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20. MECHANICAL GUITAR PLAYER, A ROBOT FOR AUTOMATIC TESTING OF STRING INSTRUMENTS PARAMETERS

20.1. Introduction

The second half of the nineteenth century is the time of creation of the first robotic musical instrument (RMI)[6]. RMI from its definition is a mechanical device that could play a musical instrument normally operated by human player. The first mechanical musician to be created is called Pianista and was built in 1863 by Jean Louis Nestor Forneaux [6]. The invention, created by the French designer, was a self-playing piano equipped with a system of mechanisms reproducing notes from properly prepared, perforated paper tapes [6]. In recent years, thanks to the significant development of advanced technologies and easier access to them, the field of robotic musical engineering (RME) has become the focus of more and more artists, designers and scientists, and thus, more and more instruments are becoming the subject of its research. Until the twentieth century, the main instruments used for automation were pianos (the designs were a development of the Fourneaux invention) [6]. Currently, one can also find solutions based on wind, percussion and string instruments.

20.1.1. Musical robots

When it comes to wind instruments, Takanishi's Anthropomorphic Flutist Robot [14] is worth mentioning due to its level of sophistication. This robot uses an advanced mechanical imitation of the human respiratory system (artificial lung), mouth, tongue and fingers to play the flute. Another anthropomorphic robot playing a wind instrument is Toyota's Robotic Trumpeter [2]. It is distinguished from other robots being programmed to follow deterministic

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rules. It is worth mentioning that a quartet consisting of Toyota robots has repeatedly presented their reproductive musical skills during concerts for the public.

Currently development of percussion robots can be considered the most advanced branch of RME. Basically, percussion robots can be divided into two groups: robots for membranophones and ideophones. Their task is to produce sound by causing vibrations in the medium by exciting it with impact. There are several ways to create an exciter motion system for drum robots. The first are robots that use actuators to produce sounds. Their construction is designed in such a way as to ensure the bounce of the stick in a frequency comparable to human drumming [4, 7, 9, 11]. The second is to create a mechanical equivalent of the human upper limb, achieving a movement that most closely matches the movement made by the drummer while playing the percussion instrument [1, 5, 20, 23, 24, 28].

From the early 2000s, RMI constructions based on stringed instruments began to appear. The first stringed RMIs actually have little to do with guitars or violins. GuitarBot [11] is composed of four independent systems equipped with a rotary exciter (composed of three guitar plucks mounted on an electric engine shaft), string and a slider. Another example of a mechanical musician who is a hybrid of a machine and a string instrument is Aglaopheme [25]. This robot is a modified electric guitar neck, which, like GuitarBot, used a slider to adjust the pitch. Solenoid-based mechanism was used to pluck the strings. These types of modified instruments are not the only robots that play stringed instruments. Fingers (Compressorhead) is a very interesting solution among robots playing the guitar. It is a humanoid robot with seventy-two string-plucking mechanisms. Along with five other robots, he is part of the Compressorhead rock band. It is also worth mentioning the Toyota solution. They used a modification of their humanoid trumpet-playing robot to play the violin [2].

In addition to the already mentioned Compressorhead band and the Toyota musical robots quartet, several other projects have been created around the world associating robo musicians. Among others, Kapur and a team of researchers [7] developed The Machine Orchestra, a project intended to combine the musical reproduction of man and machine. The orchestra consisted of seven robots operated remotely by several musicians.

20.1.2. Classification of musical robots

In 2006, Weinberg and Driscoll presented classification of music robots according to the design solutions used in it [21]. They proposed to split musical robots into two categories: robotic musical instruments - which are mechanical structures that reproduce songs according to a hard-programmed code that controls the sequence of the play or used to be played by a musician; or anthropomorphic musical robots - humanoid robots that try to imitate the way humans play an instrument in the best possible way.

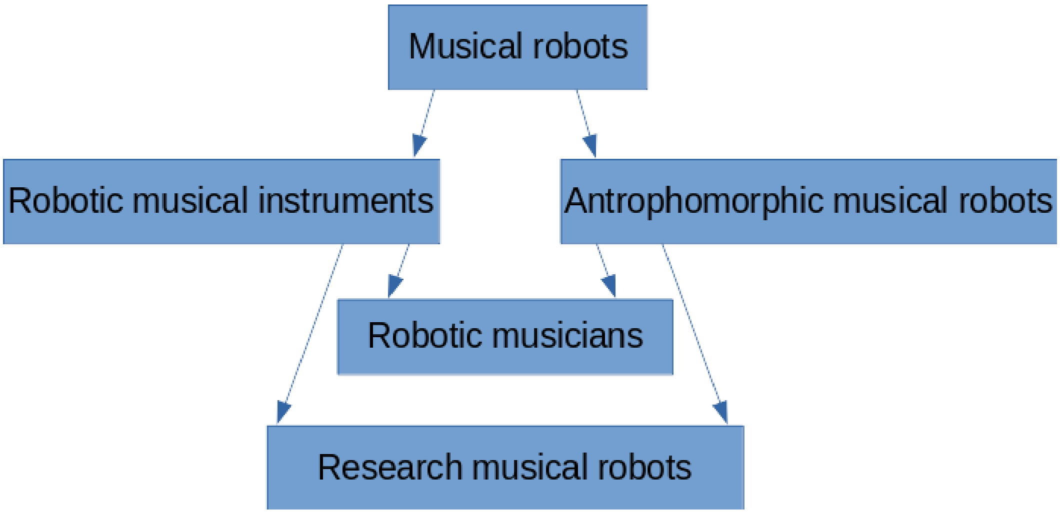

Fig. 1. Classification diagram of musical robots
Rys. 1. Diagram klasyfikacyjny robotów muzycznych

In the same article, the authors also proposed a definition of robotic musicianship as "combination of musical, perceptual, and interaction skills with capacity to produce rich acoustic response in a physical and visual manner" [21]. The proposed classification seems incomplete, especially taking into account the definition of robotic musicianship. Not every robot that can produce sound is by design a musician. It is true that the largest group of music robots is used to recreate music, but there are also constructions dedicated strictly to research purposes, supporting scientists in the development of knowledge about the construction, mechanics of the game or production of the sound of an instrument. Figure 1 presents a proposal to supplement the classification with additional subgroups: robotic musicians - robots focused on musical reproduction; and research musical robots - robots specialized in scientific research.

20.2. Mechanical guitar player

20.2.1. Motivation

There are many elements to build a musical instrument. Depending on the given instrument, these elements affect to a greater or lesser extent the sound that is produced during playing. It is similar with the guitar [3], a string instrument from the chordophone group (Fig. 2). Regardless of whether it is an acoustic or an electric guitar, in order to thoroughly investigate this effect on the resulting sound, it is necessary to compare the sound samples obtained by the most reproducible method. As Sali and Kopac write in their article [10], it is necessary to eliminate the erroneous human factor.

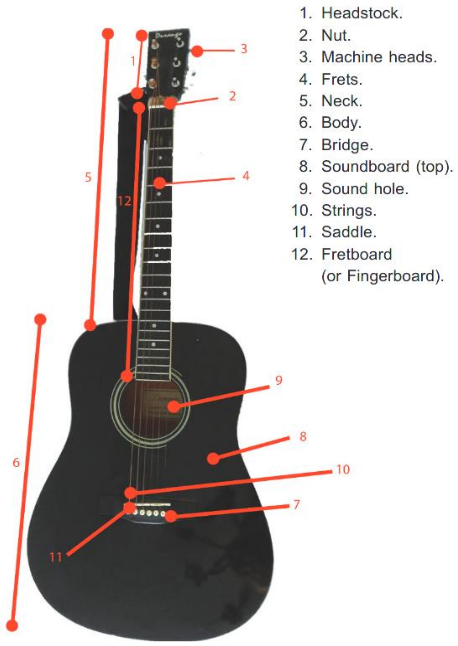

Fig. 2. Part schematic for acoustic steel string guitar
Rys. 2. Schemat części gitary akustycznej o stalowych strunach

Being aware of the inaccuracy of research using living musicians, scientists have created a mechanism that can excite a guitar string with the same force and at the same point each time. The solution proposed by them turned out to have a positive impact on the research they conducted. It also allowed us to draw conclusions that the elimination of the expression and auditory qualities imparted by the musician during the performance is the right way to attempt to parameterize the influence of the components on the resulting sound of the instrument. This is how the idea to create a robot playing the guitar was born: a robot that would have an appropriate level of repeatability (repeatability in this case refers to the time delays between played notes in the set sequences) allowing for objectively comparable sound samples.

20.2.2. First prototype

The first guitar playing robot built at the AGH University of Science and Technology was Eddie [17]. This robot (Fig. 3) has a modular structure that allows for easy installation on any acoustic guitar. Each module is equipped with calibration elements that allow for quick modification depending on the action and spacing of the strings, the type of bridge installed, or the size of the instrument's resonance box.

The robot's construction consists of three modules:

- string plucking module – for right hand simulation (Fig. 4)
- string pushing module – for left hand simulation (Fig. 5)
- control module.

Fig. 3. Eddie, a guitar playing robot mounted on an acoustic guitar
Rys. 3. Robot Eddie zamontowany na gitarze akustycznej

The right-hand module uses six pluckers, one for each string. The applied inductors were created with the use of modified electromagnetic relays, which makes it impossible to achieve the dynamics of string plucking. The relay allowed the use of two states 0 and 1, with the pluck occurring each time the transition from one state to another.

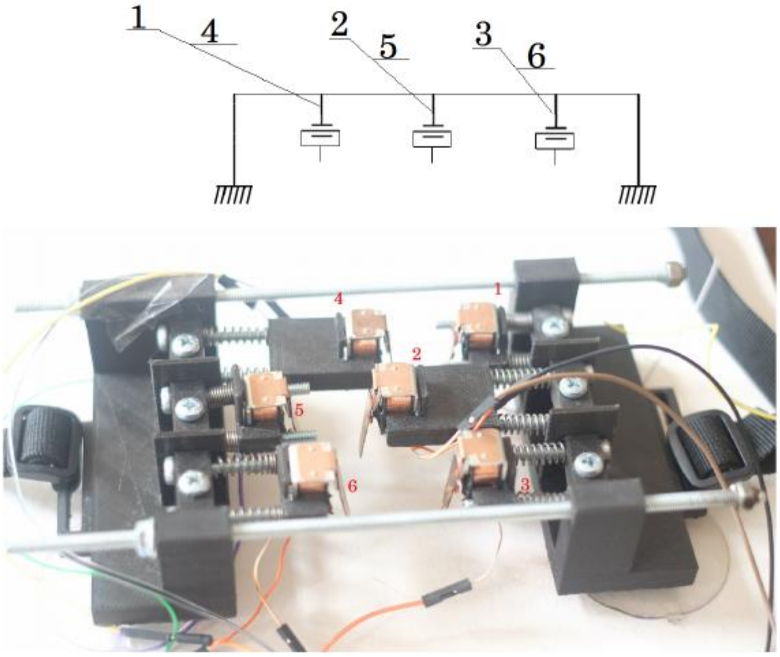

Fig. 4. String plucking module and its kinematic chain. 1,2,3,4,5,6 highlighted in the figure are relays converted into string plucking mechanisms [17]
Rys. 4. Moduł wzbudzający strunę i jego łańcuch kinematyczny. 1,2,3,4,5,6 zaznaczone na rysunku to przekaźnniki przerobione na mechanizmy szarpiące strunę [17]

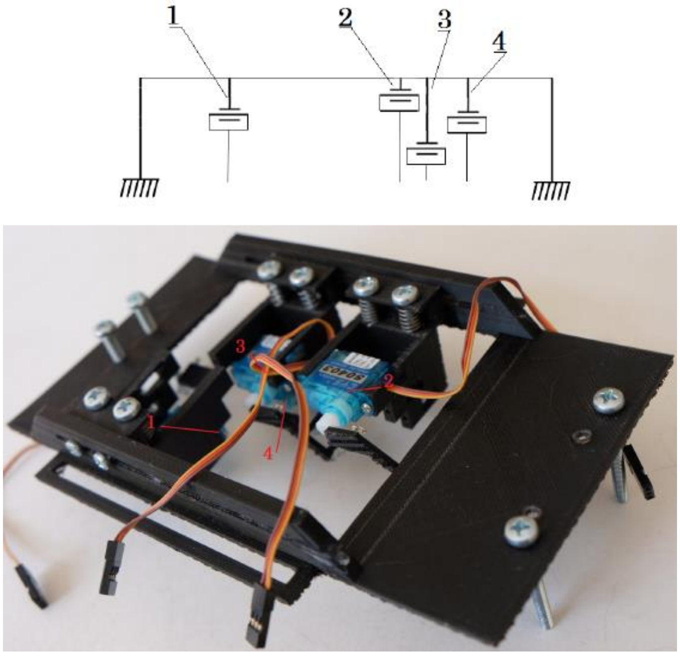

Fig. 5. String pushing module and its kinematic chain. 1,2,3,4 highlighted in the figure are servos used as string pressing devices [17]

Rys. 5. Moduł dociskający strunę i jego łańcuch kinematyczny. 1,2,3,4 zaznaczone na rysunku to serwomechanizmy wykorzystane jako urządzenia naciskające strunę [17]

In order not to cause additional undesirable plucks, at any given moment, the controller must maintain the power state on the coil until the next note is played. The downside of this solution is the high heat production by the electromagnets when they are in state 1. However, the use of relays allows to achieve high string pluck speeds. The lowest response time that could be achieved with this solution was 10 ms.

The left-hand module is used to change the pitch by shortening the string length. This is done through the use of servos equipped with pressure tips. The robot uses four mechanisms, which allows it to change the pitch of the sound on four strings. This is enough to play a few basic chords and simple sequences of single notes. Thanks to servo mounting modules, it is possible to increase or decrease their number in the system. It is also possible to manually adjust their position in relation to the guitar neck.

The described modules for Eddie's left- and right-hand simulation allows it to play ten different notes. Adding more servos will allow to increase the range of the played notes.

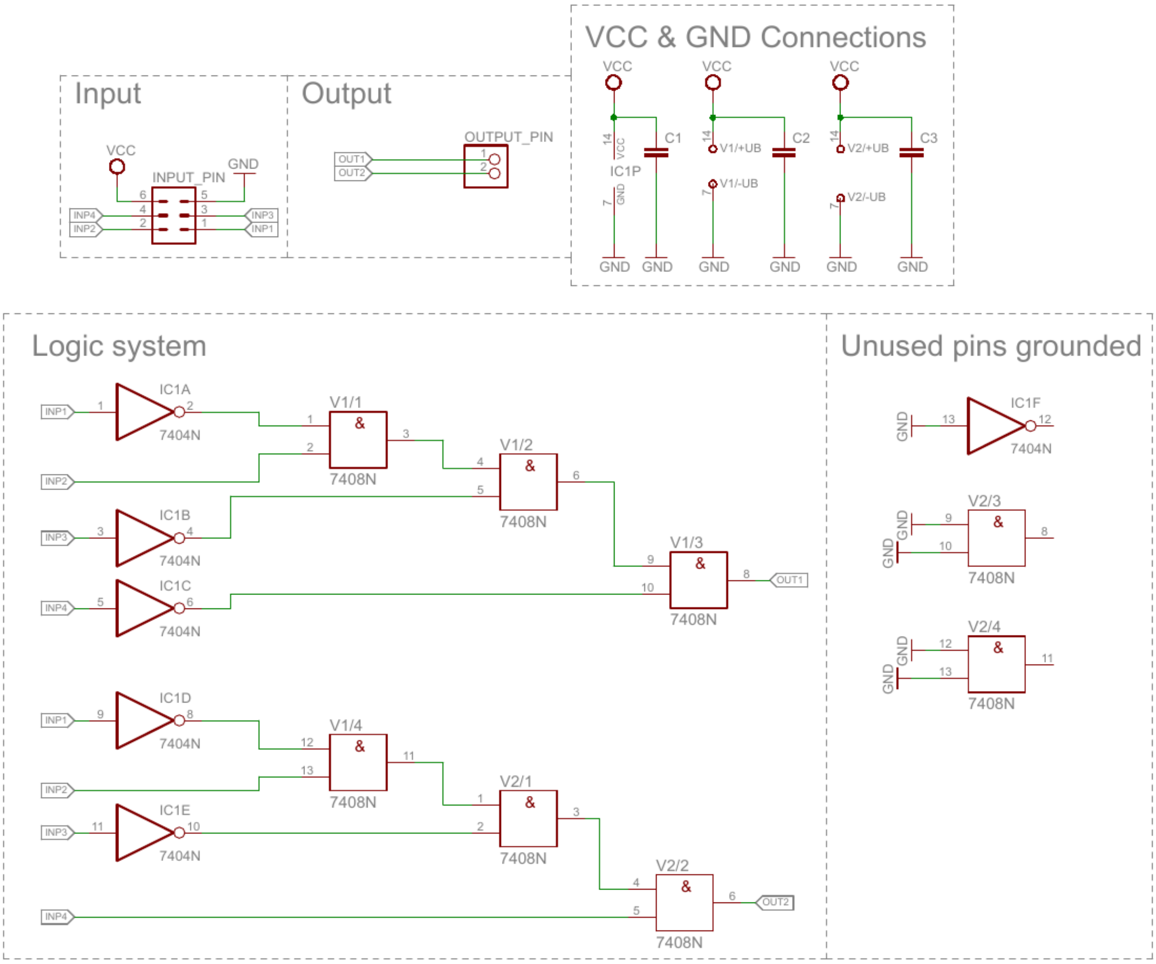

Fig. 6. Example of one logic gates board used to control the pluck mechanism
Rys. 6. Przykład jednego z układów bramek logicznych wykorzystanych do sterowania mechanizmem wzbudzenia

The first generation Raspberry Pi microcomputer was used to control the robot [19]. Due to its limitations, allowing direct use of eight GPIO pins as a control signal output, a logic gates system (Fig. 6) was used, thus increasing the number of supported outputs to ten.

The Raspberry Pi, as well as the integrated circuits used to build the robot's control system, are powered by 5 V, while the relays need 12 V to work properly. Therefore, the system uses an H-type bridge (Fig. 7) to supply the coils with proper voltage.

Several tests were conducted with the use of the described robot to determine its repeatability. A musician who played the same note sequences as the robot also participated in this research. This was to determine the differences between human and machine capabilities and to prove the validity of Salis and Kopacs assumptions [17]. The results were obtained by analyzing the homogeneity of the obtained samples. The results obtained from the musician playing the guitar had much lower sequence repeatability than those obtained from the robot's play.

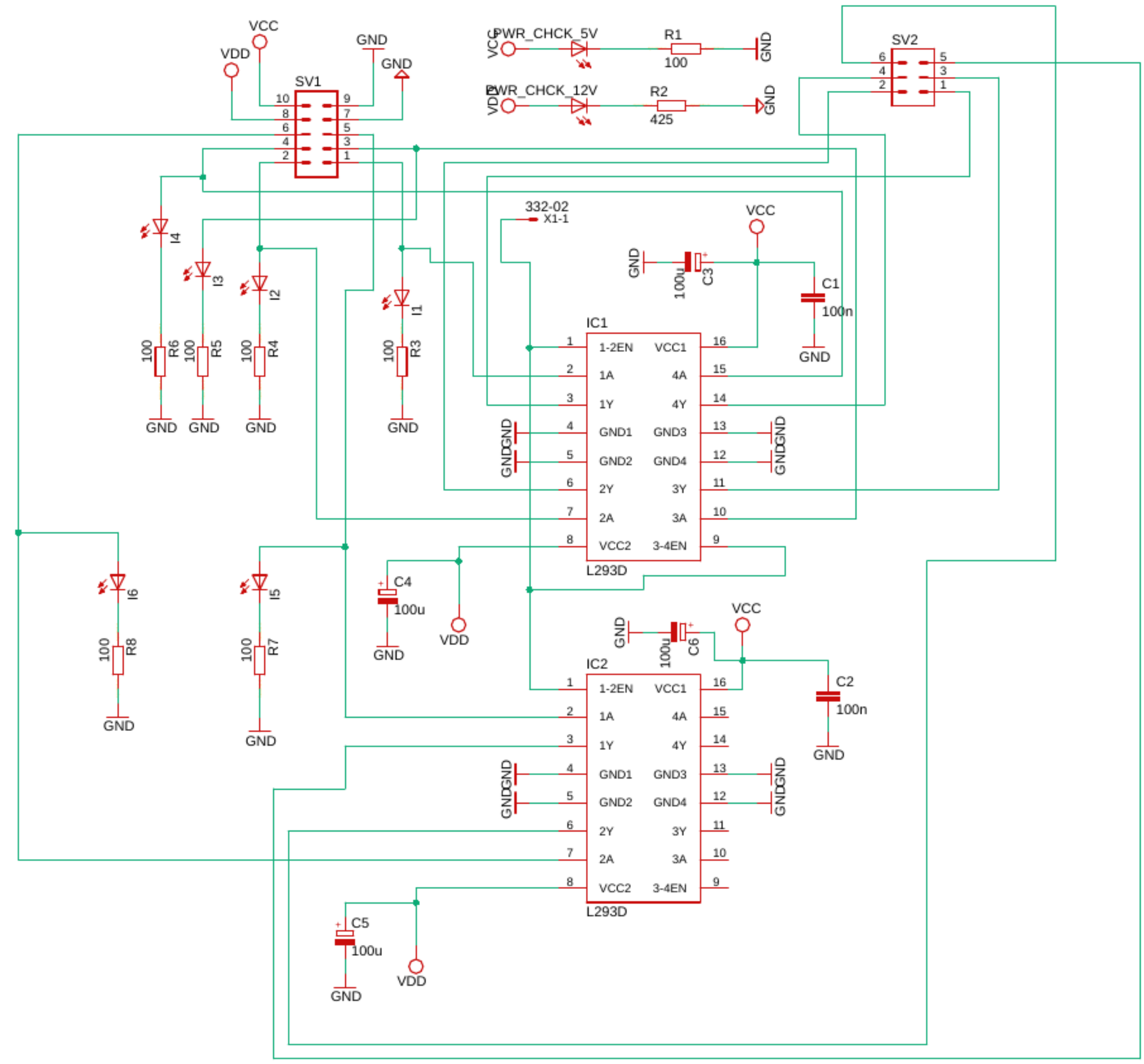

Fig. 7. H bridge schematics. Outputs SV2 were connected to the relays [17]
Rys. 7. Schemat mostka typu H. Wyjścia SV2 połączono z przekaźnikami [17]

Thanks to the obtained results, an attempt was made to modify Eddie's structure in order to maximize its potential for instruments research purposes. Thus, reducing its ability to recreate musical works.

20.2.3. String plucking prototypes

The change in concept of the robot was dictated, among others, by the complicated process of playing the stringed instrument and the accompanying physical phenomena. The authors assumed that simplifying the mechanisms and building it for specific research would give better and faster results than the construction of a complex device that would meet all necessary requirements for universal application.

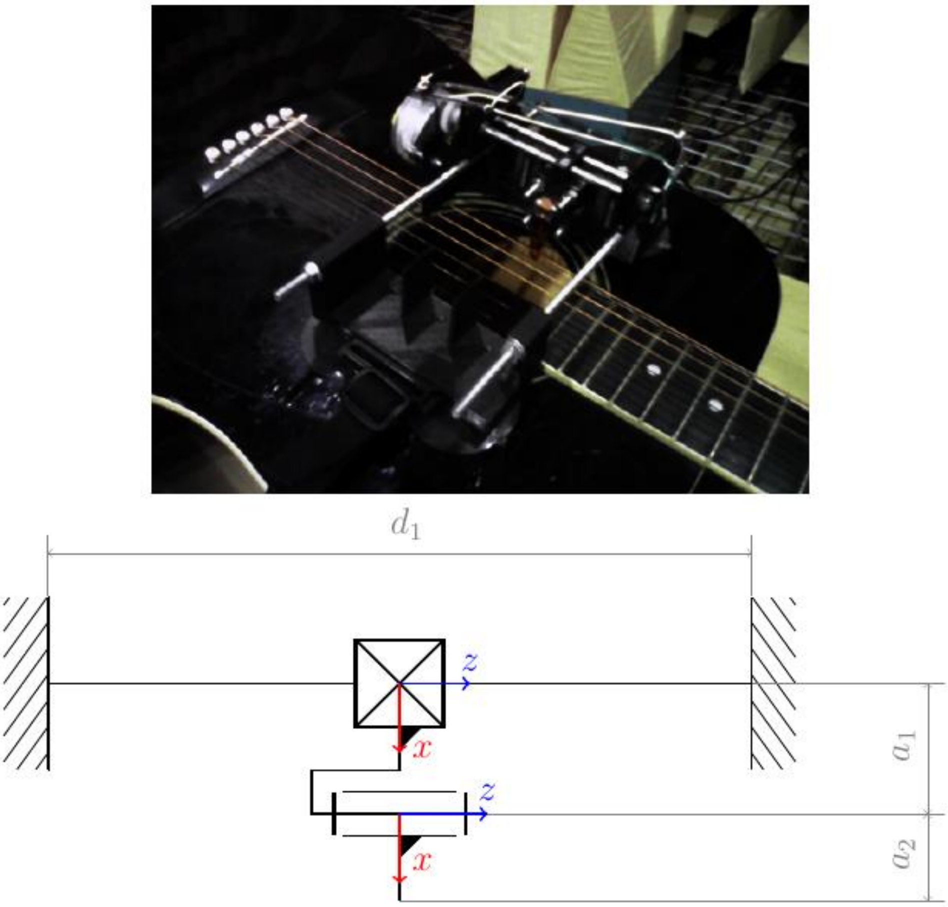

Fig. 8. Movable electromagnetic string plucking mechanism and its kinematic chain
Rys. 8. Ruchomy, elektromagnetyczny mechanizm szarpiący strunę wraz z jego łańcuchem kinematycznym

The first step was to eliminate the five plucking mechanisms, leaving the robot with ability to pull on only one string. This reduced the weight of the robot thus eliminating its influence on the vibration response of the guitar. The system was also equipped with an element moving along the string's axis on which the plucker was mounted (Fig. 8). This made it possible to study the influence of the string excitation point on the duration of the sound from an acoustic guitar [22]. In addition, in this robot it is possible to set the plectrum at an angle of forty-five degrees relative to the string axis.

Subsequent modifications in the plucking module were dictated by the need to use the robot to carry out research using an electric guitar [16]. The most important change was the replacement of the electromagnetic relay with a servo (Fig. 9 - 10). It was dictated by the need to exclude the additional electromagnetic field in the vicinity of the guitar's electromagnetic pickups. The use of a robot with a plucker based on a relay resulted in receiving the signal shown in Fig. 11. In addition, the servo allows to control the dynamics of string pluck.

One of the prototypes of the plucking mechanism is powered by a BLDC motor (Fig. 12). The motor of this type generates a low level of operating noise compared to other DC motors, therefore it was decided to check its use in research with the use of acoustic guitar. The plectrum was fixed directly on the engine shaft and mounted above the strings. Unfortunately, initial tests were unsatisfactory. Due to the low precision of the brushless motor, the times between single string excitations differed significantly between samples. This problem can be reduced by increasing the engine speed. It will increase the frequency of string excitations thus the plucking speed. Finally, it was decided that this type of plucking would be more applicable in research on the expression and dynamics of the guitar playing process. The module is currently undergoing a redesigning process.

Fig. 9. Movable servo-based string plucking mechanism for electric guitars
Rys. 9. Ruchomy, mechanizm szarpiący strunę gitary elektrycznej wykorzystujący serwomechanizmy, wraz z jego łańcuchem kinematycznym

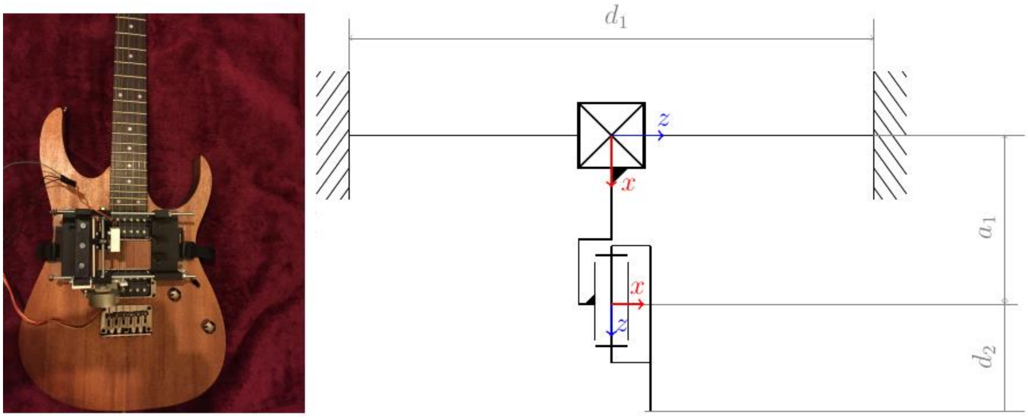

Fig. 10. Movable servo-based string plucking mechanism for electric guitars, top view and pluckers kinematic chain

Rys. 10. Ruchomy, mechanizm szarpiący strunę gitary elektrycznej wykorzystujący serwomechanizmy w widoku z góry, wraz z łańcuchem kinematycznym szarpaka

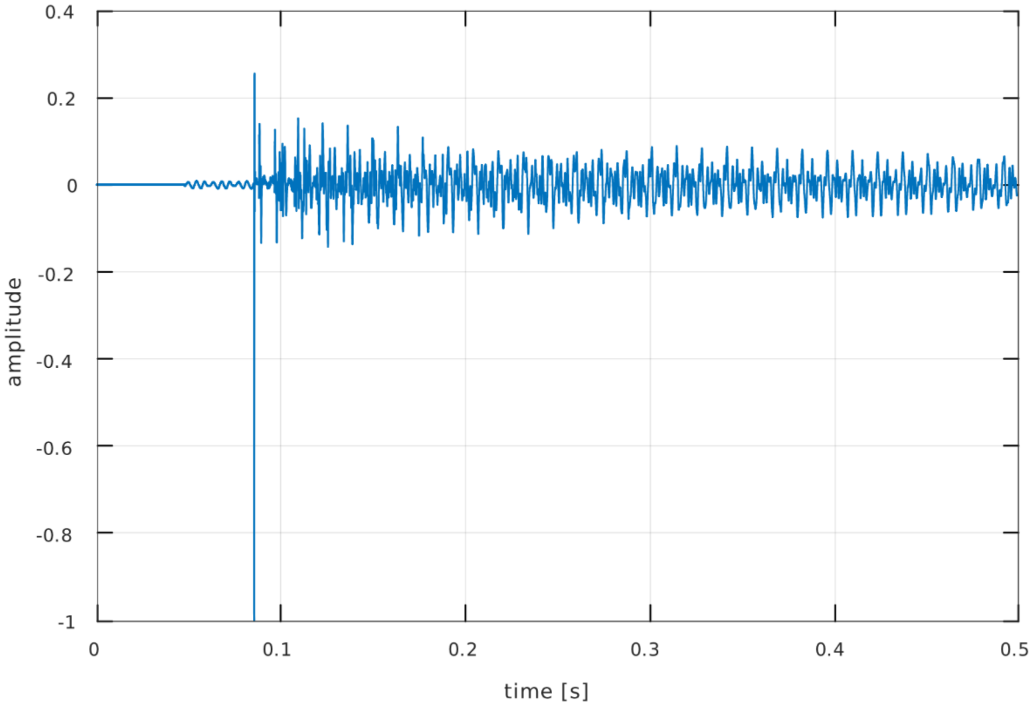

Fig. 11. Waveform of an electric guitar string plucked by a robot that used electromagnetic plucker. The powering of an electromagnet produces a clack and distorts the signal

Rys. 11. Kształt fali wygenerowanej przez wzbudzenie struny gitary elektrycznej robotem wykorzystującym wzbudnik elektromagnetyczny. Zasilenie elektromagnesu generuje trzask i zaburza sygnał

Fig. 12. Plucking mechanism based on a BLDC motor
Rys. 12. Mechanizm szarpiący oparty o bezszczotkowy silnik prądu stałego.

Another version of the mechanical guitarist was created in order to conduct research using a modular classical guitar [12].

The robot was equipped with one electromagnetic coil to excite the string and a mechanism moving the exciter perpendicular to the string axis, which allowed to change the plucked string without the need to manually calibrate the robot. In addition, the robot has a rotary element that allows to change the angle of string plucking.

20.2.4. Pitch manipulation devices

Parallel to the development of the right-hand simulation module, the pitch modulation mechanism was also modernized. With this module, it was decided to complicate the model in order to bring its operation closer to the human finger pressing the string. Five versions of the prototypes based on the mechanics of the human finger were created.

The first was a bionic hand printed on the basis of the InMoov project [27]. However, the design was not adapted to precisely hitting the strings. The prototype had a prolem with reaching the force of 15N [15] needed for a stable tension of the string to produce a clear sound.

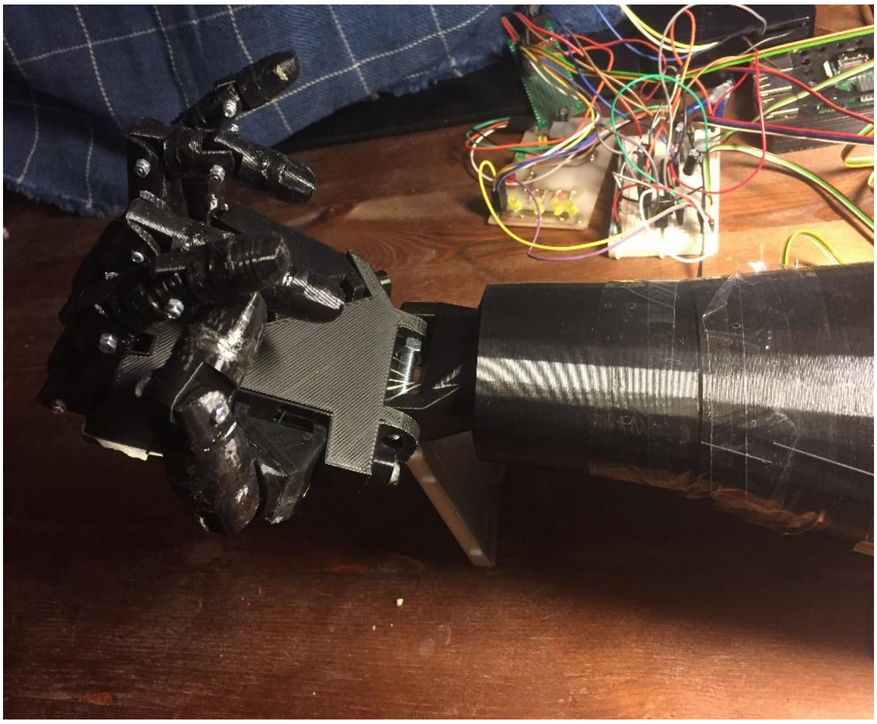

Fig. 13. Prototype of a bionic hand for guitar playing robot
Rys. 13. Prototyp bionicznej dłoni dla robota grającego na gitarze

Four prototypes were created by simplifying the palm system down to one finger. This prototypes were used to check the differences in the process of pressing the string depending on the degrees of freedom used in the pressure system [18] (Fig. 13-16). The last prototype (Fig. 17). of the string pressure module uses the capos principle of work. The pressing element is a solid block mounted transversely to the plane of the giuar's strings and neck. By making a movement towards the fingerboard, it presses down the strings, shortening their length. This change applies to all six strings of the instrument simultaneously.

Fig. 14. Prototype of a finger string pressure device
Rys. 14. Prototyp mechanicznego palca dociskającego strunę

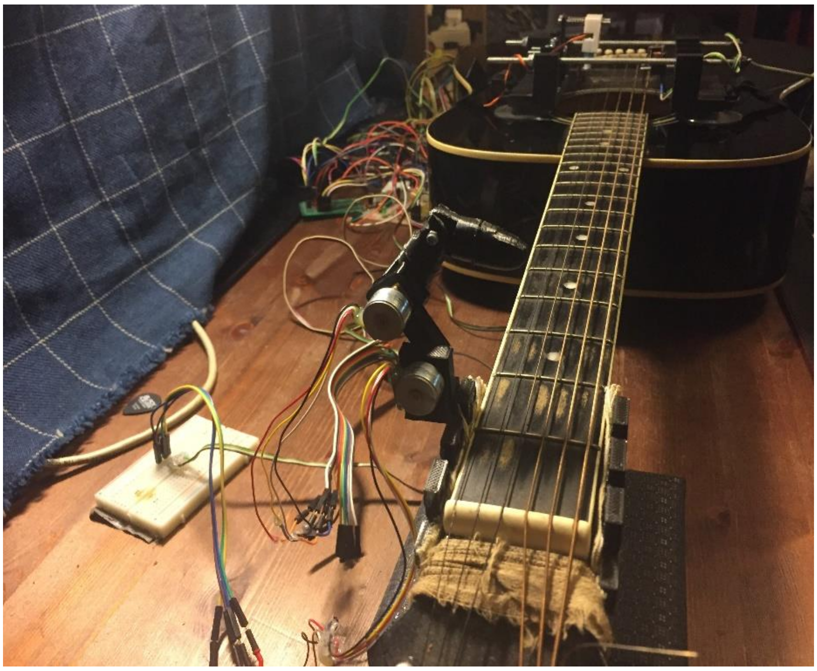

Fig. 15. Prototype of a finger string pressure device
Rys. 15. Prototyp mechanicznego palca dociskającego strunę

Fig. 16. Prototype of a finger string pressure device
Rys. 16. Prototyp mechanicznego palca dociskającego strunę

Fig. 17. Prototype of a capodaster string pressure device
Rys. 17. Prototyp mechanizmu dociskającego strunę na bazie kapodastra

20.2.5. Control unit

The control system (Fig. 18) used for the development and testing of the described prototypes is an upgrated unit, previously used in Eddie. By using the Raspberry Pi 3 controller, the number of IO pins has been extended to twenty-six without the need for additional logic circuit. The unit can control stepper motors, servos, DC and BLDC motors in various configurations. This gives the possibility of using any module configurations adapted to the research needs [8]. The proprietary robot control software allows to manually control the excitation of the string, or set the sequence of plucks and its time intervals.

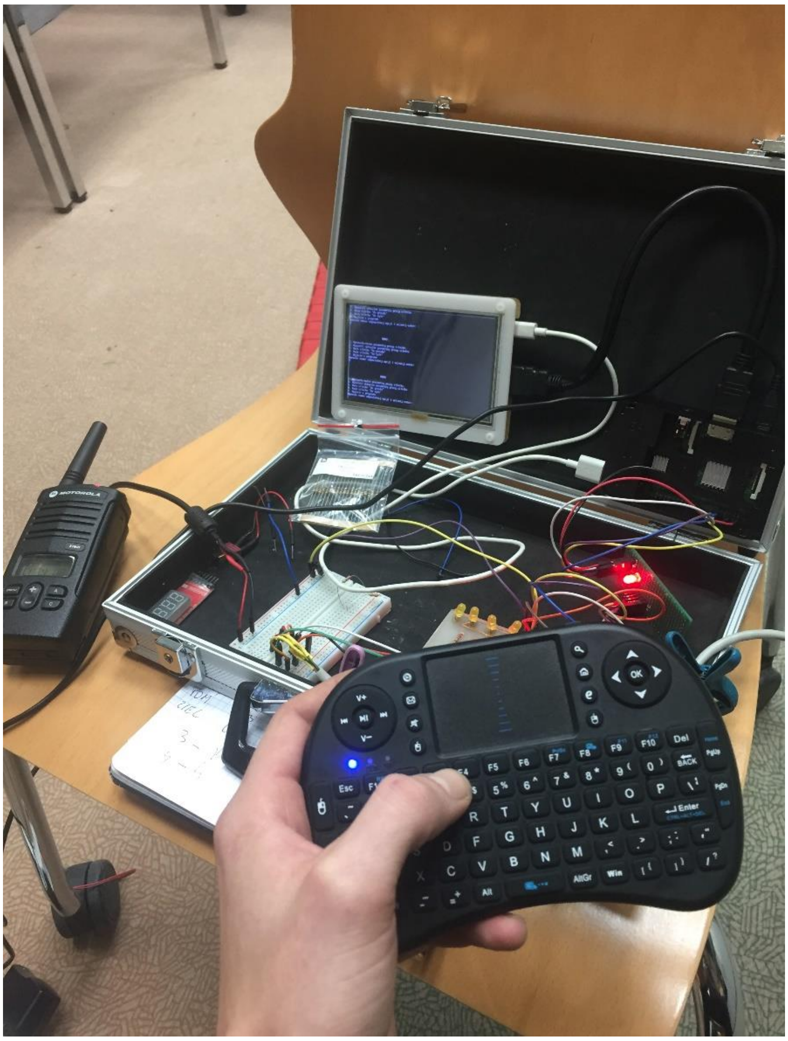

Fig. 18. Control unit used for the robots
Rys. 18. Jednostka sterująca wykorzystana w robotach

The use of a microcomputer allows network communication with the robot via RJ45, Wi-Fi and Bluetooth. The device can also be controlled directly after connecting an external screen and keyboard.

20.2.6. Repeatability testing

In order to correctly perform the repeatability test, the initial rules had to be established. Musician was instructed to play clear sounds matching the provided tempo without adding any dynamics and special plucking techniques. The reason for that was to obtain the most repeatable time intervals between the plucks as possible. Additionally it allowed to obtain similar recordings of played sequences. Research was conducted with a help of a professional musician. Firstly the guitar was tuned, then the human performer started to play several times, the same note sequence. Then the guitar was checked if it is still in tone and robot was mounted on it. Then the robot was calibrated and played the same number of times the same note sequence. Both performances were recorded and sound samples were prepared for further analysis. The research was conducted in a recording studio. The microphone was positioned according to instrument recording standards. To determine the repeatability of the robot and human it was necessary to compare the recordings' samples. The method used for that purpose was to compare the RMS values of the signal samples. The recorded data was split into samples of the same note sequence. The sampling rate of the obtained signals was 44100 Hz. In the RMS, Hamming window of size 256 was used.

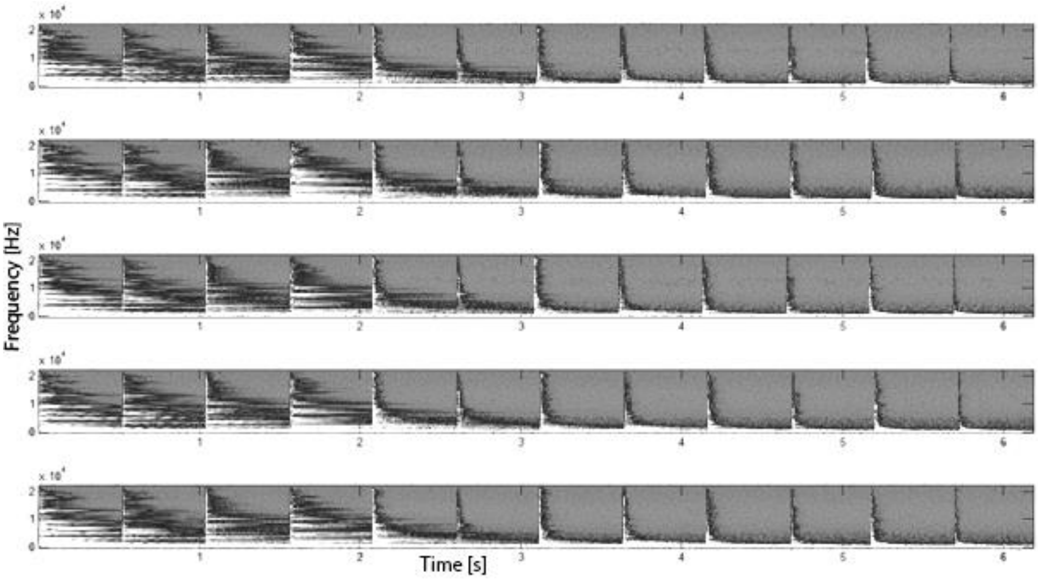

Fig. 19. Spectrogram of sounds played by robot
Rys. 19. Widma dźwięku odegranego przez robota

Five sample examples were chosen for the purpose of this article. It can be clearly seen, that the samples of the robot play are much alike each other opposing to the samples of a human play. Figures 19 and 20 show spectrograms of their performances. Each of five spectrograms on the figure represents one note sequence played. In fig. 20 the author marked one of the distortions that can be seen before the musician plucks the string. This distortion results from release the finger from a fret before the string is plucked. Due to the synchronisation of plucking and pushing the string, this phenomenon does not occur in the robots' play.

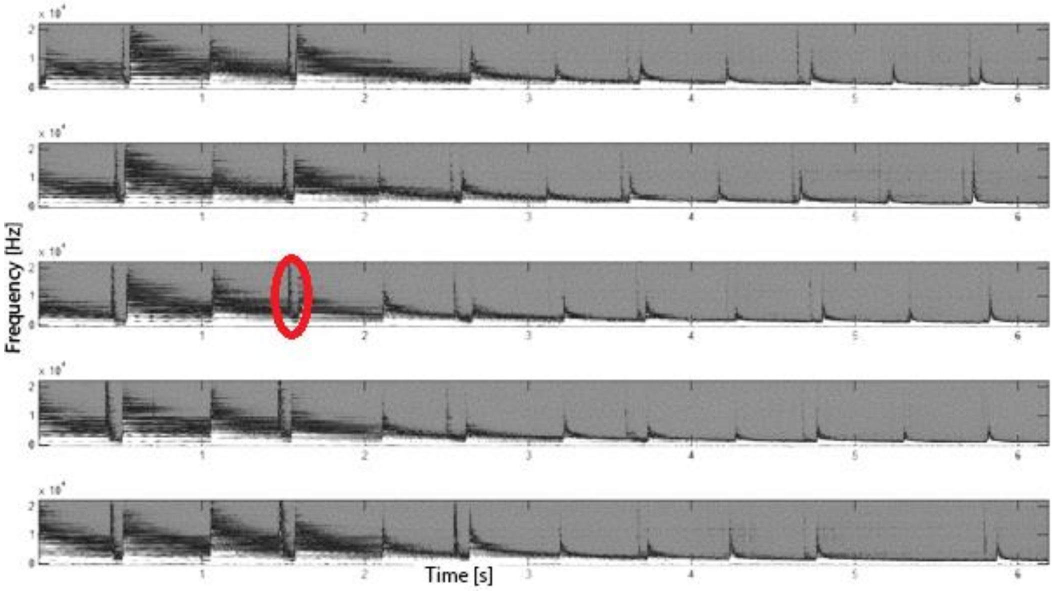

Fig. 20. Spectrogram of sounds played by guitarist. Red ellipse marks one of the distortions that resulted from early string push release

Rys. 20. Widma dźwięku odegranego przez gitarzystę. Czerwoną elipsą zaznaczono zniekształcenie wynikające z wczesnego wzbudzenia struny

Table 1 shows the result of the sound samples heterogeneity calculation. Results show that the robot has better repeatability than the human musician in aspect of the time intervals between played notes in the sequences. In order to estimate repeatability, each sound sample was compared to every other (separately for musician and robot) and plucking heterogeneity based on Euclidean distance was calculated. The perfect repeatability for this case would have the value of 0:

$$PH = \sqrt{\sum_{i=0}^{N-1} (x_i - y_i)^2} \tag{1}$$

where: x_i – values of the amplitude spectrum of one sample, y_i – values of the amplitude spectrum of another sample, N – number of samples in spectrum.

Table 1

Results of plucking heterogeneity calculation

PH values from robots play					
Samples	**S_1S_1**	**S_2S_1**	**S_3S_1**	**S_4S_1**	**S_5S_1**
Values	0	0.005	0.006	0.002	0.001
	S_2S_2	**S_3S_2**	**S_4S_2**	**S_5S_2**	**S_3S_3**
	0	0.0007	0.003	0.005	0
	S_4S_3	**S_5S_3**	**S_4S_4**	**S_5S_4**	**S_5S_5**
	0.003	0.004	0	0.003	0
Mean value of robots PH			**0.001**		
PH values from musicians play					
Samples	**S_1S_1**	**S_2S_1**	**S_3S_1**	**S_4S_1**	**S_5S_1**
Values	0	0.006	0.005	0.002	0.004
	S_2S_2	**S_3S_2**	**S_4S_2**	**S_5S_2**	**S_3S_3**
	0	0.0001	0.008	0.006	0
	S_4S_3	**S_5S_3**	**S_4S_4**	**S_5S_4**	**S_5S_5**
	0.007	0.004	0	0.003	0
Mean value of musicians PH			**0.004**		

The obtained research results show that the robotic musical instrument achieves steadier time intervals between the sound in the sequence than the ones in human musician play. Robot obtained higher repeatability for a technical play in the set pace. Elimination of the human factor reduces the errors that occur during the performance of the sequence.

20.3. Conclusions

Most of the elements used in the presented mechanisms were made using the 3D technology (Fig. 21) and Rapid Prototyping. The elements were printed from PLA (Subramaniam et al., 2019) filament. Polylactic acid at temperatures ranging from 45 to 60° C achieves the softening temperature, which has negative effects in situations such as overheating of the electronic components of the module and results in damage to the printed element. Future versions of the project will eliminate such flaws.

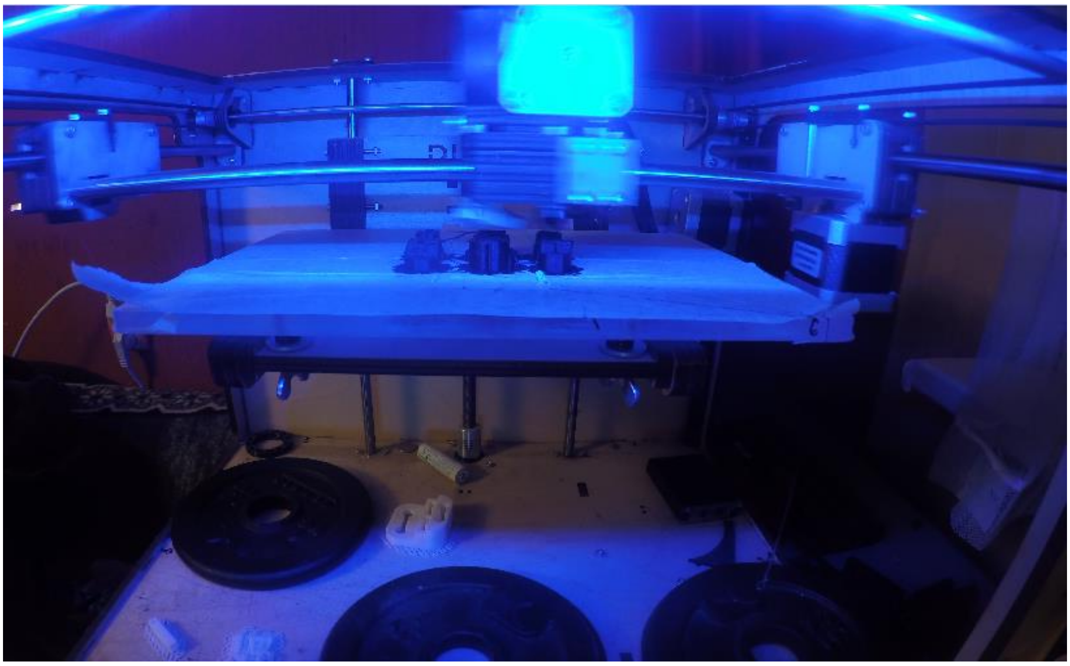

Fig. 21. The process of 3D printing of parts for robots
Rys. 21. Proces drukowania 3D części robotów

As mentioned at the beginning of the second chapter, Sali and Kopac proposed to increase the precision of results in the study of musical instruments by excluding the human factor from it. Both the results presented by them [10] and the results obtained from the tests of prototypes [8, 9, 12, 15, 16, 17, 18, 22] indicate an advantage of such an approach. As the publications mentioned in this article present, music robots are successfully used for research in various fields of music. Regarding the mechanical guitarist's design, the paper sums up its prototype process. The presented constructions allowed for drawing many conclusions and reflections regarding the construction of a device with higher precision and its use in subsequent research.

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