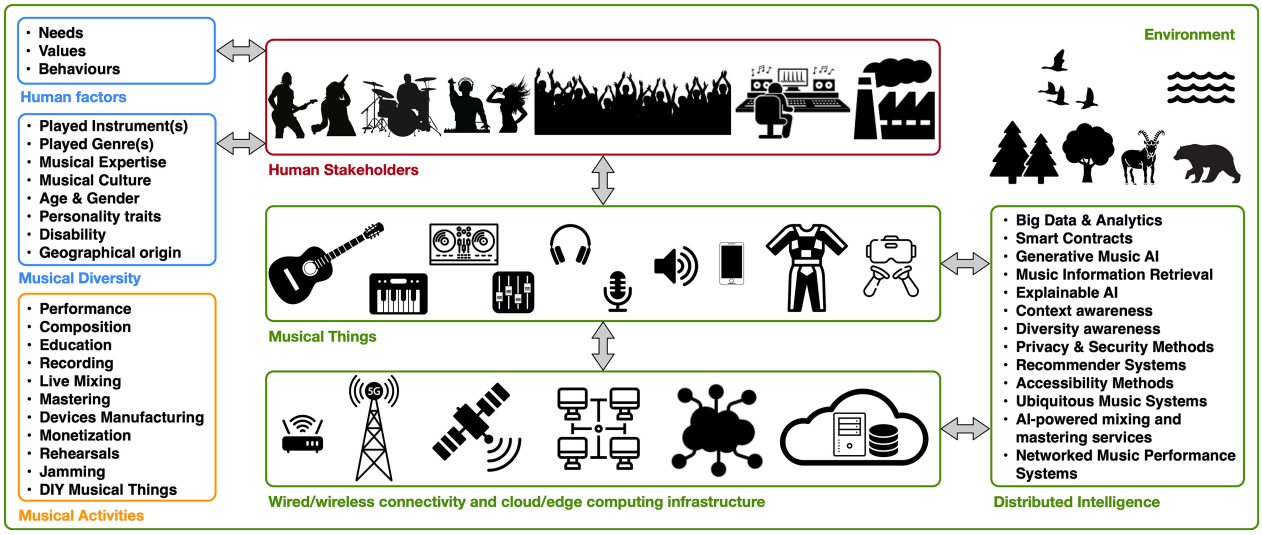

Fig. 1. Human (red) and other-than-human (green) stakeholders that participate to the entangled design of IoMusTP ecosystems, along with relevant human factors (blue) and musical activities (orange) intertwined with such stakeholders.

for progressing the field towards a human-centric perspective. A perspective that considers people as much more complex than merely system users, who have broader motivations, values, goals and interests [28]. However, as recently argued by several scholars following the post-humanistic philosophical approach, a human-centric perspective alone is insufficient for describing the complex interdependencies of human and non-human actors involved in a digital ecosystem [29], [30]. This entails an expansion of classic human-centered design approaches towards the inclusion of other-than-human elements that play a co-constitutive role in shaping the agency, meaning and interactions of a digital artefact [31].

In this paper, we advocate a closer focus on the human factors (e.g., needs, values, context, preferences, ethical concerns) in conjunction with the non-human factors (e.g., environment, autonomous AI agents) involved in musical practices mediated by networked musical devices, which is able to inform the development of the next generation of IoMusT technologies. Enabling scenarios where IoMusT technology not only is aware of the users and their surrounding context, but also is compliant to ethical and sustainable principles will make it possible more inclusive, personalized, and socially acceptable experiences for the 21st-century musical stakeholders and beyond. This entangled vision entails a paradigm shift which requires moving from the Internet of Musical Things to the "Internet of Musical Things and People (IoMusTP)". Fig. 1 illustrates a schematic diagram of the human and other-than-human stakeholders that participate to the entangled design of IoMusTP ecosystems.

This vision extends similar efforts conducted by researchers in the general IoT field [32], [33], [34], [35], who have envisioned an "Internet of People", especially from technical standpoints concerning networking and the use of Semantic Web technologies. Our proposal accounts for the works of scholars who have discussed how people and IoT devices are increasingly intertwined, and warned about the threats that this entanglement poses [36]. Notably, the formulation of the IoMusTP vision is situated in the ongoing debates promoted by the "Entanglement" wave in HCI research [37], which is impacting also the field of music technology [38], [39], [40]. This wave deals with the increasingly blurry borders between humans and devices and the distribution of agency among these actors, positing that we may become what we build for ourselves and questioning whether our designs is who we want to be. Relatedly, our vision is rooted in the tenets of "more-than-human" design approaches [29], [30], [31], which highlight the co-constitutive role of non-human stakeholders (such as the environment) and consider the impacts of design choices and technology utilization on them.

Nevertheless, the present work aims at addressing the peculiarities of the networked musical domain, which are not considered in previous studies given their lack of focus on the artistic dimension and on the specificities of the involved IoMusT stakeholders and activities. On the other hand, previous scholarly efforts focusing on music performance ecosystems [41], [42] or existing frameworks conceived for describing, designing, or evaluating musical systems [43], [44] did not integrate either the networking component at the basis of the IoMusT or a specific more-than-human-centric perspective. To bridge these gaps, we propose a framework to support designers in the process of creating IoMusTP applications and ecosystems, and we formulate directions for future research aimed at building a more empowering, socially acceptable and environmentally friendly IoMusT.

The contributions of our study are as follows:

1) We identify what is missing today from the IoMusT to make it more-than-human-centric;
2) We propose an IoMusTP framework to integrate entangled human and non-human factors in the design of IoMusT systems;

3) We apply the framework by analyzing a set of IoMusT systems to identify which elements need to be integrated to turn them into IoMusTP systems;
4) We discuss the challenges ahead of us to implement the IoMusTP vision.

II. Background: IoMusT Ecosystems and Enabling Technologies

It is worth noticing that the IoMusT is no longer a futuristic vision but is increasingly becoming a reality. Since the IoMusT is emerging, now is the best time to propose guidelines for the development of the next generation of IoMusT technologies. Today, IoMusT ecosystems are rapidly emerging around dedicated Musical Things and communities of musical stakeholders using them. In general, IoT ecosystems form around commonly used technologies focusing on a specific application domain [45]. Whereas IoT ecosystems have been investigated under technological and ethical perspectives [46], [47], similar investigations have yet to be performed for the IoMusT. This is due to the fact that IoMusT enabling technologies are emerging only recently, and consequently IoMusT ecosystems are in their infancy.

Examples of technologies enabling IoMusT ecosystems include *i)* embedded systems (i.e., small computer systems that can be embedded in objects) dedicated to real-time sensor and audio processing tasks [48], [49]; *ii)* networked music performance systems [50], [51]; *iii)* Semantic Web solutions applied to the musical domain [18], [52]; *iv)* artificial intelligence methods to analyze and generate musical signals [6]; *v)* 5G networks used in musical contexts [53], [54]. Meanwhile, communities are forming around these technologies [55] providing the ground for the emergence of IoMusT ecosystems. An example of IoMusT ecosystem is that formed around the Lava Me guitars by Lava Music, which involves guitars connectable to Internet and a community of musicians using such technology. Another example is that formed around the app of Yousician.com, which involves methods from music information retrieval, recommender systems, and cloud computing. The company offers an app for mobile devices to support self-learning of various musical instruments. A further example is that of music systems to play together at a distance, such as JackTrip [56], Elk Live [49], or LoLa [57], which have a large user base.

III. Methodology

The proposed framework is the result of the adoption of the methodological approach depicted in Fig. 2. Such an approach begins with the use of autoethnographic methods to derive a conceptualization of the IoMusTP vision. This phase is then followed by the definition of the framework as a design and evaluation tool. Subsequently, the framework is applied to existing technologies as a way of illustrating its usage. Autoethnography is a research method that combines elements of autobiography and ethnography, where a fieldworker's own experiences are examined alongside those of other observed social actors. This approach aims to describe and systematically analyze personal experiences to gain insights into cultural phenomena [58]. Such a method is increasingly adopted by researchers in the HCI field [60]. A description of the conducted research activities is reported hereinafter.

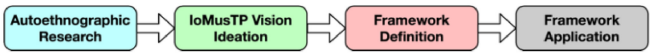

Fig. 2. Overview of the adopted methodological process.

Authors' personal reflections: Such reflections are based on the authors' extensive experience as active practitioners in the IoMusT field at both the technical and artistic levels. The authors have developed or extensively used several enabling technologies for the IoMusT field, including a dedicated operating system for low-latency audio processing tasks over embedded systems [49], 5G networks [54], semantic Web systems [18], [52], and different kinds of musical things such as smart musical instruments [13], [60], [61] and musical haptic wearables [62], [63]. Importantly, most of these technologies have been co-designed and evaluated involving several musical stakeholders, as well as directly used by the authors in their own artistic practice.

Analysis of the existing literature: We collected and analyzed 311 scientific, technical, artistic and popular sources between 2014 (when the first works or projects related to the IoMusT started to emerge) and 2024 (the time of this writing). These publications comprised the relevant IoMusT literature and the works in related fields. Keywords such as "networked music performance", "Internet of Musical Things", "embedded audio", "AI and musical instruments", or "ethics and music", were mainly used to perform the search over Google Scholar, Google Patents, IEEE Xplore Digital Library, ACM Digital Library and Elsevier Scopus. We adopted the following inclusion and exclusion criteria: *i)* we excluded works with theoretical or practical elements not pertinent to our investigation; *ii)* we included contributions published in peer-reviewed journals, conferences, and book chapters, as well as Master's and PhD theses, patents, and technical reports; *iii)* we excluded non-English sources and duplicates; *iv)* we considered Web pages with articles or blog posts (not written by academics) explicitly mentioning the IoMusT.

Discussions with IoMusT practitioners: Since 2014 the authors have interacted with at least 80 among the most prominent IoMusT researchers in both industry and academia worldwide, sharing perspectives and concerns about the field and its evolution. These discussions included heterogeneous topics such as the impact of online services and AI agents on musical creativity and education, trustworthiness and energy efficiency of IoMusT systems, accessible Musical Things, and economic and diversity issues in the music industry.

Events attendance: A relevant source of inspiration for the framework has been the authors' participation to events promoted by the IoMusT community. These have included the past five editions of the IEEE International Symposium on the Internet of Sounds (2020-2024), which have included several keynotes, panels, tutorials and dedicated workshops. The programs and proceedings are available online (see [64]).

IV. Academic and Industrial Research Gaps

A. The Lack of Understanding of Socio-Technical Aspects of the IoMusT

IoMusT cultural meaning: Up to now, critical discourse on the cultural impact of the IoMusT has been limited, with most literature focusing on technological advancements. IoMusT ecosystems involve a large number of Musical Things and humans that are connected via the Internet anytime and anywhere to provide communication and contextual services [65]. Thus, the IoMusT creates a new social, economic, and ethical landscape that needs new enhanced legal and ethical measures for privacy protection, data security, and trust improvement. The IoMusT adoption depends on whether the ecosystems of companies would succeed in delivering to the market solutions attractive to the users. However, the effects of the IoMusT usage are not yet understood, it is not clear how the provided services may influence individuals and society as a whole, and personal data issues represent a paramount topic. As the IoMusT emerges, there is a concrete need to bring insights into these urgent matters [66], [67].

Ethics and music technology: Scholars in the HCI field have produced a large body of work aimed at discussing political and ethical considerations of interaction design [68], [69]. However, the study of ethics in music technology is not yet well established, with only a few authors dealing in recent years with the importance of related ethical dilemmas. Researchers have questioned the practices of music streaming services in monitoring users and inducing behaviors, warning about the associated risks [70], [71]. Other authors have examined the ethical dimensions of the field of Music Information Retrieval (MIR), arguing that MIR technology is not value-neutral but is influenced by design choices, and so has ethically relevant implications [72], [73], [74], [75]. In the field of New Interfaces for Musical Expression (NIME), some authors have discussed political issues inherent in new musical instruments [71], while others engaged with topics such as environmental sustainability [76], gender diversity [77], accessibility [78], [79], inclusion [81], and value-driven design approaches [82]. All these research strands are also pertinent to the IoMusT [10], [27], although no investigations have been conducted yet on such topics.

Ethical research in the general IoT has identified major issues such as privacy, security, transparency, trust, social equity, social equality, and responsibility according to law. Research has also identified the factors that can increase the acceptance of the IoT and proposed a set of guidelines to interact with the IoT from a social perspective [47], [82], [83]. There is a strong need to follow some policies that support social issues also in IoMusT in order for it to be socially acceptable and undertaken in the public interest. Nevertheless, the IoMusT is distinguished from the general IoT field for its artistic focus. While some technical and societal challenges are common to the two fields, the IoMusT poses music-specific challenges that arguably cannot be simply addressed by using the same methods and tools of the IoT. Although principles for an Ethical IoT design have been proposed [83] aiming at empowering the user in the interaction with the IoT, these cannot be translated or adapted in a direct and straightforward way to the IoMusT case. There is a need to define principles for an Ethical IoMusT that can inform design, development, and evaluation of IoMusT ecosystems, their hardware and software components, and the interactions of stakeholders. Initial steps in this direction are represented by the recent studies reported in [84] about an ethics framework for the IoMusT and in [85] about environmental sustainability strategies for the IoMusT.

B. The Lack of Technical Solutions for a Human-Centric IoMusT

Musical Things: Musical Things are devices able to generate, control, or track responses to musical content. They are characterized by sensors, actuators, connectivity options, and software to collect, analyze, receive, and transmit data. Various kinds of Musical Things exist in both academy and industry. The most prominent category is that of "smart instruments", a family of musical instruments enhanced with wireless connectivity and embedded intelligence. Examples from industry and academia include the Lava Me 3 smart guitar by Lava Music, the Sensus Smart Guitar by Elk Audio, or the Smart Cajón [60]. Recently, Turchet proposed a vision where smart instruments have capabilities of advanced reasoning on, learning from, and adaptation to the player's actions and data from connected devices, which will confer them with unprecedented context-awareness and proactivity features [61]. However, current smart instruments have limited intelligent capabilities and have only marginally exploited the possibilities offered by their underlying technology. Existing smart instruments are not equipped with the ability to understand the context around them, e.g., who is the user, what musical activity is being conducted, as well as how, where and when. Consequently, no services related to smart instruments exist which are able to adapt to or proactively support musicians during various musical activities. The same situation occurs for audience members and their interactions with musical content, performers or other audience members, which are mediated by Musical Things.

Context-awareness and proactivity: The capability of IoT devices and social networks of being aware of environments or situations around their users enables the creation of networked services that can respond proactively based on such awareness. State-of-art machine learning methods are used to mine patterns from users' longitudinal data, which allows to make predictions about users' likely next steps and provide recommendations. Whereas the concepts of context-awareness and proactivity have been investigated extensively in computer science and IoT disciplines [86], they have been overlooked by music technology research. Thus far, the application of such concepts to the musical domain has been limited to the development of recommendation systems for music listening [88], being this research fostered by big corporations dealing with music streaming (e.g., Spotify). There is a need to shift the focus of this research inquiry not only from the listener to the player, but also from context to the wider concept of user diversity. In this way personalization mechanism can be set

in place so that intelligent services can be tailored to the needs and specificities of each user. User diversity has not been exploited yet in the creation of online services able to support musical stakeholders in developing and maintaining their social relationships. Especially for musicians it is essential to build and maintain social relationships not only to foster musical collaborations that can lead to enjoyable shared experiences or business opportunities, but also to ensure that they are exposed to different repertoires, styles, and musical instruments that can enrich their vocabulary and knowledge. Current technologies fail to provide tools for musicians to leverage user diversity and cope with social challenges that arise from it (e.g., inclusion, equality). Existing musical social networks (e.g., Soundcloud) are not meant to truly answer to musicians' connectivity needs, as they are intended as a method for self-promotion or offer basic connection services that are not faithfully accounting for the users' specificities. On the other hand, generic social networks (e.g., Facebook) are not conceived to properly search for musicians with specific characteristics. Relatedly, the envisioned ability of Musical Things to understand, especially in real-time, what, where, when, why, and how musicians play, requires the definition of new techniques for sensor fusion and pattern recognition on embedded systems.

Privacy and security: Musical Things have the ability to collect large quantities of data from users (e.g., musical signals, user profiles). Such data gathering process may occur continuously for all musical activities a user is involved in. This comes with the risks of malevolent attacks capable of stealing sensitive information, such as identity and intellectual property. However, privacy and security methods are currently poorly investigated in the IoMusT. There is a concrete need for defining strategies specific to the IoMusT so that users not only feel but, most importantly, are safe when participating to IoMusT-based activities. A well-grounded starting point would be to apply methods devised for the general IoT field [88], [89], adapting them to the peculiarities of Musical Things and their supported interactions.

Explainable AI: The rise of deep learning has spurred numerous debates in the applied ethics research community concerning the trustworthiness and responsibility of AI-based systems [90], [91]. Similar discussions are occurring in the musical domain. The vast majority of advanced deep learning models developed today for music analysis or generation tasks do not expose their internal decision process, thus hindering users from a clear understanding of the mechanisms that led the algorithm to produce certain outputs. Such a lack of explanations hinders the adoption of reliable and trustworthy systems in a sensitive area such as the IoMusT, where a plethora of user-related data are expected to be gathered, processed and manipulated. Establishing trust between human and artificial agents represents an unsolved issue to date in creative settings such as those of the music technology field [92]. To mitigate the lack of trust in AI-based systems, tools from the field of eXplainable Artificial Intelligence (XAI) [93] need to be integrated to explain AI agents' decision making, thus ultimately enhancing trust in AI-based systems [94], [95]. This is especially relevant in situations when the explanation needs to be provided in real-time, at the moment in which the musical activity unfolds [96]. However, the integration of XAI methods in the IoMusT has been largely overlooked thus far. More broadly, existing methods to assess trustworthy AI in practice [97], [98] have not yet been utilized in IoMusT settings.

C. The Lack of Investigations on More-Than-Human Designs

If on the one hand, investigations about human-centric approaches have scarcely been addressed by IoMusT researchers and practitioners, on the other hand discussions on the application of recent more-than-human design approaches [29], [30], [31] has been even more largely overlooked. The highly interconnected nature of the IoMusT, the autonomy of musical agents at the basis of IoMusT services, the diversity of IoMusT stakeholders, and the implications that IoMusT manufacturing processes have on the environment suggest that a mere human-centered design approach needs to be expanded towards the consideration of the complex underlying musical entanglements. This entails designing not just for and with the musical stakeholders, but also for and with the involved non-human actors, such as Musical Things, AI-based musical services, and the environment. There is thus the need of considering more carefully the inevitable lack of total control by humans during IoMusT-based musical activities, the distributed nature of the intelligence in IoMusT settings and the resulting shared agency with machines, which necessarily casts non-human actors as partners in entangled designs.

V. A Framework for the Entangled Internet of Musical Things and People

Section IV identified a number of research gaps existing today which prevent us for establishing a more-than-human-centric IoMusT. Such gaps motivate our proposal for a framework that aims at providing designers of IoMusT systems with guidance towards the dimensions that need to be considered to realize the proposed IoMusTP vision. The move from the IoMusT to the IoMusTP is a move from a network of musical devices to a network of musical stakeholders, whose interactions with musical resources as well as other stakeholders are empowered by devices.

The following ten dimensions, along with their subcomponents, need to be explicitly considered in future efforts towards building a more empowering, socially acceptable and environmentally friendly IoMusT. The framework, summarized in Table I, also serves as a method to assess existing designs, and as a basis for reflecting about the future research directions. For each dimension, the text provides an example of practical application showing the social implications of the application of the framework.

It is worth noticing that the framework is intended as dynamic: it could be modified in future versions to make adaptations as society changes and new technologies emerge. Moreover, the framework could be used in tandem with other

TABLE I
THE PROPOSED IOMUSTP FRAMEWORK

Dimension	Sub-component	Goal
Ubiquity	• Self-contained device • Wireless connectivity	Support ubiquitous creativity, music making and learning
Data protection	• Privacy & security of personal data • Privacy & security of intellectual property	Make sensitive data private and make users' interactions safe while participating in IoMusT-based activities
Personalization	• Customization by the user • User adaptation by AI	Make the IoMusT system context-aware and proactive so that personalized services can be provided to users
Musical diversity capitalization	• Diversity-awareness • Connection through diversity	Connect musical stakeholders to address their needs in relation to given tasks, by leveraging their individual peculiarities
Inclusiveness	• Musical expertise • Cultural & geographical origin • Gender & age	Cater to the needs of the widest possible number of users of IoMusT systems
Accessibility	• Visual-impairments • Auditory-impairments • Motor-impairments	Ensure equal access to IoMusT services to all users regardless of their physical abilities
Tailored algorithmic transparency	• Explainable algorithms • Explanation presentation methods tailored on the user	Increase the user trust in the usage of IoMusT systems
Environmental sustainability	• Low impact of Musical Things • Low impact of networking infrastructures • Low impact of applications & services	Reduce the negative impact of IoMusT systems on the environment at all levels, from production to distribution
Fair remuneration	• Royalties payment methods	Ensure direct, correct and fast payment of artists' royalties
Content democratization	• Support to non-experts	Lower the entry barriers to music making and learning

evaluative tools to ensure optimal outcomes for people and other-than human stakeholders.

A. Ubiquity

To maximize the potential for individual and collaborative creativity, users should be freed from the need to conduct their musical activities at a specific venue. To work independently of a given location, IoMusT technologies should be designed to support ubiquitous usage so that musical activities can be conducted anywhere. This can be achieved by using self-contained intelligent musical instruments, as those proposed in [61], and portable devices used for musical purposes, as well as by leveraging their connection to wireless technologies and the cloud. As an example, a musician can start a music project using a hardware console, continue it using a digital audio workstation running on their laptop, then edit it on their smartphone when walking in a park because a creative idea emerged there and then. Other musicians can remotely edit such piece collaboratively contributing to the creative process.

B. Personal Data & Intellectual Property Protection

A crucial issue that IoMusT developers must address is the integration of privacy preserving methods in all applications gathering, processing and repurposing data from users involved in individual or collaborative musical activities. These include personal data and copyright-protectable artistic outputs, such as scores, compositions, recordings, or arrangements. A possible avenue is the adoption of "privacy-by-design" approaches [99], [100], [101] where privacy issues are tackled since the initial stages of the creation of a service, device or interactions among users. Moreover, it is possible to leverage guidelines and frameworks developed by IoT research for protecting data at each stage of the sensing-processing-service provisioning chain [102]. Furthermore, it is crucial to strictly adhere to national and international regulations concerning the handling of personal data (such as the EU GDPR). As an example, a musician feels comfortable in using a smart musical instrument and related applications that continuously monitor and provide feedback about his musical productions since the instrument and applications use advanced encryption methods and only part of the data produced is stored, namely the one that the musician had agreed to store.

C. Personalization

To provide services that are tailored for the user rather than being general, the intelligence embedded in Musical Things, and/or distributed in the network, needs to be exploited. On the one hand, this can be achieved by providing users with mechanisms to customize their interaction with IoMusT systems (e.g., via manual configurations of the user interface); on the other hand, by endowing the Musical Things with advanced context-awareness and proactivity features so that the system behavior adapts to the user. Methods from Semantic Web (such as ontologies, automatic reasoning and recommender systems) as well as from HCI (e.g., user modelling, participatory design, and more-than-human design) can be utilized for this purpose. As an example, a novice musician customizes the behavior of her smart musical instrument to fit her musical expertise level: the instrument does not provide all possible complex behaviors or the complete range of timbres and interaction methods, but only the ones that are actually useful to the musician so that she feels comfortable while playing.

D. Musical Diversity Capitalization

By "musical diversity" we refer to the variability that exists across musicians, their instruments, musical activities, musical culture, and social relations. Finding, in a personalized way, specific online resources or specific musical stakeholders to

interact with, represents an unmet need of IoMusT users. While the personalization dimension aims at providing each user with customized individual services, the dimension of diversity capitalization aims at offering services that provide connections among users or with online resources based on each individual's peculiarities. The goal is to connect musical stakeholders, or to retrieve content, to address their needs, for instance by finding the right musical stakeholder(s) or resource(s) for accomplishing a given musical task. Methods from Semantic Web in conjunction with social media and networked music performance systems could be employed to create such kind of services that capitalize on the diversity of the users. As an example, a flute player may want to find and join an online Irish folk music session made available via the social media of a networked music performance system. Or a guitar beginner may want to find an interactive group lesson delivered online by a jazz player via an educational platform supporting low-latency audio-visual streaming.

E. Inclusiveness

In order for the IoMusT to benefit society, it is paramount that an optimal usability and a satisfactory user experience are ensured for all users regardless of their diversity factors. Thus, IoMusT systems should be designed to accommodate the widest possible number of people within a certain category of users targeted by the specific application (e.g., performers, composers, audience members). This entails the adoption of strategies that take into account aspects such as the users' musical expertise level, the type and cultural/geographical origin of musical instrument and genre played or listened, or diversity factors such as gender or age. For instance, this translates into the usage of datasets, to train machine learning models employed by IoMusT services, which do not discriminate a particular category of users, musical genres or musical instruments. This parallels ongoing efforts to address similar ethical issues in MIR [72] and NIME research [103]. As an example, the IoMusT connectivity infrastructure based on satellites enables a music teacher to reach students in rural areas not served by musical education offers. Another example is a haptic vest for audiences of IoMusT concerts that provides different intensities of vibration for males and females in different parts of the body, to accommodate the diverse sensitivities thus making the experience equally comfortable to both genders.

F. Accessibility

Users with disabilities should be fully provided with equal access to IoMusT-based activities. Thus, developers must ensure that IoMusT devices, services and ecosystems are accessible to as many people as possible [104]. This entails creating systems that are capable of targeting different kinds of physical abilities. The adoption of the Universal Design principles can contribute to achieving designs that satisfy such crucial requirement [105]. For instance, an IoMusT service should be designed to be used by both sighted and visually-impaired musicians, or an IoMusT performance should be enjoyable by audience members with and without hearing impairments. Moreover, the IoMusT should support the participation in musical activities of individuals with motor impairments. As an example, an auditory-impaired audience member can enjoy the music at a live concert thanks to a dedicated haptic wearable that compensates via the sense of touch their deficits at the auditory level.

G. Tailored Algorithmic Transparency

As AI systems are at the basis of the intelligent behaviors of Musical Things, it is crucial that users can trust such behaviors when participating to IoMusT activities. This is especially true in critical real-time situations such as a performance, where a musician must feel comfortable when interacting with an AI agent while playing in front of an audience. The usage of XAI methods to explain the reasons for an output of a deep learning model, along with methods to convey to the users such explanation, is of paramount importance to build trust in IoMusT users [106]. Moreover, on the one hand such explanations and their presentation forms need to be tailored to individual users on the basis of their skills and background [107]; on the other hand, they need to be tailored for the specific type of musical activity at hand, where temporal factors play a relevant role and may [92]. As an example, a music learner interacts with an AI-based virtual teacher that not only provides indications on how to improve but also explains the exact reasons leading to such indications.

H. Environmental Sustainability

The production and usage of IoMusT devices, ecosystems and services need to be compliant with green policies, so that negative impacts on the environment are minimized. Therefore, IoMusT designers must consider the impact of their decisions on the environment at all levels, from production to distribution. Like for the general IoT field, also Musical Things as well as IoMusT networking and computing infrastructures may have a heavy environmental footprint in terms of greenhouse gases emissions, pollution and soil consumption. Thus, it is paramount to consider the massive production and use of electronic devices, inherent to the diffusion and adoption of the IoMusT, that could jeopardize current efforts towards a green transition. As an example, musicians and audience members feel comfortable in participating in IoMusT activities promoted by a company having a demonstrated history in producing devices and services with low environmental footprint.

I. Fair Remuneration

To date, the recorded music industry suffers from a lack of fair monetization of artists' royalties: often non-negligible amounts of revenues do not reach the artists, but ends up in black boxes in which it is not possible to identify in an accurate way who are the rightful owners of royalty revenue. Therefore, the IoMusT should be designed to ensure that the involved producers of creative outputs are rewarded with fair monetization schemes. Blockchain technology may represent a concrete solution, as proposed in [8], since it would allow

artists to be remunerated directly and immediately after their music is consumed by a listener (e.g., via smart contracts). The same would occur for any musical activity leveraging the IoMusT other than music consumption (e.g., teaching). As an example, due to blockchain technology, music venues only need to pay the performers when a concert takes place, as payments to composers are handled by the performers' smart musical instruments. These instruments recognize the music played and automatically ensure composers are compensated. This eliminates the need for venues to pay a Rights Society to manage composers' rights. Consequently, composers no longer rely on a Rights Society, as all transactions are managed by a smart contract on the blockchain.

J. Content Democratization

An IoMusT designed for people and machines needs to guarantee that access to systems and resources is as easy and open as possible, so that users can achieve their musical goals while saving time and reducing costs. This essentially entails lowering the barriers of entry for non-experts, so that as many users as possible can make or learn music via IoMusT technologies. For this purpose, remote computing coupled with AI technologies can not only support novices in addressing complex tasks in individual and collaborative music activities, but also complement the skills of advanced users with their knowledge gaps. Notably, such-AI-based services are intended as a creativity support rather than a replacement of human beings, where a musician can select and refine with manual adjustments what the AI generated. As an example, AI-powered mixing and mastering services may save time and effort in the music production process (i.e., they make good mixing and mastering results accessible to musicians who could not otherwise afford the services of a human mixing/mastering professional). Or generative AI music systems running on the cloud may help a keyboard player create a bass line without having to rely on a human bass player.

VI. Evaluation

In this section, we show how our proposed IoMusTP framework can be concretely used to assess existing IoMusT applications and systems in order to find gaps in more-than-human-centric dimensions.

A. Methodology

Step 1: Identify the various hardware and software components of the system/ecosystem (which may encompass multiple Musical Things), along with the data flow among the involved users.

Step 2: Build a table where rows represent the dimensions reported in Table I. In case of ecosystems, the table should be repeated for each involved node.

Step 3: Go through each dimension and use the color codes proposed below to assess the system/ecosystem. The table may be complemented with notes justifying the decisions taken (i.e., choice of color). Our proposed color coding is as follows:

1) Gray: when a particular dimension sub-component is not applicable for a given system;
2) Green: when a particular dimension sub-component is fully supported by the IoMusT system;
3) Red: when the presence of a particular dimension sub-component would make sense or would be desirable, but is not supported at all;
4) Yellow: when a certain dimension sub-component is partially supported.

B. Case Studies Analysis

For evaluation, we used three prominent case studies of IoMusT applications described in the literature. The evaluations are reported in Tables II, III and IV.

1) Queries-by-Playing to a Music Repository via a Smart Guitar: This IoMusT system, reported in (Turchet et al., 2020b) comprises a smart guitar that supports users in retrieving content from a musical repository via content-based queries rather than the usual textual queries. The system was devised to support recreational music-making, improvisation, composition, and music learning. Specifically, the instrument is a conventional guitar enhanced with embedded processing and wireless connectivity, which is able to interact with the Jamendo repository of Creative Commons music content. Through the use of a touchscreen embedded in the instrument, the player records a short a short audio excerpt with the wanted characteristic of the music to be retrieved from the repository (such as tempo, chords, keys, and melody). The guitar automatically extracts from the recording such characteristics and sends them to the cloud as a query. These characteristics are the same features which the Jamendo repository is indexed upon, thus a match is performed by the cloud computing system with the music pieces having those features. A selection of the matching pieces is then wirelessly transmitted to the smart guitar, which will reproduce them thanks to an embedded loudspeaker.

2) Networked Music Performance Ecosystem: Elk Live is a networked music performance system that enables geographically displaced musicians to play together over the network [49]. It works both as an application for a desktop computer and through a dedicated hardware that minimizes the latency of the signal acquisition and delivery. The system comes with a dedicated social media where musicians can connect, thus leading to an IoMusT ecosystem of musicians and devices. The system has been also tested over 5G [54].

3) Haptic-Enhanced Performance: This system, reported in [63], comprises a smart mandolin (i.e., a conventional mandolin enhanced with sensors, embedded processing and Wi-Fi connectivity) and a set of haptic gilets used by the audience. The instrument extracts in real-time some features from the musical signal produced by the performer (e.g., onset and pitch of each note, sounds related to sensors activations) and wirelessly transmits such information to the haptic gilets. Thanks to composed mappings between the music features and vibration patterns, the gilets will produce some tactile sensations concurrent to the heard music.

TABLE II
EVALUATION OF THE QUERIES-BY-PLAYING IOMUST SYSTEM

Dimension	Code	Notes
Ubiquity		
Self-contained device		There is no need of equipment external to the smart guitar
Wireless connectivity		No support to 4G/5G mobile networks (only Wi-Fi)
Data protection		
Privacy & security of personal data		A secure smart guitar-cloud connection is established; no personal data is collected; Recordings are not stored
Privacy & security of intellectual property		
Personalization		
Customization by the user		The user cannot customize the system
User adaptation by AI		There is no adaptive AI behavior
Musical diversity capitalization		
Diversity-awareness		There is no diversity-aware algorithm for resource retrieval
Connection through diversity		
Inclusiveness		
Musical expertise		The system targets both beginners and experts
Cultural & geographical origin		MIR algorithms only support Western music
Gender & age		The system is equally accessible by all genders/ages
Accessibility		
Visual-impairments		A vocal interface could be added
Auditory-impairments		The system is intended for musicians
Motor-impairments		The system could be integrated into accessible instruments
Tailored algorithmic transparency		
Explainable algorithms		There is no explanation about why a given music piece is returned
Explanation presentation methods		
Environmental sustainability		
Low impact of Musical Things		A conventional guitar and off the shelf platform are used
Low impact of networking infrastructures		The system leverages the existing commodity internet
Low impact of applications & services		Computing optimizations needed to be less energy hungry
Fair remuneration		
Royalties payment methods		Creative Commons content is utilized
Content access democratization		
Support to non-experts		The AI takes care of all computations, thus lowering the entry barriers

TABLE III
EVALUATION OF THE ELK LIVE IOMUST ECOSYSTEM

Dimension	Code	Notes
Ubiquity		
Self-contained device		Portable small box
Wireless connectivity		No direct 5G connectivity via a dedicated system on chip, but connectable via an external 5G router
Data protection		
Privacy & security of personal data		Fully protected
Privacy & security of intellectual property		No data collected or stored about the produced music
Personalization		
Customization by the user		User customizations are fully supported
User adaptation by AI		No AI involved in context-aware and proactive tasks
Musical diversity capitalization		
Diversity-awareness		There is no diversity-aware algorithm involved in recommendations about which users to connect with
Connection through diversity		
Inclusiveness		
Musical expertise		Full support of any musical expertise
Cultural & geographical origin		Full support of any musical instrument
Gender & age		Full support of any gender or age
Accessibility		
Visual-impairments		There is no alternative interface
Auditory-impairments		System conceived for users without hearing impairments
Motor-impairments		The system enables users to avoid travelling
Tailored algorithmic transparency		
Explainable algorithms		There is no AI involved
Explanation presentation methods		
Environmental sustainability		
Low impact of Musical Things		The system enables users to avoid travelling, thus zeroing pollution; a standalone software is available without the use of a hardware device
Low impact of networking infrastructures		
Low impact of applications & services		
Fair remuneration		
Royalties payment methods		There is not a system for monetizing creative outputs
Content access democratization		
Support to non-experts		There is no AI involved that puts in touch users

VII. CHALLENGES AND FUTURE DIRECTIONS

The analysis conducted in Section VI showed how current systems are not yet fully adhering to the IoMusTP vision. While some dimension sub-components are not applicable in a given system, others would be desirable for achieving more-than-human-centric designs. The most critical factors identified are: *i)* the lack of measures to make the systems accessible; *ii)* the lack of XAI methods to increase trust in the systems; *iii)* the absence of techniques that automatically

TABLE IV
EVALUATION OF THE HAPTIC-ENHANCED PERFORMANCE IOMUST SYSTEM

Dimension	Code	Notes
Ubiquity		
Self-contained device		The smart mandolin and haptic gilets are self-contained
Wireless connectivity		The system can be used wherever there is Wi-Fi
Data protection		
Privacy & security of personal data		No data are collected from users
Privacy & security of intellectual property		
Personalization		
Customization by the user		Customizations are supported for instrument not for gilets
User adaptation by AI		No AI involved for customizing the audience experience
Musical diversity capitalization		
Diversity-awareness		For this system a service based on diversity-aware algorithms would not make much sense
Connection through diversity		
Inclusiveness		
Musical expertise		The instrument is intended for expert composers/performers
Cultural & geographical origin		The extracted music features are broad enough
Gender & age		The gilet is not comfortable for women due to the breast
Accessibility		
Visual-impairments		The gilet can target visually-impaired audiences
Auditory-impairments		The gilet can target auditory-impaired audiences
Motor-impairments		The gilet can target motor-impaired audiences
Tailored algorithmic transparency		
Explainable algorithms		No AI algorithm is involved for music features extraction or tactile patterns generation
Explanation presentation methods		
Environmental sustainability		
Low impact of Musical Things		A conventional mandolin and off the shelf platform are used
Low impact of networking infrastructures		The system leverages a common Wi-Fi network
Low impact of applications & services		The energy consumption of the system is low
Fair remuneration		
Royalties payment methods		There is not a system for monetizing creative outputs
Content access democratization		
Support to non-experts		There is no AI involved that puts in touch users

adapt the behavior of the system to the user; *iv)* the absence of methods to make the systems diversity-aware. These represent the most promising future directions that research could focus on. However, addressing such aspects entails overcoming a number of challenges described hereinafter.

A. More-Than-Human-Centered Design

Today, the vast majority of IoMusT development in both academia and industry is mostly driven by top-down technological requirements. Instead, it is necessary to involve the end users in the design process of IoMusT systems so that their needs, values, desires and expectations are addressed in a satisfactory way. The use of co-design techniques is a valuable avenue for this purpose, but only a few examples are reported in the IoMusT literature thus far (see, e.g., [62]). Approaches from the field of human-centered AI [94], [106] are also relevant, but thus far have been rarely employed in the design of intelligent IoMusT applications.

At the same time, it is necessary to acknowledge the increasing autonomy of Musical Things, and investigate methods that leverage the resulting shared agency in IoMusT ecosystems. This calls for more entangled design research, in particular to address accessibility, sustainability, gender and cultural issues from which IoMusT systems should be devoid to truly benefit society. Furthermore, it is of fundamental importance that IoMusT developers rely on privacy-by-design approaches [100], [101] and on successful privacy-preserving guidelines proposed in the literature [102].

B. Adaptive, Context-Aware and Proactive Systems

The IoMusTP vision here proposed entails radically new intelligent abilities for Musical Things. These include the adaptation of the device and services to the user's behaviors, the understanding, especially in real-time, of what, where, when, why, and how musical stakeholders conduct musical activities (individually or collaboratively), as well as the offering of proactive services based on such understanding. To achieve these advanced forms of intelligence, first of all there is the need of devising a technology capable of modelling the users, their behaviors and their Musical Things. A ground work has been already conducted in this direction, by proposing the IoMusT Ontology [52] along with Semantic Web systems using it [18]. However, new ontologies and AI services based on them are needed for endowing Musical Things with truly context-awareness and proactivity features. Secondly, there is the need of defining interaction paradigms that ensure a correct balance of delegation and control.

C. Trustworthy IoMusT

There is a need for insights and increased efforts to build a socially acceptable IoMusTP, where restoring trust in the devices, infrastructures and ecosystems is essential. To be truly trustworthy the IoMusTP needs first of all to provide services that prevent any sort of risk or damage for users, from the psychological to the physical level. This entails first of all integrating methods and policies for security and privacy so that users feel comfortable when participating in IoMusTP-based activities. Future research needs to focus on these aspects that to date have been poorly investigated by the IoMusT community. Secondly, users need to trust the Musical Things they are operating so these can be treated as ally during their musical activities.

On the one hand, there is the need of progressing the capabilities and performances of AI methods to be integrated in Musical Things and services, by leveraging more-than-human design approaches [31]. On the other hand, there is the need of adopting methods and guidelines developed in the human-centered AI field [106], as well as of complying with regulations existing in the countries where IoMusT products are utilized (such as the European Commission's AI Act). Furthermore, there is the need of understanding when and how providing explanations about the decision-making process of an AI agent is actually worth and relevant to users involved in given IoMusT activities. The integration of XAI methods in IoMusT systems has not been properly addressed yet, with only a few authors starting exploring this matter [96]. This emerging area of research is relevant to both offline and real-time services and to both music analysis and generation.

D. Capitalization on User Diversity

The benefits of the IoMusT for society could derive from an appropriate and value-driven exploitation of the musical diversity existing across musical stakeholders, their Musical Things, musical activities, and social relations. To achieve services and ecosystems leveraging the many forms of musical diversity so to empower IoMusT users with richer and more inclusive social interactions, there is the need of creating entirely new diversity-aware algorithms. To date, reflections about how to exploit user diversity in musical settings have been mostly limited to listeners, in terms of music recommender systems [75]. There is an urgent need to bring those reflections also to the case of making, teaching, composing, and experiencing music in networked settings and for all musical stakeholders.

E. Sustainable Approaches

Today, debates about the environmental impacts of IoMusT technologies (from production processes to utilization) have been largely overlooked by the IoMusT community. The study reported in [108] has recently provided a survey of the environmental issues produced by current information and communication technology and related these to some use cases that the IoMusT envisions. On the basis of this survey, the authors identified some key aspects to reduce the footprint of IoMusT services and products as well as provided suggestions to make advancements in environment-aware IoMusT development processes. In the same vein, design strategies for a sustainable IoMusT have been recently proposed in [85]. Nevertheless, despite these efforts, there are major gaps in our understanding of how to concretely design IoMusT ecosystems in a sustainable way and how IoMusT ecosystems can support sustainability. This calls for more research on this and related topics.

F. Musical and Cultural Impact of the IoMusT

Another next big step to make the IoMusT more socially acceptable is the study of the musical and cultural impact of IoMusT ecosystems, their advantages and weaknesses, how musicians interact within them, and what are the best strategies to cope with the associated ethical issues. Thus far, research has largely overlooked such aspects. The understanding of these aspects will contribute to the design of new sociotechnical ecosystems and services capable of positively impacting a wide variety of musical stakeholders (both human and other-than-human) and fostering creativity and the well-being associated to musical activities.

VIII. Conclusion

As the IoMusT consolidates its importance and increases its impact on musical stakeholders, it is important to account for the ethical implications and the societal impact that musical practices based on such technology can have. While human aspects are to a certain degree taken into account in current IoMusT systems, the technology's capabilities are limited in deeply reflecting human values, needs, behaviors and diversity. This paper proposed a paradigm shift from the current wave of IoMusT research, which is mostly centered on technological development, towards a new wave focusing on musical stakeholders and their entanglements with devices, services and environment, which entails the adoption of a strong more-than-human-centric perspective able to inform IoMusT development. To this end, we described a framework with ten dimensions that can concretely guide designers of IoMusT technologies in considering the human and non-human factors relevant in the IoMusTP. We illustrated our framework by analyzing a set of case studies, which ultimately showed how existing systems are insufficient to comply with the IoMusTP vision. Subsequently, we reflected on a number of challenges ahead of us to concretely implement the envisioned paradigm shift. The identified future directions are based on entangled design concepts [40] and serve to inform the development of the next generation of IoMusT technologies that can effectively lead to user empowerment and let users feel comfortable in participating to IoMusT-based musical activities. It is expected that the major socially-related questions that proposals such as ours raise will set a new horizon for the IoMusT research in the coming years. It is hoped that the present study could encourage other IoMusT system developers and researchers to pay a closer attention to the entangled relations between people and IoMusT technologies.

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