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# Empiric Evaluation of Robot Dancing Framework based on Multi-Modal Events

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***Abstract***

*Musical robots have already inspired the creation of worldwide robotic dancing contests, as RoboCup-Junior's Dance, where school teams, formed by children aged eight to eighteen, put their robots in action, performing dance to music in a display that emphasizes creativity of costumes and movement. This paper describes and assesses a framework for robot dancing edutainment applications. The proposed robotics architecture enables the definition of choreographic compositions, which result on a conjunction of reactive dancing motions in real-time response to multi-modal inputs. These inputs are shaped by three rhythmic events (representing soft, medium, and strong musical note-onsets), different dance floor colors, andthe awareness of the surrounding obstacles. This layout was applied to a Lego-NXT humanoid robot, built with two Lego-NXT kits, and running on a hand-made dance stage.We report on an empirical evaluation over the overall robot dancing performance made to a group of students after a set of live demonstrations. This evaluation validated the framework's potential application in edutainment robotics and its ability to sustain the interest of the general audience by offering a reasonable compromise between musical-synchrony, animacy and dance performance's variability.*

***Keywords***: *Robot dancing,Human-robot interaction evaluation, Edutainment robotics*

## 1. Introduction

Musical robots are increasingly present in multidisciplinary edutainment areas thrilling fanciers worldwide with ensemble performances with professional dancers and musicians [1], and being active intervenients in pedagogical and therapeutic scenarios [2].They already inspired the creation of worldwide robot dancing contests where school teams, formed by students of various ages, program their robots for dancing to music in a display that emphasizes creativity of costumes and movement [3]. Although these robotic systems undeniably demonstrate personality, they typically lack from musical awareness and animacy, withpre-programmed deaf robots or dancing robots strictly tuned to music with no human control.

In this paper we present a framework for robot dancing edutainment applications. Contrasting to other approaches, the developed system supplies a flexible interface for defining choreographic compositions for Lego-NXT-based [4] dancing robots in reactive response to external multi-modal events. In order to assure an autonomous and expressive behavior, the developed system explored the rhythmic phenomenon beyond music, which is composed of a succession of note-events that generally makes people move[5]. To parse these musical rhythmicevents from polyphonic audio signals on-the-fly we implemented areal-time onset detection algorithm based on the signal's spectral flux. On top of the computed onset detection function we applied an adaptive peak-picking algorithm to retrieve three levels of rhythmic intensity. In combination with these rhythmic events, the framework deals with external inputs in the form of sensorial events, such as floor colors and obstacles. Such multi-modal support enables the creation of more varied and dynamic dancing sequences, while assuring the avoidance of obstacles.On top of the system, a user-interface gives high-level control over the musical analysis and the Lego-NXT robot's sensorimotor parameters. Moreover, it provides an online visualization of the detected note-onsets for the calibration of the performedonset detection.

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From an educational point of view this framework provides an intuitive environment for learners and children to experiment the creation of their own dancing behaviors, by generating robot dancing motions in response to multi-modal events. Its autonomy and its basis on Lego robots, allied to the use of an amusing aesthetics,enable the generation of varied and expressive dance performances capable of entertaining vast audiences, of various ages.

To validate our approach, and considering such applications, a vast audience formed by students ranging from 6 to 17 years old empirically evaluated the developed robotic system. Their judgment suggested that our implementation serves its edutainment purposes but, mainly due to hardware limitations, is still far from promoting the requested variety of human-inspired movements and musical-synchrony. Nevertheless, the proposed architecture can be used as a plausible platform for robot dancing contests such as [3] and [6].

The paper structure is as follows. The next section describes dance-oriented robotic platforms for edutainment, and focuses on existing methods for evaluating Human-Robot Interaction (HRI). Section 3 describes the proposed architecture by presenting an overview of the developed implementation and its built-in methodologies. Section 4 describes the setup for live demonstrations of the robot dance performance and the empiricevaluation of the implemented system.Section 5 discusses the overall empiric results after statistic analysis. Finally, Section 6 concludes this paper and points paths for future work.

## 2. Related Research

Dancing robots and human-robot musical interaction are moreover common terms in the academia while in the robotics industry such topicsare already becoming serious business [7].Nowadays, companies worldwide arestarting to commercialize edutainment toy-robots with embedded choreography editors and high-level motion controllers, which already demonstrate some ability to interact with humans. The most popular edutainment robotic platforms oriented for dancing are the RoboSapien robots created by WooWee Robotics (*e.g.*, RoboSapien, RoboSapien V2, FemiSapien, and RoboSapien RS Media) [8]. These robots' dancing behaviors may be composed by means of visual programming environments, such as Robo-Go Choreographer, and users may control and trigger their dance creations via voice commands, the Nintendo's Wii Remote, or via the RoboRemote. Similar low-cost edutainment humanoid platforms, with *ad-hoc* motion editors for easily composing continuous point-to-point dancing sequences, include Kondo Kagaku and Speecys robots, as well as Hitec'sRobonova-I [9] and Aldebaran Robotics' robot NAO [10, 11].Other trendy dancing toy-robots include the SegaToysiPets (*e.g.*, iCat, iDog, iFish, iCYPenguin, and iSpin) [12]and the USB Dancing Robot [13]. These Tamagotchi-like plastic pets were especially designed for being connected to an iPod (or other MP3 player) or placed next to a loud speaker. These little robots come in a variety of colors and are "fed" with music by interacting with it through flashing LEDs in time to the music and bopping/moving to the beat. Some of them even display mood sensations according to the type of music and the level of music deprivation.

Ultimately, we may refer worldwide robot dancing contests where school teams and research groups use the former platforms to program and design their robotic creations to dance in creative displays of costumes, movement and music. The most emblematic competitions are presented by RoboCup Junior's Dance [3], the ROBO-ONE GATE Dance Competition [6], and by the Austrian's Hexapod Dancing Championship [14].

Besides the required technological and behavioral specifications that should be considered in the system design and implementation, HRI researchers also need to concern with efficient methods for evaluating their systems with respect to the involved human-centered interactive aspects. These aspects are typically measured in terms of people's expectations, comfort, acceptability, and believability [15]. Given the multi-dimensionality of HRI, these methods need to follow adequate metrics and guidelines [16] in order to efficiently evaluate social robotics algorithms in real-world environments, while keeping standards for the sake of comparison between different approaches [17]. Besides, these metrics should orient theanalysis of live field sessions towards the intended goals while measuring standard key-concepts in HRI, such as anthropomorphism, animacy, perceived intelligence, and perceived safety [18].

Rooted in the cognitive sciences of psychology and human factors, and inspired in traditional marketing research techniques [19] and affective-computing approaches from Human-Computer Interaction (HCI) [20], current HRI evaluation methods assume a diversity of forms which differ on their level of objectiveness and on their qualitative or quantitative methodologies.Following Kidd and Breazeal [21], general HRI evaluation methods may so be divided into four main classes, all of which are typically followed by careful statisticanalyses:*i)*self-report measurement, which relies on empiric user-assessment over live or video demonstrations (*e.g.*, used in [22, 23]);*ii)* behavioral measurement, which is traditionally based on systematic observational studies on which researchers analyze and label videos of HRI trial sessions, following target-oriented coding schemes (*e.g.*, used in [2]); *iii)* Psycho-physiological measurement, which measures the user emotional state while interacting with the robotic system, such as electrodermal activity, cardiovascular variations, respiratory frequency, and brain activity (*e.g.*, [20], [24]); and *iv)* Hybrid measurement, which considers the correlation of at least two of the former measures (*e.g.*, used in [21]).

Inspired on dancing toy-robot applications, in this paper we propose a framework for generating autonomous robot dancing tunedto multi-modal events and with enough variabilityandanimacy to sustain the audience'sinterest. To empirically evaluate the proposed framework and the implemented robot dancing systemwe took advantage of the ease of gathering and analyzing data by means of self-report measurement. For this purpose, we designed a Likert-scale questionnaire made to a group of students after a set of live demonstrations of the robot dance performance, and discussed its results after proper statistic analysis.

## 3. Proposed Method

The implemented robot dancing system architecture was firstly proposed in [25] and fully described in [26]. This system iscomposed of a robotic agent (see Fig. 1), built with two Lego Mindstorms NXT kits; a hand-made dance environment, composed of a multi-color floor and a covering wall to delimit the dancespace (see Fig. 4); and a robot dancing control software constituted by three modules (see Fig. 2a)): *Music Analysis*, *Robot Control*, and *Human Control*.

The proposed architecture generates reactive robot dancing behaviors in response to multi-modal events formed by three *rhythmic* events: *Low*, *Medium* or *Strong* onsets; and two *sensorial* event classes defined by the stepped color: *Blue*, *Yellow*, *Green*, *Red*; andthe proximity to a surrounding obstacle: *OK*, *Too Close*. By playing with these inputs a user can, through a proper interface, flexibly define a set of dance moves, which are sequenced during the dance performance. Contrasting to some other approaches, every body movement, as their progression during the dance, is produced by the robot in an autonomous way without former knowledge of the music. Besides, the proposed framework abdicates from strict music synchronization in favor of sustaining the long-term interest of the general audience.

A video displaying an overview of the framework's functionalities is available in [27].

### 3.1.Dancing Robotic Agent

Following the idea that humanlyshaped robots greatly provide theanthropomorphism requested by natural interactions and thatdance, as a bodily language, requires a physical body, our dancing roboticagent was designed as a humanoid with six degrees-of-freedom (DoF), as illustrated in Fig. 1a). For its conceptionwe used two Lego Mindstorms NXT kits, each composed of an NXT-brick (*i.e.*, a brick-shape automaton) with Bluetooth support, and eachconnected to three servomotors. In total, the six motors control two legs,which form an omni-directional base, two arms, the head (along with a spinning fan), and a rotating hip. In addition, we connected a color sensor to our robot for detecting and distinguishing visiblecolors, and an ultrasonic sensor for obstacle detection. Ultimately, to increase the animacy and amusementof our robot's aesthetics, we dressed it with a red skirt that spins with the robot hip while dancing (see Fig. 1b)).This humanoid robot's design allowed the definition of 14distinct dance movements,defined as *BodyPart-Movement* ("L" to the Left, "R" to theRight, or "Alternate" to combine alternated movements): *Legs-RRotate*, *Legs-LRotate*, *Head-RRotate*, *Head-LRotate*, *Body-RRotate*, *Body-LRotate*, *RArm-RRotate*, *RArm-LRotate*, *LArm-RRotate*, *LArm-LRotate*, *2Arms-RRotate*, *2Arms-LRotate*, *2Arms-RAlternate*, and *2Arms-LAlternate*.

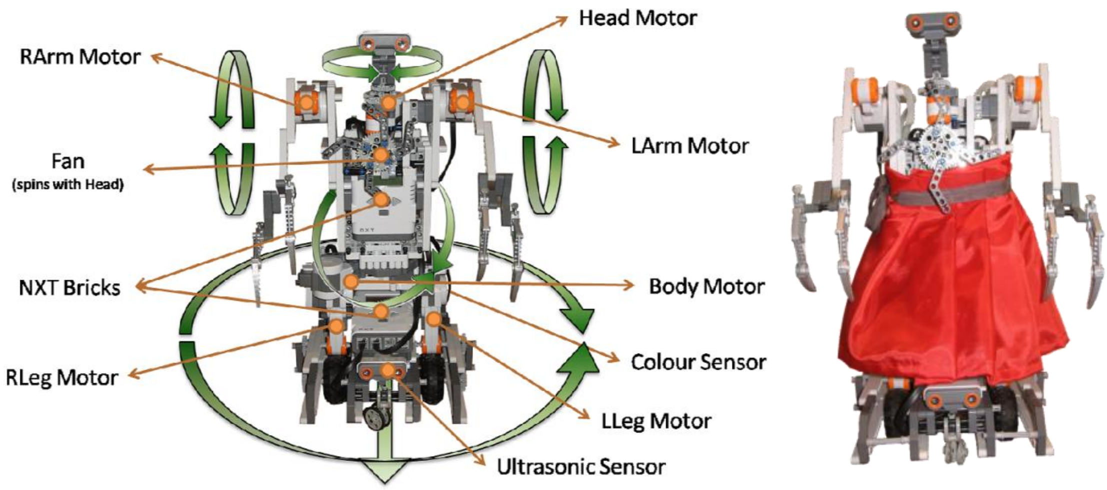


Figure 1. Lego NXT humanoid robot: a) Robot's sensorimotor constitution; b) Robot outfit.

### 3.2. Dancing Control Modules

The modular architecture of the proposed system was designed to controlthedance of the robot tuned to multi-modal events while supplying flexiblehuman control. As illustrated in Fig.2a), this implementation was composed of three control modules. Initially,the*Music Analysis* module applies a real-time onset detection algorithm to detect musical rhythmic events (*i.e.,* note-onset times), at three defined levels of prominence. These events are then sent in real-time, via UDP/IP sockets, to the *Robot Control Module*. By combining these rhythmic events with sensorial events, received from the robot's sensors, this module decides on the motor commands that are sent to the robot via Bluetooth to control its dancingbehavior(see Fig. 2b)).Above the former two, a *Human Control Module*, composed of a Graphical User Interface (GUI), enables flexible user control over the system behavior. It provides a control panel for the configuration of the analysis' parameters, and an interface for the dance sequence composition.To keep the parallelism of behaviors and the demanded real-time sensorimotor processing all these modules run in a multi-threading architecture.

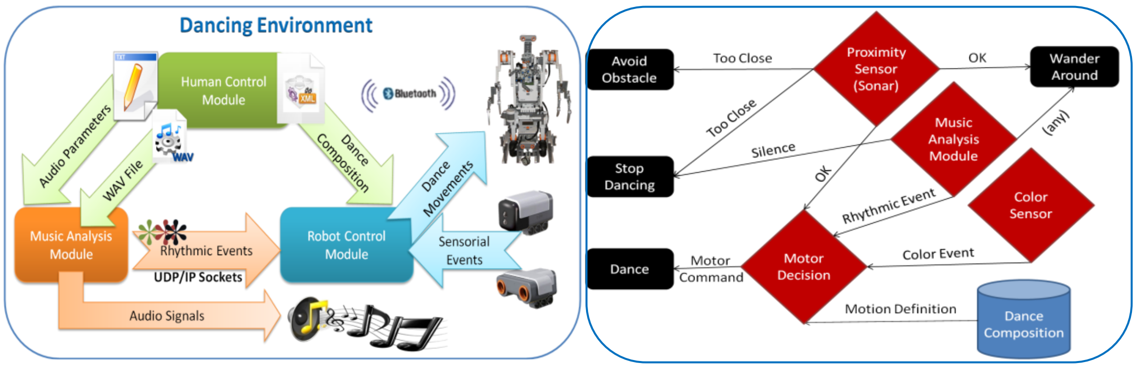


Figure 2. Robot dancing sensorimotor control: a)System architecture; b) Control decision data-flow of the robot dancing behavior.

#### 3.2.1.Music Analysis Module

Our *Music Analysis Module* was designed in MARSYAS,an open-source framework for MusicAnalysis, Retrieval and Synthesis for Audio Signals [28]. Under this platform, we implemented areal-time onsetdetection function for polyphonic audio signalsbased on the signal's spectral flux. The spectral flux, $SF(n)$, measures magnitude variations across all frequency bins, $k$, of the signal'sspectrum, $X(n, k)$, along consecutive analysis frames, $n$. Ourimplementation computes the time-frequency representation ofthe signal through a Fast Fourier Transform (FFT), using aHamming window envelope with $\omega = 4096$ samples (46.4msat a sampling rate of *Fs = 44100Hz*) and 67% overlap. As proposed in [29],the spectral flux is calculated using the L1-norm over a linear magnitude, which is half-wave rectified, ——, to retain only increasing variations in themagnitude spectrum:

_

**(1)**

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To remove spurious peaks while retaining themost salient, a low-pass second-order Butterworth filter (witha normalized cutoff frequency of $\omega_n = 0.28 rad/s$) is appliedto the accumulated *SF* at every time-step of the analysis. Thisfilter is applied in both forward and reverse directions resulting in zero-phase distortion.

Upon the *SF*we apply anadaptive peak-picking algorithm, *PP(x)*, whichdistinguishesincreasinglevels of rhythm events on-the-fly,in proportion to the current *SF*'s maximum*peak*:

**(2)**

where, . **(3)**

This process results in three rhythmic events corresponding to different levels of magnitude in the detected note-onsets:*Strong*, *Medium* or *Soft*onsets.Finally, these rhythmic events are sent on-the-fly to the *Robot Control* module via UDP sockets. The values of *thres1*, *thres2*,and *thres3* can be flexibly assigned in the application's GUI.Due to the potential inconsistencies in the beginning of somemusicdata,the computation of the *PP(x)* waits approximately 2.5s before starting todeterminethe current spectral flux's highest peak.

### 3.2.2 Robot Control Module

The *Robot Control Module* uses the C++ NXT Remote API[1] to remotely control the robot from an external CPU unit. This module is responsible for acquiring the sensor data from the robot, transform it in sensorial events, combine these sensorial events with the rhythmic events received from the *Music Analysis Module*, and decide on motor commands sent back to the robot.The control decision data-flow of therobotdancingbehavior is depicted on Fig. 2b).

### 3.2.3 Human Control Module

The *Human Control Module* is positioned on top of the wholesystem giving the user a higher flexible control over the robotdancingbehavior.This module consists of a user graphical interface composed oftwo blocks (see Fig.3): a*Robot Control Panel*and a *Dance Composition Menu*. The *Robot Control Panel*(see Fig. 3a)) is auser-definable control interface where one can set the Bluetooth andsensorimotor connection ports, with one or two NXT bricks;pick the audio file to be analyzed and reproduced, and define thecorrespondent music analysis parameters (which can be possibly saved in a proper text file).The *Dance Creation Menu* (see Fig. 3b)) enables the user to flexibly defineeach individual dance movement in correspondence to a givenrhythmic and color event; as well as their velocity of execution:*High*, *Medium*, *Low*, *None*. The resulting dance can be saved in aproper XML file and imported into the system *a posteriori*. Hence, the user has some control over the whole system's behavior by flexibly defining the robot choreography, through a set of dance movements to be executed during performance;by selecting the audio data (WAV or MP3 file) to be reproduced and analyzed; and by setting the threshold parameters for calibrating the music analysis. In addition, we included a real-time

[1] For additional information consult http://www.norgesgade14.dk/index.php.

plottinginterface (based on MATLAB) that enables the visualization of the detected note-onsets on-the-fly for the proper calibration of the music analysis.

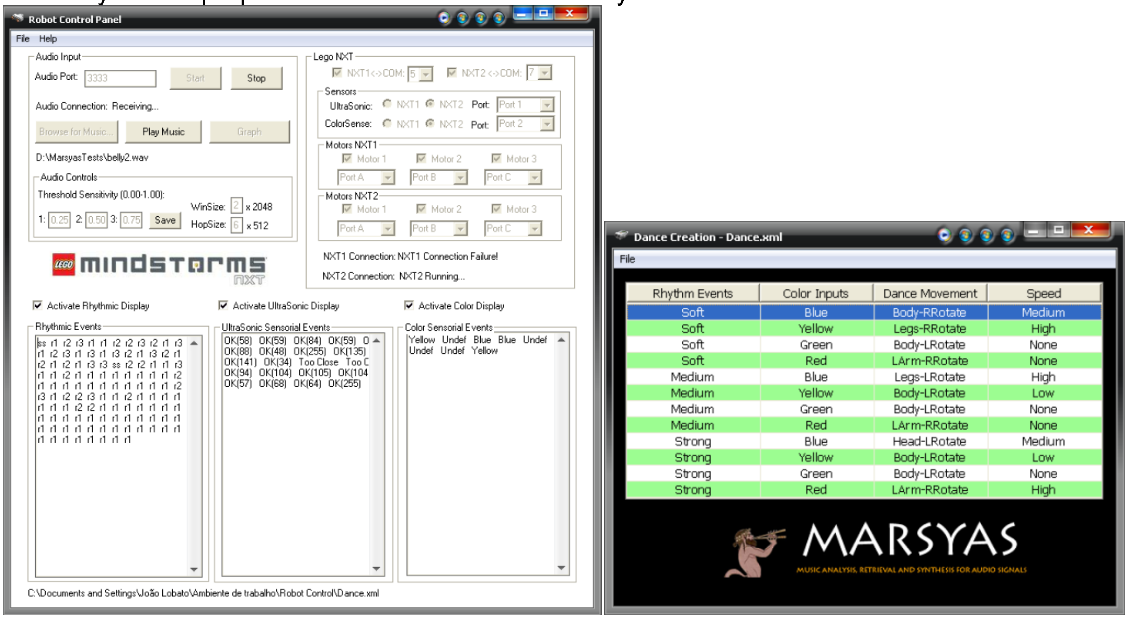



Figure 3. Human Control Module GUI: a) Robot Control Panel. b) Dance Composition Menu.

## 4. Research Method

In order to fully assess the proposed framework and the implemented robot dancing system, this section depicts the setup for the live demonstrations of the generated robot dance performance, and describes the performed empiric evaluation.

### 4.1.Live Demonstrations of the Robot Dance Performance

For evaluating the resulting robot dance performance webased its assessment on live empiric observation.For this purpose, we considered a student population constituted by 254 individuals, 118 girls and 136 boys, with ages comprising 6 to 17 years old. The focus on a young audience composed of children and teenagers was demanded by the educational and entertaining applications of our dancing robotic system. For such evaluation we performed several demonstrations run during theEngineer Open-Week at the Faculty of Engineering of the University of Porto (FEUP), and at College Dom Diogo de Sousa, in Braga, during an open-session to aware students of the power of mathematics and its applications. This system was also exhibit in Portugal Tecnológico, a major technological event, where a variety of people, from all ages, also gave their feedback. In order to better demonstrate the adaption of the robot's dancing to the music, while enforcing the symbiosis with the public, different mainstream musical excerpts were chosen, and distinct dance compositions were defined *a priori* for each.

Fig. 4 illustrates the real-world dance environment where the demonstrations took place. A video demonstration of the robot dance performance can be observed in [30].

### 4.2. Empiric Evaluation of the Robot Dance Performance

For evaluating the quality of the robot's dancing and the system's overall performance each student fulfilled a Likert scaled questionnaire [31] after observing one live demo of the robot dance performance. This questionnaire assessed the system in respect to the robot's musical-synchrony, its variety of movements, its human characterization, and about the flexibility of the user control over the system. Besides, the audience was also inquired about the potential application of such robotic system in educational settings, and about its degree of amuse. Namely, this questionnaire approached a set of three qualitative aspects of the robot dance performance. It objected the evaluation of *technical issues*, through the questions:

*a)* Was the robot dancing tuned to the music?
*b)* Does the robot show a good variety of movements?
*c)* Does the application supply a flexible control over the robot?

*d)*Does the robot resemble human behavior?

It objected the evaluation of the *system's potentiality in educational and entertainment applications*, through questions:

*e)* Was the robot dancing performance amusing?

*f)* This robot may have applications in education?

Finally, this questionnaire assessed the *student's appreciation* of the dancing robot and performed demonstration:

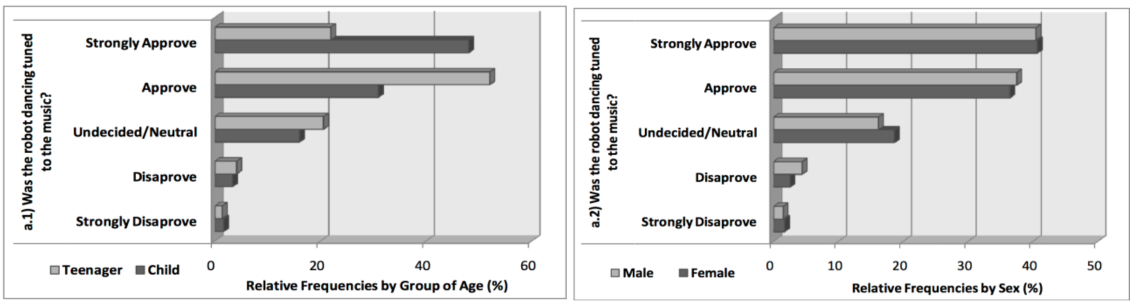
*g)* Do you like to own a Lego robot dancer?

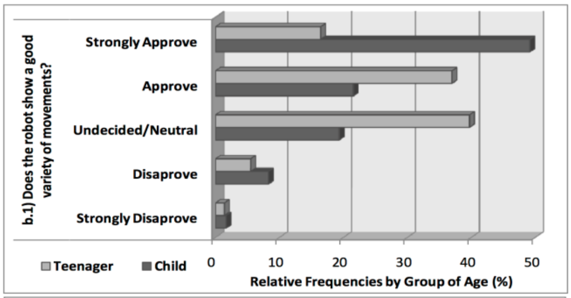
*h)* Did you like the robot dancing demo?

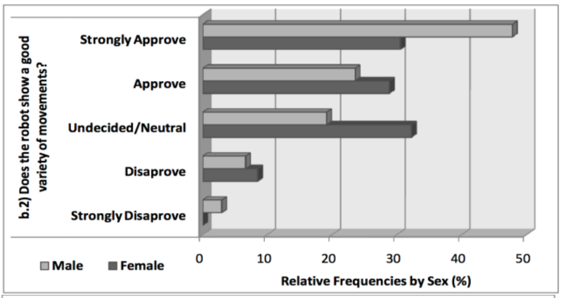
Figure 4.The robot dancing environment with 4 floor colors and a surrounding wall.

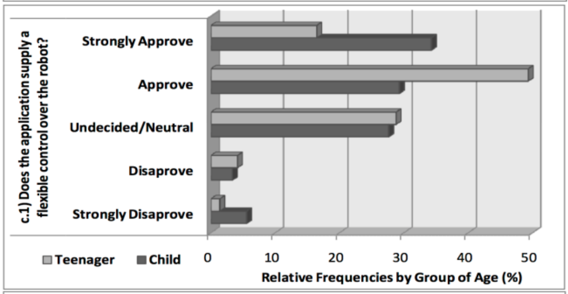
## 5. Results and Discussion

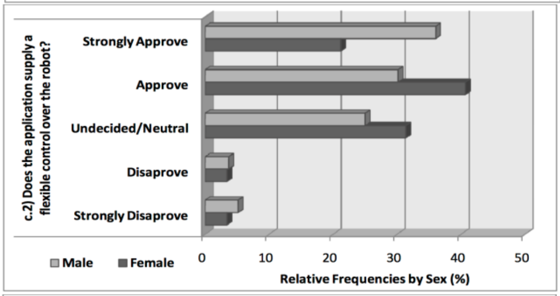
The first step was to determine the correlations between the variables, measured through Spearman's Correlation [32]. Next, we evaluated the association between them by recurring to the Chi-square test. Ultimately, we investigated if the distribution of the variables were significantly different by sex and age, using the Mann-Whitney test [32]. Given the high statistical difference between the variables distribution, Fig. 5 presents the relative frequency graphs for each question of the questionnaire, distributed by Group of Age (1 – left charts) and Sex (2 – right charts). A discussion of these results is presented in the following section.

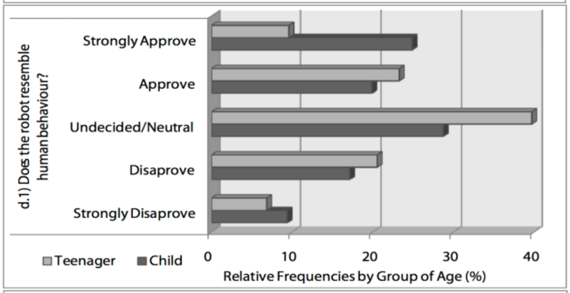


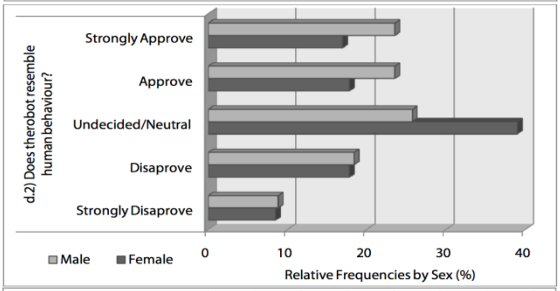

b.1) Does the robot show a good variety of movements?
Strongly Approve
Approve
Undecided/Neutral
Disaprove
Strongly Disaprove
Teenager
Child
0 10 20 30 40 50
Relative Frequencies by Group of Age (%)

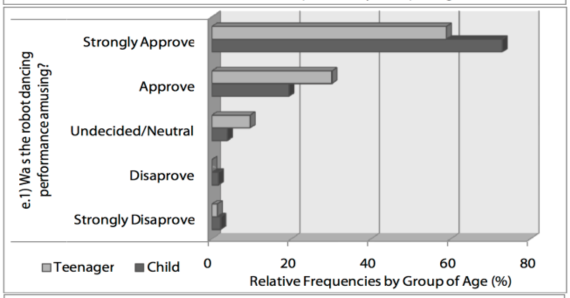

b.2) Does the robot show a good variety of movements?
Strongly Approve
Approve
Undecided/Neutral
Disaprove
Strongly Disaprove
Male
Female
0 10 20 30 40 50
Relative Frequencies by Sex (%)

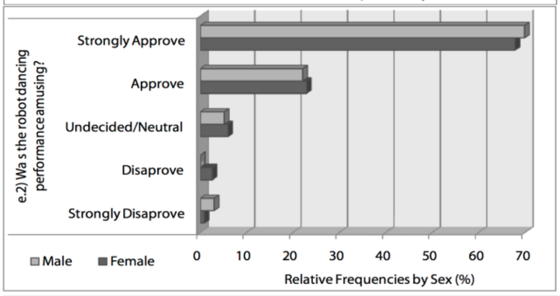

c.1) Does the application supply a flexible control over the robot?
Strongly Approve
Approve
Undecided/Neutral
Disaprove
Strongly Disaprove
Teenager
Child
0 10 20 30 40 50
Relative Frequencies by Group of Age (%)

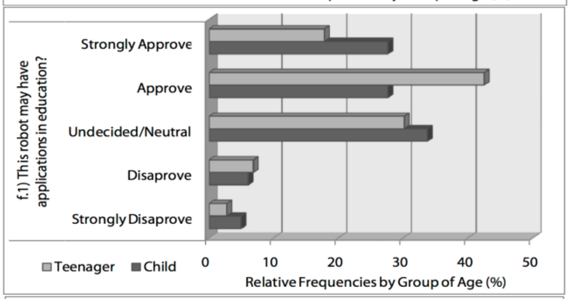

c.2) Does the application supply a flexible control over the robot?
Strongly Approve
Approve
Undecided/Neutral
Disaprove
Strongly Disaprove
Male
Female
0 10 20 30 40 50
Relative Frequencies by Sex (%)

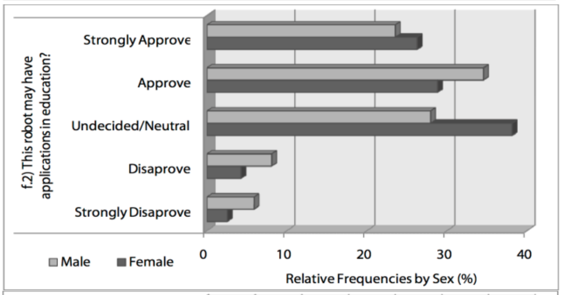

d.1) Does the robot resemble human behaviour?
Strongly Approve
Approve
Undecided/Neutral
Disaprove
Strongly Disaprove
Teenager
Child
0 10 20 30 40
Relative Frequencies by Group of Age (%)

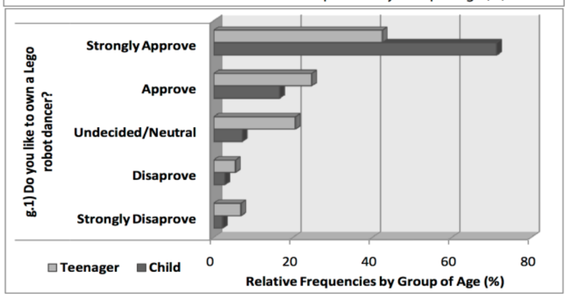

d.2) Does therobot resemble human behaviour?
Strongly Approve
Approve
Undecided/Neutral
Disaprove
Strongly Disaprove
Male
Female
0 10 20 30 40
Relative Frequencies by Sex (%)

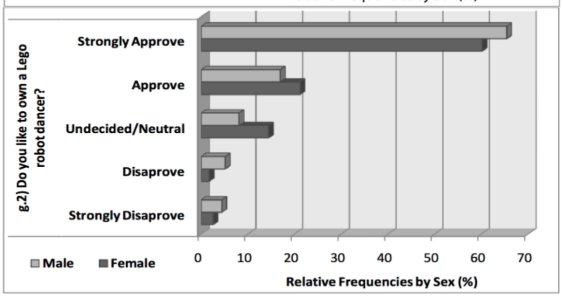

e.1) Wa s the robot dancing performance amusing?
Strongly Approve
Approve
Undecided/Neutral
Disaprove
Strongly Disaprove
Teenager
Child
0 20 40 60 80
Relative Frequencies by Group of Age (%)


e.2) Wa s the robot dancing performance amusing?
Strongly Approve
Approve
Undecided/Neutral
Disaprove
Strongly Disaprove
Male
Female
0 10 20 30 40 50 60 70
Relative Frequencies by Sex (%)


f.1) This robot may have applications in education?
Strongly Approve
Approve
Undecided/Neutral
Disaprove
Strongly Disaprove
Teenager
Child
0 10 20 30 40 50
Relative Frequencies by Group of Age (%)


f.2) This robot may have applications in education?
Strongly Approve
Approve
Undecided/Neutral
Disaprove
Strongly Disaprove
Male
Female
0 10 20 30 40
Relative Frequencies by Sex (%)


g.1) Do you like to own a Lego robot dancer?
Strongly Approve
Approve
Undecided/Neutral
Disaprove
Strongly Disaprove
Teenager
Child
0 20 40 60 80
Relative Frequencies by Group of Age (%)


g.2) Do you like to own a Lego robot dancer?
Strongly Approve
Approve
Undecided/Neutral
Disaprove
Strongly Disaprove
Male
Female
0 10 20 30 40 50 60 70
Relative Frequencies by Sex (%)

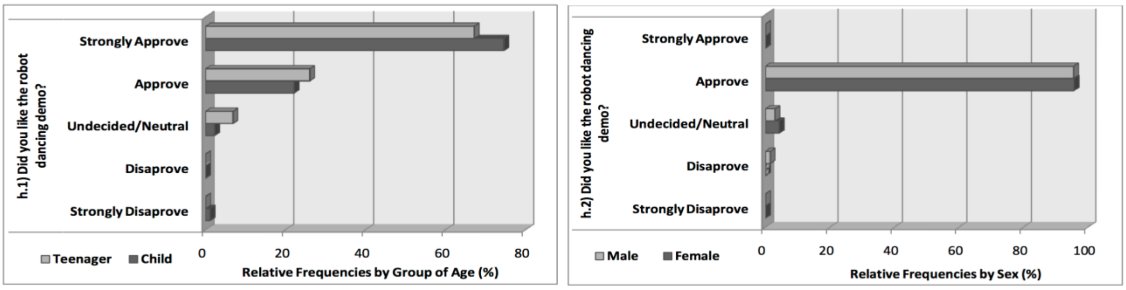



Figure 5.Relative frequency graphs of the questionnaire's responses by Group of Age (1 – left charts) or Sex (2 – right charts).

Using the Spearman's coefficient correlation we identified strong correlations between every pair of questions, getting the highest correlation, $r = 0.449$, between questions *e)* and *h)*, and the lowest, $r = 0.105$, with the pair *e)* and *d)*. To reveal statistical evidences on the differences of the answers' distribution by Sex and Group of Age we applied the Mann-Whitney test. The variable age was recoded into child (≤ 11 years old) and teenagers (≥ 12 years old) to establish a frontier between the youngest and the ones with higher maturity. The mean and standard deviation were, respectively, x = 8.68 and $s = 2.34$ for the child group, and $x = 14.49$ and $s = 2.37$ for the teenagers. In fact, the variability of the age is very similar in the two groups and the mean of ages are really apart. When analyzed by Sex, the resultant p-value was lower that the level of significance ($p = 0.05$) in question *b)*, with $p \approx 0.014$. This evinces a different distribution of the variable for males and females. This is supported by a graphical analysis of Fig. 5b.2), which points for a more positively asymmetric distribution of males in comparison to females. This may be interpreted as a more positive attitude of males towards the variety of movements. When analyzed by Group of Agethe p-values were also lower than the level of significance for questions *a)*: $p \approx 0.002$; *b)*: $p \approx 0.000$; *e)*: $p \approx 0.038$; and *g)*: $p \approx 0.000$, separating them into two independent samples. In these cases there are statistical evidences to affirm that the distributions of the variables are different within the groups of children and teenagers. This points for the higher expectations of teenagers in comparison to young children, revealing that we need to enhance the variation of the robot moves for captivating older kids. Besides, the answers to these questions reveal that despite some system flaws and inconsistencies most of the subjects do not realize it, which suggests that strict musical-synchrony may not be so relevant for keeping an interesting dancing behavior. On a global descriptive analysis we may still infer some relevant conclusions. Question *d)* denotes higher frequency on undecided/neutral answers, revealing a relative frequency of 41.4% of answers with negative connotation. This may be implied by the aesthetics of the robot and its 360-degrees rotating movements, suggesting the need of replacing it with a different, more humanly shaped robot design. On the other hand, question *e)* reveals the great amusing potentiality of this framework, where 66.1% of the subjects strongly approved it, uniformly across all ages (within a total of 91.3% approvals). It is also interesting to notice that 81.9% approve or strongly approve the intention of acquiring a Lego robot dancer (see Fig. 5g.1)), with a greater adherence of the male group. We strongly believe that the robot aesthetics, dressed with a proper outfit (see Fig. 1b)), along with its reactive strong moves was determinant for keeping an entertaining atmosphere. The artisanal aspect of the dance environment (see Fig. 4) and the chosen music were also fundamental to keep the spectators' attention during the demonstrated dance performance. Ultimately, we may refer the ambiguity of question *c)*'s responses since the inquired did not have the opportunity to configure and control the system by themselves.

By corroborating the subjects' opinions with our personal overall assessment, we finalize our discussion by focusing on three requisites that we consider of most relevance for a meaningful and interesting robot dance performance:

- <u>Musical-Synchrony</u>: essentially due to processing and Bluetooth communication delays we verified some flaws in musical-synchrony. The use of a multi-threading architecture granted the required simultaneity between the modules' processing but caused some synchrony flaws due to race conditions in theprocessing of the dance movement decision mechanism. In terms of hardware-software communication, the Bluetooth had to constantly deal with communication overflows, as it can only receive/send data in time-intervals of approximately 50-100ms while taking around 30ms to transit from transmit mode (*i.e.*, send motor data), to receive mode (*i.e.*, receive sensor data). In addition tosuch limitations, the high number of detected onsets in many occasions surpassed the refresh rate of the robot's sensorimotor processing which also induced flaws by the fault of not executing the requested movement. Although all these flaws represent detachments with the music it enforces autonomyto the robot dancing behaviors that ultimately enhance the performance's variety, and consequently the interest to the spectators. The solution to these problems demands the use of a more robust and dynamic humanoid robot with an embedded CPU [33], capable of higher clock rates for accompanying the music with sequenced dancing behaviors.

- Variability: the variability of our framework's architecture was granted by the great variety of possible dance stylecompositions (in a total of $15^{12}$-1), formed by 14 distinct individual dance movements (plus *None*) distributed through 12 conjunctions of events (3 rhythmic events x 4 colorevents); and enforced by the robot's perambulation around the dance environment while avoiding its obstacles. This dynamic behavior is ultimately transposed to the human decision, which has theversatility to adapt the robot performance*a priori* through a flexible definition of the robot dancing behavior. Although, in theory,these characteristics enable a more varied behavior, the lack of individual dance moves, imposed bythe robot's limited degrees-of-freedom, restricted theperformance to repetitive dancing sequences, whichonly differ in velocity of execution or orientation. Again, morevariety of movements demands the use of a morearticulated humanoid robot with balance stability [34].
- Animacy: As the public suggested, although the robot's dancing was greatly inspired on human dancing,its performance is still far from being human representative, by presenting mainly 360-degree spinningmoves. However, our robotic system is inspired on human behavior by interacting with thereal-world in a reactive behavioral-basis that connects perception to action. Notunexpectedly, a robot dance performance comparable to human behavior is greatly dependent on theformer requisites and as such also requires a moreadvanced humanoid robot. Yet, despite the undeniable improvements, such robot might bring toartificial dancing its rigid, strict mechanical moves,greatly attached to music, which may decrease therobot'sanimacy and consequently the spectator's interest.

In conclusion, despite some musical-synchrony issues, referred above, the robot seems to react in real-time to the external music and other external eventswhiledemonstratingreasonable variability and animacy. This suggests that a varied and flexible robot dancing behavior in compromise with a reasonable extent of musical-synchronyassuresthe required interest and entertaining relationship between the artificial agent and its human audience.

In contrast to the robotic systems that participate on general robot dancing contests [3], [6], [14] the proposed framework enables the definition of autonomous robot dancing performances, which react in real-time to multi-modal events in the form of rhythmic and sensorial inputs, while permitting the easy composition of different dance styles and robot configurations with flexible human control over the robot's behavior.

## 6. Conclusions

We developed a flexible framework for autonomous robot dancing applications. The proposed architecture was applied to a Lego NXT mobile humanoid robot that bodily reacts, in real-time, to multi-modal events by performing autonomous dance movements alternated through a variety of motion styles.We report on an empirical evaluation made to a group of students over the overall robot dance performance after a set of live demonstrations.The empiric evaluation validated our approach suggesting that, despite the system's limitations, the resulting robot dance shown a reasonable level of musical-synchronywith variable motion sequences while interacting with the surrounding environment. In addition, the developed framework was able flexible human control over the robot's behavior.

The discrepancies in the overall opinions between the younger and the older subjects indicate clear differences in their expectations, typically younger children being less critical about the robot's dancing behavior than the older subjects. Besides, giving the age and/or the unawareness of the audience about the technical issues underneath the system, their technical opinions may be quite optimistic. This also suggests that the robot's variety of movements and its physical aesthetics and outfit, interleaving from musically attached movements to others more freely executed (manydue to system flaws), may have increased the audience's interest.By being more enthusiastic about the dance performance the subjects might have consequently ignored eventual flaws or unpredictable behaviors. Concerning the inquired genders we could not realize relevant differences in opinion, except when inquired about the robot variety of movements (question *b)*), which pointed for greater approval by males.

In conclusion, the multidisciplinary concepts and the Lego foundations of the implemented robotic system,allied to an amusing aesthetics through dance performances interchanging musically-synchronous withvariabledancemovements validated the edutainment purposes of the proposed framework.Itenforced the idea that designing robotic entertainment systems exhibiting such dynamic compromise between short-term synchronization and long-term autonomous behavior might be the key to maintain the interest of the general audience.

In the future, we shall enhance the proposed robot dancing framework by improving its limitations. To this extent, we should investigatemeans to improve the animacy and variability of the robot dance movements by mapping them from a proper representation of captured human movements of different dance styles [35]. Besides, we should research methods from music information retrieval (*e.g.*, beat tracking [36]) and robot audition [37] to create an interactive robot dancing system capable of accurately and robustly processing live music and speech signals and responding with verbal and non-verbal interactive behaviors while assuring a reliable human-robot interaction [38].

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