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Development of Waseda Flutist Robot WF-4RIV: Implementation of auditory feedback system

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***Abstract*—Up to now, different kinds of musical performance robots (MPRs) and robotic musicians (RMs) have been developed. MPRs are designed to closely reproduce the motor skills displayed by humans in order to play musical instruments. From this approach, MPRs are used as benchmarks to study the human motor control from an engineering point of view and to understand better the human-robot interaction from a musical point of view. In contrast, RMs are conceived as automated mechanisms designed to create new ways of musical expression from a musical engineering point of view. Our research, at Waseda University, has been focused on developing an anthropomorphic flutist robot. Our research aims in studying the human motor control from an engineering point of view, understanding the ways to facilitate the human-robot interaction and proposing new applications for humanoid robot in musical terms. As a result of our research, the Waseda Flutist Robot No.4 Refined IV (WF-4RIV) has been developed. In a previous research, we focused on improving the mechanical system in order to enhance the clarity of the sound. However, we require performing further improvements to the control system in order to enable the robot to autonomously improve the quality of the sound during the flute performance. For this purpose, we proposed to implement an auditory feedback control system on the flutist robot. The proposed system is composed by a music expressive generator, feed-forward air pressure control system and a pitch evaluation module. From the experimental results with the WF-4RIV, we could confirm the improvements on the flute performance.**

I. Introduction

The relation between the human and the music has a long history dating from the antiquity, during which poetry, dancing and music were inseparable and constitute an important mean of communication of everyday life. During the golden era of automata (17th and 18th centuries), music also served as a mean to understand how the human brain is able of coordinating multi-degrees of freedom in order to play musical instruments.

In particular, some researchers were interested in studying how the human is able of performing musical instruments, such as the flute. As an example, the mechanical flutist player developed by Vaucanson was used as a mean for understanding human breathing mechanism. Vaucanson presented "The Flute Player" to the Academy of Science in 1738 [1]. For this occasion he wrote a lengthy report carefully describing how his flutist can play exactly like an alive person. This first automaton was a life-size figure capable of playing a flute and it had a repertoire of twelve pieces which included the "Le Rossignol" by Blavet. The technical details of the operation would be too long; therefore, we will simply give the broad outline of the mechanism. The driving movement is composed of nine bellows, which are arranged by groups of three of them, connected each other using levers and cords. Each group of three bellows sends air into a pipe leading to one of the compartments of a small tank arranged in the chest of the automaton. A cylinder, made up of points and bridges, is placed above the six lower bellows. On the cylinder there is a keyboard provided with fifteen levers. Each end has a nozzle which is raised in the passing of the points and the bridges. On the other end, these levers pull on wires communicating with the moving parts of the automaton (fingers, lips, tongue, etc).

More recently, several researchers have developed different musical performance robots. The first attempt of developing an anthropomorphic musical robot was done by Waseda University in 1984. In particular, the WABOT-2 was able of playing a concert organ [2]. Then, in 1985, the WASUBOT built also by Waseda University, could read a musical score and play a repertoire of 16 tunes on a keyboard instrument. Prof. Kato argued that the artistic activity such as playing a keyboard instrument would require human-like intelligence and dexterity [2]. After the developing of WABOT-2, several researchers have been presented different kind of robots able of playing conventional musical instruments.

Authors have been developing an anthropomorphic flutist robot. In particular, our research is focused on understanding the human motor control from an engineering point of view, facilitating the communication between human and robots in musical terms and proposing novel applications for humanoid robots [3-8]. In order to achieve our goals, the Waseda Flutist

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Robot has been designed to reproduce the organs involved during the flute playing such as: lungs, vocal cord, fingers, tongue, lips, neck, etc. As a result, the flutist robot is able of performing nearly similar to an intermediate flutist as well as interacting with musical partners.

Shibuya [9] has been developing an anthropomorphic arm which reproduces the movement required to play a violin. In particular, this violin robot is being designed to produce expressive sounds by considering *kansei* (sensitivity). The arm has a total of 7-DOFs actuated by DC motors. From experimental results, the violin robot is able of playing notes with a high level of repetitiveness.

Takashima [10] has being developing different music performance robots that are able of playing wind instruments such as: saxophone, trumpet, trombone and shakuhachi (traditional Japanese bamboo flute). In particular, the saxophone playing robot has been developed under the condition that the musical instrument played by robots should not be change or remodeled at all. This robot is composed by an artificial mouth and fingering mechanisms and air supplying system. Due to the complexity of replicating the motion of human fingers, the fingering mechanism is composed by twenty-three fingers so that each finger can press each key of the saxophone. The saxophone robot is able of performing nearly similar to human performance.

Shimojo [11] has been developing a violin-playing robot, which it is composed by a commercial 7-DOF manipulator and a 2-DOFs fingering mechanism. The end-effector of the manipulator has been designed to hold a bow. A force/torque sensor has been attached to the end-effector to control the bowing pressure. As a result, the violin-playing robot is able of performing simple musical scores.

More recently, some companies such as Toyota has being introducing musical performance robots, such as the trumpet-playing robot, for introducing novel ways of entertainment and assistance for elderly care [12]. For this purpose, Toyota has developed an artificial lip designed to mimic the motion of the human lips and human-like hands that enable the robot to play trumpets like humans do. Such a robot also is able of walking while performing.

Other researchers have being developing automatic musical instruments from the musical engineering point of view. Weinberg and Driscoll [13] are developing an improvisational robotic marimba player which is composed by four robotic arms designed to hold the mallets. Typically, human players hold four mallets (two in each hand). The robotic arms are arranged in pairs with overlapping workspaces to allow various combinations of chords to be player. Each of the arms has 4-DOFs, which are actuated by a linear guide and servo motors. From preliminary results, the marimba robot is able of musically interacting with humans.

Goto and Yamasaki [14] are developing different kinds of automated percussionist mechanical instruments which can be commanded through a gesture controller. Performers wears the gesture controller (*data-suit*) whose movements are identified and transformed into musical commands. Hayashi [15] developed an automatic piano which is able of producing soft tones. Such an automatic piano employs feedback control the movement of an actuator used to strike a key. Singer [16] introduced the LEMURs musical robots. LEMUR is a Brooklyn-based group of artist and technologists who create robotic musical instruments.

In resume, we may notice that the research on MPRs and RMs has been particularly intensified in recent decades. In fact, we may distinguish four different researches approaches [7, 8]: study of human-robot interaction [4, 6, and 10]; study of human motor control from an engineering point of view [4, 5, 6]; study of new ways of art/entertainment [9, 10, and 11]; and study of new methodologies of musical teaching [4].

Authors have been particularly focused on understanding the human motor control from an engineering point of view. Therefore, we are aiming in developing an anthropomorphic flutist robot from two research points of view:

1. Reproduce the required motor dexterities to play the flute.
2. Display cognitive functionalities to coordinate the motion of simulated organs to express emotions in musical term.

Regarding the first approach; in [7], we have presented the mechanical improvements achieved on the Waseda Flutist Robot No.4 Refined IV (WF-4RIV). The WF-4IV has a total of 41-DOFs designed to mechanically simulate the human organs involved during the flute playing (Figure 1). This new version has improved the design of the lips and the tonguing mechanism (2-DOFs). The lips mechanism was designed to produce a more natural sound and the tonguing mechanism was designed to improve the attack time of the sound as well as enhancing the double tonguing technique (extended technical skill).

In contrast, regarding the second approach, the WF-4RIV

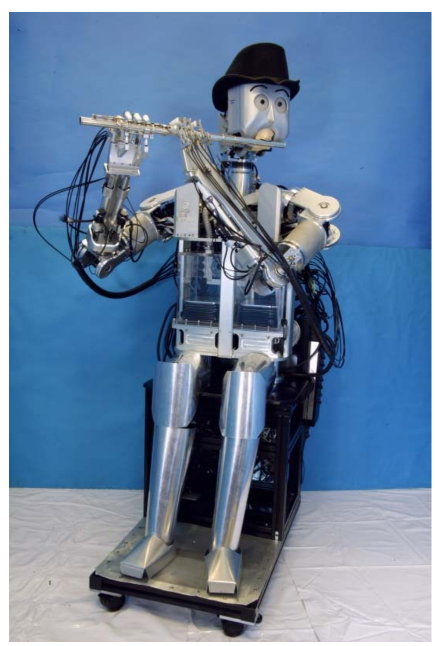

Fig. 1 a) The Waseda Flutist Robot No.4 Refined IV is composed by 41-DOFs. In particular, a new lips and tonguing mechanisms were designed.

still requires to improve its cognitive capabilities. In fact, human players are not only required to accurately control and synchronize the movements of each of the organs required. In fact, human players are able of improving their musical skills by practicing scores. For this purpose, human players perform several times a score. For each single note, humans listen and evaluate its quality. If the quality is not acceptable, they adjust some parameters (i.e. lips shape, etc.) until the produced sound is acceptable (Figure 2).

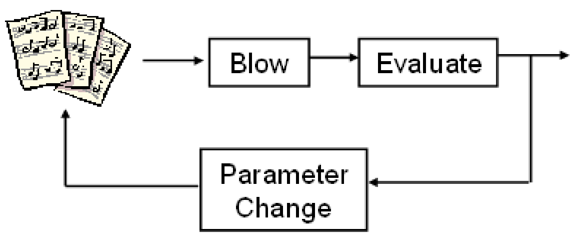

Fig. 2 Human players are able of enhancing their musical skills by continuously practicing scores. Humans change parameters such as shape of the lips, posture, air beam velocity, etc.

Up to now, the flutist robot has not been programmed to analyze its own performance so that it cannot improve the quality of the sound produced during the performance. As a result, the quality of the robot's performance depends exclusively of the calibration of the parameters done beforehand the performance.

Therefore, in this paper, we focused on implementing an auditory feedback system on the WF-4RIV. The proposed system has been designed to enable the robot to enhance its musical skills during the performance. In particular, the proposed auditory feedback system is composed by three main modules (Figure 3): Expressive Music Generator (ExMG), Feed Forward Air Pressure Control System (FFAiPC) and Pitch Evaluation System (PiES).

This paper is organized as follows: at first, the description of each of the components of the proposed auditory feedback system is detailed. Then, a set of experiments were proposed in order to identify the effectiveness of the auditory feedback system.

II. Auditory Feedback

A. Expressive Music Generator

Basically, a musical score is defined by the note information and its duration. By defining these two parameters, it is possible to play any kind of instrument. However, the sound becomes monotonous. Therefore, human players add expressiveness to the performance by adding other parameters such as (Figure 3): vibrato, staccato (tonguing), dynamic marks, slurs, etc.

Up to know; there is no scientific method to describe how human players add such kind of parameters to express emotions, feelings, etc. For this purpose, we have implemented an *Expressive Music Generator* (ExMG) which has been designed to output musical information required to produce an expressive performance. The ExMG uses as an input the musical parameters (i.e. pitch, volume, tempo, etc.) from the performance of a professional flutist. Those parameters are analyzed and extracted by using our FFT tool [3]. As an output, a set of musical performance rules (which defines the deviations introduced by the performer) are produced (offline). The process of modeling the expressiveness features of the flute performance is done by using Neural Networks.

In particular; in [5], we have considered the *note duration*, *vibrato frequency* and *vibrato duration*. Thanks to the mechanical improvements of the lips and tonguing mechanisms on the WF-4RIV, this year we have also considered the *attacking time* and *tonguing* as part of the musical performance rules. The resulted music information is then sent directly to the robot's control system by sending MIDI messages from a sequencer device (personal computer). As a result, the flutist robot is able of performing a musical performance with expressiveness.

However, it is important to consider that music is not defined by a set of independent events sent trough the MIDI data (Figure 2). In fact, musical sounds are continuously produced by taking into consideration adjacent notes. From this, human players may require adjusting some dynamic parameters during the performance (i.e. air pressure, pitch, etc.).

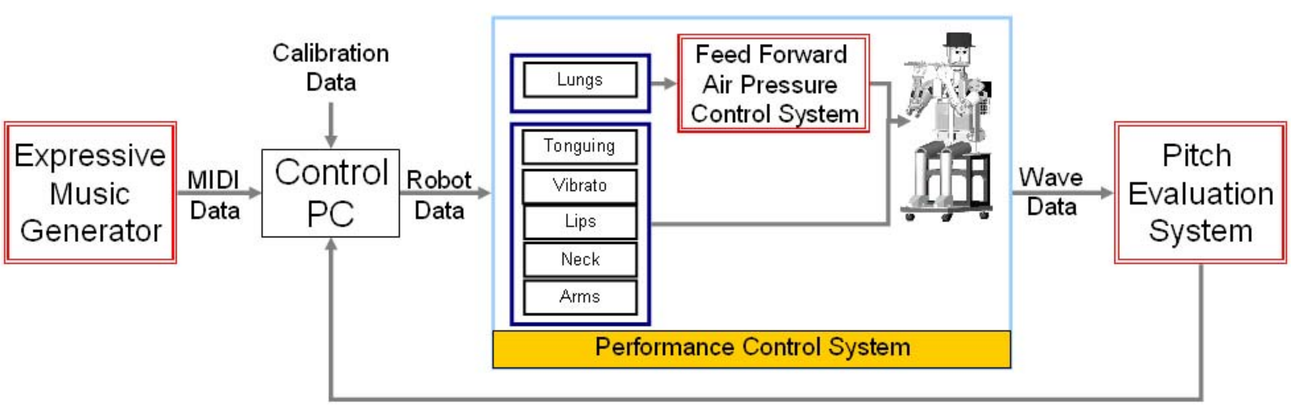

Fig. 3 In order to enhance the flute performance of the WF-4RIV, we have proposed an auditory feedback system (AFS). The AFS is composed by an expressive music generator, feed-forward air pressure control system and pitch evaluation system.

B. Feed-Forward Air Pressure Control

In particular, in this paper, we have focused in implementing a feed-forward to control the air pressure which is sent to the embouchure hole of the flute. Up to now, due to the complexity of the system; we have considered an open-loop control strategy. However, this approach may difficult the implementation of the auditory feedback system.

In this paper; as a first approach, we propose implementing a feed-forward control system to control the air pressure coming out from the lungs. Such an improvement is related to enable the robot to produce an attack time of the note more similar to the human. For this purpose, we propose to compute the inverse model of the lung system to control of the air pressure during the attack time. It is quite well known that the control of breath is directly related with the attack time. In order to implement the feed-forward control system of the air pressure from the lungs, we proposed to compare two methods for the computation of the inverse model: transient response method and feedback learning error learning.

Regarding the first method, the computation of the inverse model was defined by a second-order lag transfer function (1). H(s) represents the Laplace transformation of an overdamped second-order transfer function determined by the parameters k, $\tau 1$ and $\tau 2$. Those parameters were experimentally determined.

$$H(s) = \frac{k}{(\tau_1 s + 1)(\tau_2 s + 1)} \quad (1)$$

Regarding the second method, the feedback error learning is based on the use of the Neural Networks. The feedback error learning is a computational theory of supervised motor learning proposed by Kawato [19]; which is inspired by the way the central neverous system (Figure 4). In addition, Kawato extended that the cerebellum, by learning, acquires an internal model of inverse dynamics of the controlled object [20]. From this extension, the feedback error learning can be also used as training signal to acquire the inverse dynamics model of the controlled system. In our case, the teaching signal is the data collected from a pressure sensor placed at the simulated lungs. In our case, *y(t)* is defined as the lung velocity and *u(t)* is defined as the air pressure.

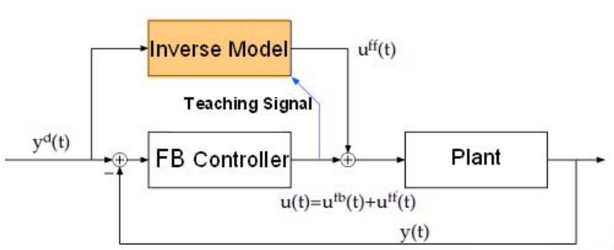

Fig. 4 Block diagram of the feedback error learning used to determine the inverse model.

C. Pitch Evaluation System

In order to evaluate the flute sound produced by the robot, we have developed the Pitch Evaluation System (PES). The PES has been designed to detect both the pitch of the flute sound as well evaluation its quality.

The PES is designed to estimate the pitch or fundamental frequency of a musical note. Basically, four different approaches can be implemented for this purpose [17]: time-domain analysis, autocorrelation, adaptive filter, frequency area, modeling human auditory system (neural networks).

As a first approach, we have considered implementing the Cepstrum method. This method is probably the most popular pitch tracking method in speech as it can be computed in real-time. First, the Cepstrum is calculated by taking the Fourier transform (STFT) of the log of the magnitude spectrum of sound frame. In our case, the sound is sampled at 44.1Hz; where the frame size was defined to 2048 with 50% of overlapping (Hanning window) so that a time resolution is 23ms. Then, the Cepstrum is inspected for a peak by dividing the frame into bins, corresponding to the period of the signal, as well as for a second or third peak an equal distance (period) away from the first or second peak. However, this method presents the problem of deciding how to divide the frequency.

Therefore, we proposed implementing the Cepstrum method and synchronize with the MIDI-data of the score. This approach provides information to the pitch detection algorithm about where the pitch is supposed to be located. As it is shown in Figure 5; for each frame window, different areas of searching are defined. By tracing the peaks, we are able of identifying the pitch of the note.

After the detection of the pitch, it is possible to evaluate the quality of the sound. In particular, by using the information provided by the pitch detection algorithm, the harmonic structure can be also computed. By using the harmonic structure, we have proposed a sound quality evaluation function which is based on the experimental results of Ando [18], who analyzed the acoustical properties of the flute sound by using a mechanical blowing apparatus. Basically,

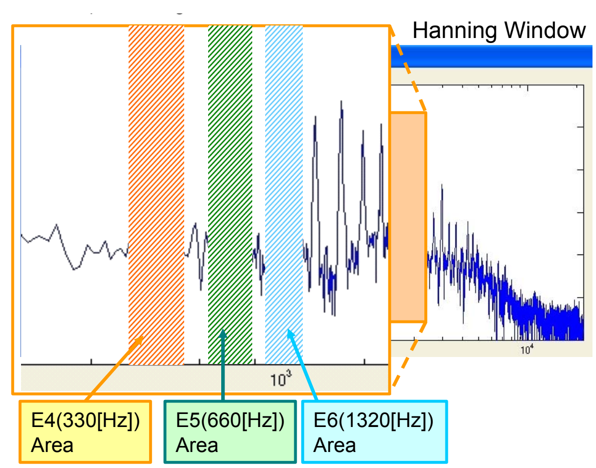

Fig. 5 The pitch detection is done by implementing the Cepstrum method and synchronizing with the MIDI-data of the score to enhance its resolution.

the quality of the sound is determined by considering the relation among the harmonics structure content; as it is shown in (2). In order to compute the volume level, the power of the signal was computed by the sum of squares of modulus of the Fourier coefficients of each sampled frame, as it is shown in (3). From this, the sound intensity is obtained as (4). The sound intensity describes the rate of energy flow through a unit area (Watts/m2). Finally, by using (5), the volume level is calculated in terms of the sound intensity on the decibel scale; where the reference value I_0 corresponds to the threshold of hearing intensity at 1000 Hz and is equal to 10^{-12} W/m^2.

$$Eval = \frac{(M-H)+(L_e-L_o)}{Volume} \quad (2)$$

M: Harmonic level [dB] *H*: Semi-Harmonics level [dB]
L_e: Even-harmonics level [dB] L_o: Odd-harmonics level [dB]
Volume: Volume level [dB]

$$P_{RMS} = \sqrt{\frac{\sum_{i=1}^{N}\left[\left|FFT\right|_i\right]^2}{N}} \quad (3)$$

$$I = \frac{P_{RMS}}{4\pi r^2} \quad (4)$$

$$Volume = 10 \cdot \log 10\left(\frac{I}{I_0}\right) \quad (5)$$

Basically, by using the proposed *PES*, the WF-4RIV is able of autonomously detecting when an note was incorrectly played (when the Evaluation Score is lower than a predefined threshold). Therefore, during a performance, when a note is incorrectly played, the *AFS* automatically put a mark to indicate the performance control system to adjust the required parameters. In particular, the air beam parameters (width, angle and thickness) and lung velocity are modified based on the General Position proposed on [3], which it is implemented by means of an orthogonal table.

III. Experiments and Results

A. Air Pressure Control

At first, we have proposed an experiment to compare the result of computing the inverse model by the second-order lag transfer function and by the feedback-error-learning method.

For this purpose, we programmed the WF-4RIV to blow a note. In order to determine the transient response, a step-unit function was used as an input reference. The air pressure was then measure by a pressure sensor attached to the lungs. By this, we can determine the attacking time required by the robot to reach the target note.

The experimental results are shown in Fig. 6. As we may observe, the computation of the inverse model by the feedback-error learning approach was more effective for the control of the air pressure.

B. Robot Auditory Feedback

In order to verify the effectiveness of the proposed auditory feedback system, we have proposed a set of experiments with the WF-4RIV. For this purpose, we have programmed the flutist robot to perform three different scores with different levels of difficulty: Le Cygne (beginner level), Flute Quartet kv. 298 (intermediate level) and Polonaise (advanced level).

At first, we focused in verifying the effectiveness of the proposed auditory feedback control system to enhance the quality of the produced flute sound and to adjust the parameters of the robot when an incorrect note is detected by the PES. In particular, the quality of the sound was determined by using (2). The experimental results are shown in Fig. 7. As we may observe, for all the considered scores, the average of produced notes with high quality was higher with the proposed auditory system. Furthermore; in Table I, the number of incorrect notes (low sound quality) detected by PES are shown. As we may observe, the flutist robot WF-4RIV enhanced the quality of its performance while using the proposed auditory feedback system.

In order to confirm our experimental results, we have asked 14 subjects to hear the recordings of the performances of the robot while using the open-loop based system and the auditory feedback based system. Each of the subjects was asked to evaluate from 1 to 10 the performance of the WF-4RIV while comparing the performance of a professional flutist. As a result, subjects evaluated with an average of 3.9

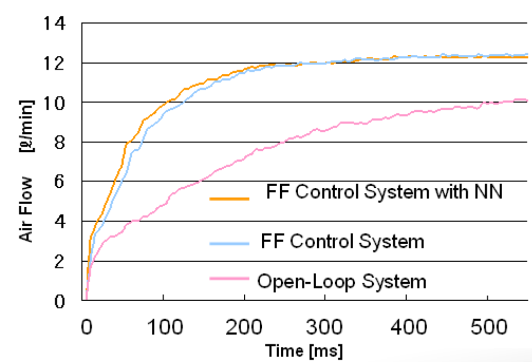

Fig. 6 Experimental results obtained while measuring the air flow at the lungs system.

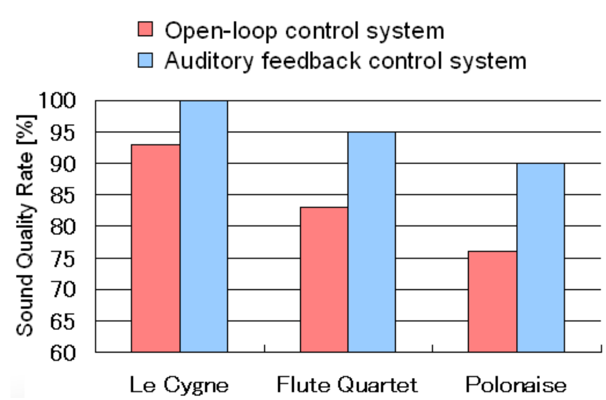

Fig. 7 Experimental results of the sound quality rate while comparing the open-loop control system with the proposed auditory feedback system while programming the WF-4RIV to perform different scores .

to the performance with the open-loop based system and an average of 6.1 to the performance with the auditory feedback based system.

Table I. Number of incorrect notes detected by PES on different melodies performed by the WF-4RIV

Score	Open-loop Control System	Auditory Feedback System
Le Cygne	8	0
Flute Quartet kv. 298	42	13
Polonaise	81	35

IV. Conclusions and Future Work

In this paper, the improvements on the control system of the Waseda Flutist Robot No.4 Refined IV are presented. In particular; an auditory feedback control system was implemented so that the flutist robot is able of autonomously improving the quality of the sound. The proposed auditory feedback control systems of a musical expressive generator, air pressure control system, and pitch evaluation system.

From the experimental results, we determine the effectiveness of the propose air pressure control system to control the air flow at the lungs by implementing the feed-forward control system. In particular, we confirm that by using the feedback-error learning approach, a better control of the air pressure can be achieved. As a future work, we will extend our analysis to the vibrato and tonguing mechanisms.

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