Exploring Emerging Drumming Patterns in a Chaotic Dynamical System using ZRob

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ABSTRACT

ZRob is a robotic system designed for playing a snare drum. The robot is constructed with a passive flexible spring-based joint inspired by the human hand. This paper describes a study exploring rhythmic patterns by exploiting the chaotic dynamics of two ZRobs. In the experiment, we explored the control configurations of each arm by trying to create unpredictable patterns. Over 200 samples have been recorded and analyzed. We show how the chaotic dynamics of ZRob can be used for creating new drumming patterns.

Author Keywords

Robotic Drumming, Emergent Patterns, Chaos, Rhythm

CCS Concepts

•**Computer systems organization** → **Robotics;** •**Applied computing** → *Sound and music computing;*

Figure 1: Two Zrob robots playing the snare drum.

1. INTRODUCTION

Historically, humans have been inspired by ambient (natural and artificial) rhythms and patterns for creating music [6]. There are numerous examples in different cultures that nature sounds—including animal sounds—were the source of inspiration for music making. Even artificial sources such as machines, trains or cars have influenced music in different time periods. The important aspect of this influence is that the generated sounds are basically the result of the physical characteristics of the source. For example, the rhythmic pattern of a running horse depends on the size of its legs, its weight, its biomechanics and generally its body.

On the other hand, the performance of a musician is fundamentally shaped by the physical constraints of the human body [4]. According to the embodied cognition theory, our perception of the environment and its patterns directly depends on our body and how we can move and interact with the environment [2]. Thus, for creating new rhythmic patterns we should look for different dynamics in physical systems, or create physical systems with different dynamics.

ZRob is a robotic system designed for performing and learning different drumming tasks. The body of the robot and the interaction between the robot and the drum during the performance result in a unique dynamical behaviour that can generate emergent rhythms. ZRob has a flexible gripper with passive springs that makes chaotic behaviour in the motion of the drumstick. A chaotic system is a deterministic system which has unpredictable behaviour [12]. The chaotic dynamics of the robot—similar to a double pendulum—can be exploited to create unpredictable and complex rhythmic patterns.

In this study, we have used two ZRobs with different con-

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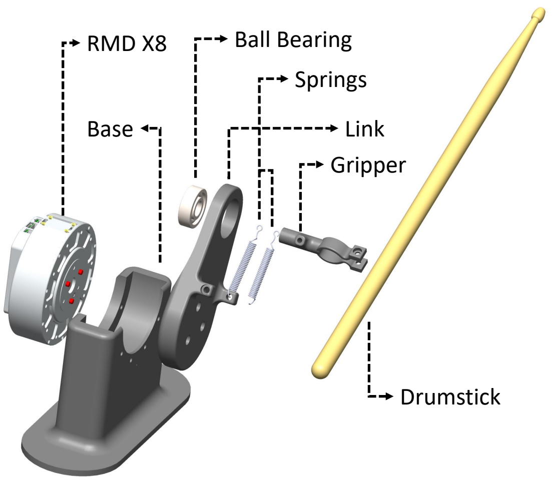


Figure 2: Exploded view of the 3D design of ZRob.

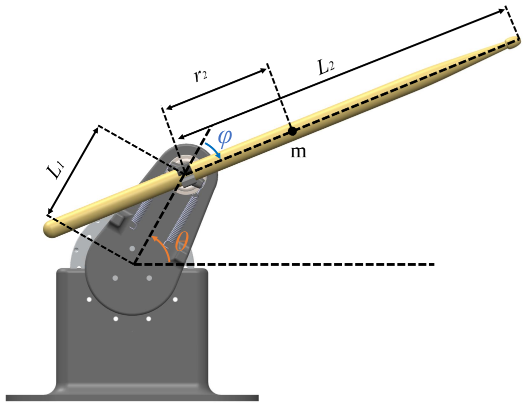


Figure 3: Physical model of ZRob.

figurations in an experiment to explore emergent drumming rhythms (Figure 1). The main contribution of this study is to develop and use a musical robot for creating novel and unique patterns using chaotic dynamics, a topic that has received relatively little attention so far.

2. BACKGROUND

Previous work on drumming robots have largely focused on optimizing stroke control and replicating well-known drumming tasks. In several cases, significant results have been achieved. In a work by Hajian et al. a single-joint, variable stiffness robotic arm using pneumatic actuators in an agonist–antagonist arrangement was developed [7]. Stiffness has also been researched by others, including the use of variable stiffness actuators to reproduce single and double snare drum strokes [10].

A robotic arm can overcome limits of body, such as in the robotic drumming prosthesis for an amputee drummer, controlled by electromyography (EMG) signals [1, 5]. The performance and control of the arm has been improved by using different actuation system and optimizing the control torques needed for different tasks [16, 15].

ZRob is mainly developed for exploring the dynamical potentials of a robotic system in drumming. A significant difference between ZRob and other drumming robots is that ZRob has two degrees of freedom with a passive flexible joint. Prior to this study, we tried to develop a learning method for adjusting the gripper stiffness for double-stroke drum rolls [8] and conducted an experiment for studying the effect of passive impedance on drum rolls performed by the first prototype of ZRob [9]. In this study, we use two ZRobs with an improved design to perform two-arm drumming.

3. *ZROB*, A DRUMMING ROBOT

ZRob is a robotic system designed for performing drumming tasks. The system consists of the body of the robots, control hardware, and software. In this section, these parts are briefly explained.

3.1 Mechanical Design

The robots are basically 2-degree-of-freedom (2-DoF) arms each actuated by one servo motor. The arms have one flexible joint with passive springs as the gripper. The arms are designed so that the dynamics of the drumstick could be exploited to create complex and emergent rhythmic patterns. Using passive springs in the flexible gripper makes the rebounding forces create double or triple strokes according to the natural dynamics of the physical interaction between the robot and the drum membrane. It has been shown that the stiffness of the spring determines the robot's response in different ranges of motion frequency [8, 9].

In Figure 2 the 3D design of one robotic arm is illustrated. The link, base and gripper parts are printed using a Markforged 3D printer with carbon fiber. This material is much more robust than the PLA and ABSplus thermoplastic prototypes [9]. In addition, we used a larger ball bearing and gripper to make the robot capable of playing faster rolls and stronger strokes in the high-frequency range. The actuator used for each arm is an RMD-X8 servo motor including a 6:1 gear ratio and CAN-BUS connectivity. In this study, we used two arms that have springs with different stiffness ratios. Using different stiffness ratios for the grippers expands the feasible rhythmic patterns performed in 2-arm drumming. We will discuss this impact in more detail later.

3.2 Robot Dynamics

To describe the chaotic motion of the drumstick, we need to look into the dynamical equations of the robot. The physical parameters of the robot are shown in Figure 3.

The dynamical equation of the robot according to [14] can be written as:

$$M(\theta,\varphi)\begin{bmatrix}\ddot{\theta}\\ \ddot{\varphi}\end{bmatrix}+C(\theta,\varphi,\dot{\theta},\dot{\varphi})\begin{bmatrix}\dot{\theta}\\ \dot{\varphi}\end{bmatrix}=\tau \tag{1}$$

where $M(\theta,\varphi)$ is the inertia matrix, $C(\theta,\varphi,\dot{\theta},\dot{\varphi})$ is the Coriolis matrix and τ is the torque vector.

Since θ is the rotational position of the motor and the motor has an internal PID controller, we can assume that θ is known and set by the control commands. Additionally, the applied torque in the first joint is generated and adjusted by the motor. Thus, the dynamical equation of the angular position of the second joint is only derived from the second differential equation of the robot:

$$\tau_2=(\delta+\beta cos(\varphi))\ddot{\theta}+\delta\ddot{\varphi}+\beta sin(\varphi)\dot{\theta}^2 \tag{2}$$

where

$$\delta=I+mr_2^2 \tag{3}$$

$$\beta=mL_1r_2 \tag{4}$$

$$\tau_2 = \tau_{ext} + \tau_k - \tau_d - \tau_{grav} \quad (5)$$

In these equations, τ_k is the torque generated by the passive springs, τ_d is the damping torque, τ_{grav} is the torque caused by gravity, τ_{ext} is the torque caused by interaction between the drum membrane and the drumstick and I is the inertia of the drumstick.

According to Equation (2), the motion of the drumstick is similar to a double pendulum and can be considered a chaotic phenomenon. A chaotic system is a deterministic dynamical system which has unpredictable behaviour. The source of unpredictability is nonlinear dynamics which makes the system super sensitive to initial conditions and physical parameters [12]. For instance, in ZRob, the source of nonlinearity consists of (a) the nonlinear dynamics of the robot, (b) nonlinear passive springs used in the gripper, and (c) the external force from the drum.

The difference in stiffness of the springs of the arms makes the drumming result of each arm completely different. This behaviour allows us to exploit the complexity of the system to generate unpredictable combinations with the two arms.

3.3 Control Hardware and Software

The motors have internal drivers with PID controllers for the position, velocity and torque control modes. They use the CAN-Bus communication interface for receiving control commands. We have used an Arduino board with a CAN-Bus shield to communicate with the motors.

The trajectory of each motor is generated by the Arduino programmed with C++. The Arduino board is also connected to a laptop with a serial port that runs Python code to process the recorded drumming sound and set the control parameters for generating the trajectories. The codes are available online [1]. The block diagram of the system is shown in Figure 4.

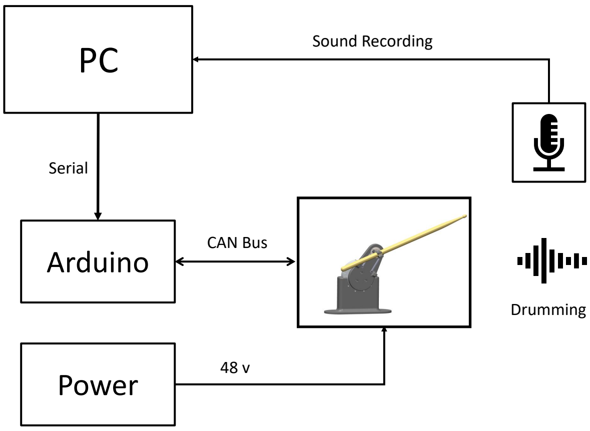


Figure 4: Diagram of processing units and communications between them.

4. THE EXPERIMENT

In the present experiment, we explored how the control variables of the robots can be used to explore emergent rhythmic patterns. Especially, we were interested in novel and unpredictable patterns. In the experiment, we used two arms with different springs and generated a periodic trajectory for each arm with modified control parameters. The desired trajectory for θ in each arm is:

Table 1: Parameter values

Control parameter	Variable	Unit	Range
Angular Bias	B_i	rad	0-0.15
Amplitude of Motion	A_i	rad	0-0.3
Frequency of Motion	f_i	Hz	1-10
Phase Shift	ϕ_i	rad	0-2π

$$\theta_i = B_i + A_i sin(2\pi f_i t + \phi_i) \quad (6)$$

By using Equation (6), we can generate the trajectory of each θ by calculating the derivative of the desired trajectory at each time step:

$$\dot{\theta}_i = 2\pi A_i f_i cos(2\pi f_i t + \phi_i) \quad (7)$$

The values of the control parameters for generating the trajectories for the motors are described in Table 1.

For making the rhythmic patterns describable with conventional musical metres, we calculate each f_i according to a fixed tempo:

$$f_1 = mT/60, f_2 = nT/60 \quad (8)$$

where T is tempo in beats per minute (BPM), and m and n are integer numbers from 1 to 8. Figure 5 shows one example of generated trajectories for two robots.

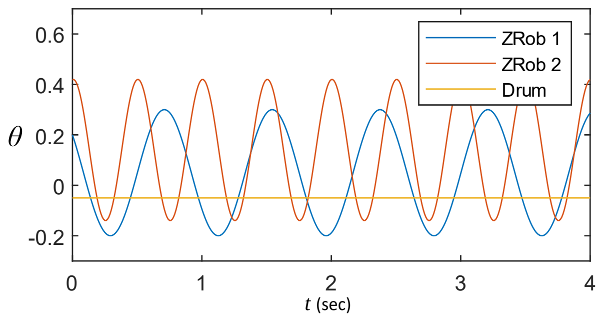


Figure 5: A sample trajectory generated for the angular position of each motor (Equation 6). The contact point of the robots with the drum membrane is specified by the orange line.

5. RESULTS

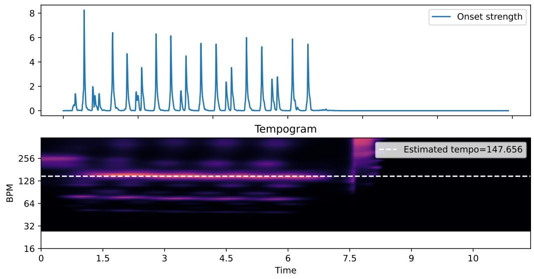
In the experiment, we recorded over 200 samples of drumming with different control parameters. The video of selected samples is available online [2]. Figure 6 shows visualizations of audio features extracted from some of the recorded samples. This includes graphs of onset strength calculated using Librosa library for Python [13]. We also include tempograms for each recording. The parameter values of each sample are described in Table 2. Since the two robots are playing on one snare drum, we are unable to identify individual arms from these recordings.

6. DISCUSSION

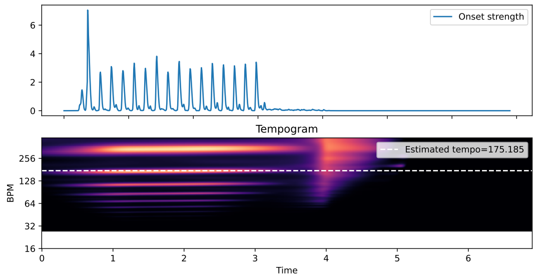
Our goal in this paper has been to explore the potential of musical robots for musical expression. We are more interested in creating interesting rhythmic patterns than optimizing a specific task. It is therefore hard to find a quantitative measure for comparison. Instead, we have focused on

[1] https://github.com/mojtabak-rob/Zrob

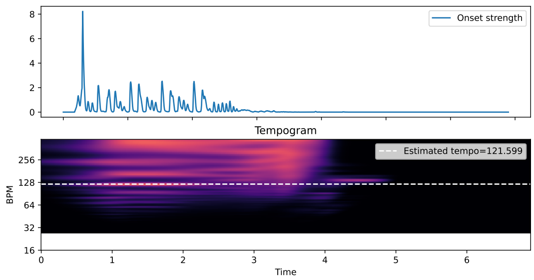
[2] Project in osf.io



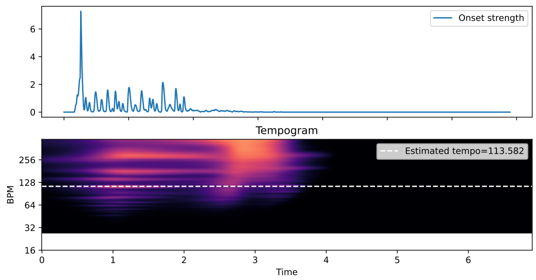
(a) Sample 1



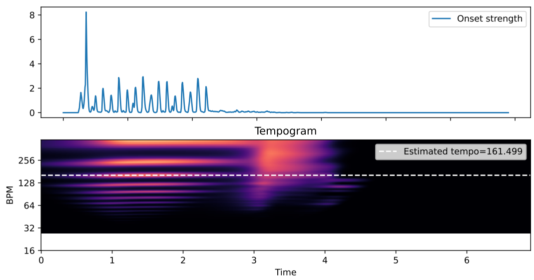
(b) Sample 2



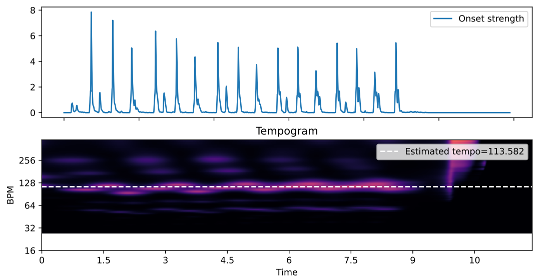
(c) Sample 3



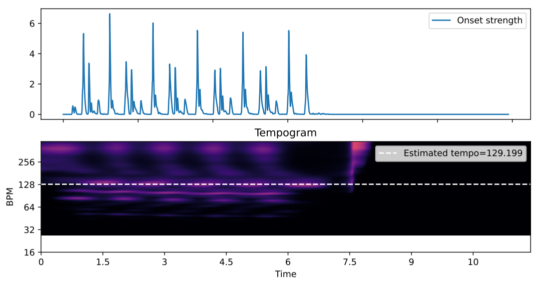
(d) Sample 4



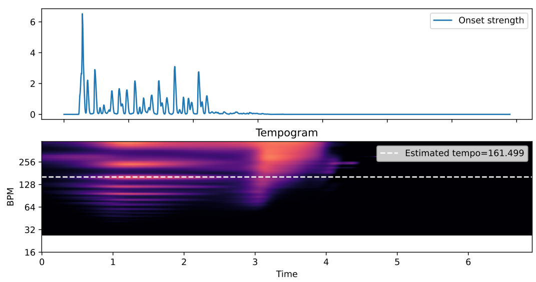
(e) Sample 5



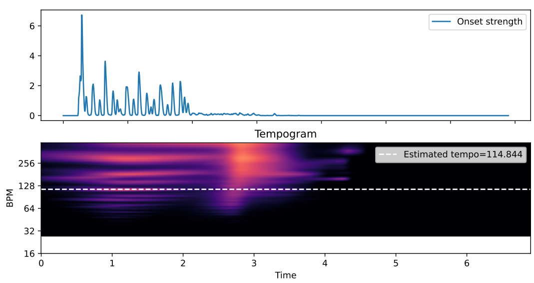
(f) Sample 6



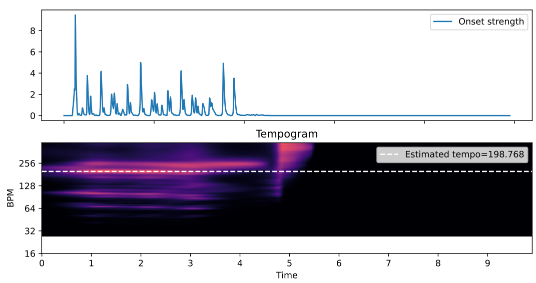
(g) Sample 7



(h) Sample 8



(i) Sample 9



(j) Sample 10

Figure 6: Sample recordings; in each sample the onset strength and tempogram indicate the rhythmic features of the recording.

Table 2: Values of control parameters for the sample recordings.

Sample number	A_1(%)	A_2(%)	B_1(%)	B_2(%)	m	n	$\phi_1 - \phi_2$(degree)
1	47	50	40	40	2	3	291
2	50	40	73	17	4	4	4
3	51	42	99	1	3	4	307
4	65	37	63	33	3	5	3
5	68	54	74	95	3	5	336
6	70	61	15	80	3	2	326
7	72	30	74	93	2	3	15
8	81	50	94	65	3	5	260
9	91	58	90	60	3	5	233
10	92	35	58	86	3	4	257

a qualitative evaluation based on identifying novel rhythmic patterns.

The 200 recorded performances show great variability in rhythmic patterns; each of which has emerged from a specific control configuration and unpredictable behaviour of the arms. Additionally, the vibrations of the drum membrane connect the physical response of the arms. For instance, if Zrob 1 plays with a certain frequency that resonates with the natural frequency of the springs of ZRob2, the physical response of ZRob 2 would be affected. In addition, the difference in the amplitude of motion of the robots can emphasize the onsets and weaker beats. In some cases, syncopation and contrasting beats emerge.

We are particularly intrigued by the polyrhythmic patterns emerging when the robots play different meters. For example, if the robots play with $m = 8$ and $n = 3$ and the same tempo, the first robot would play a quadruple and the second robot would play a compound metre. In this case, we can expect a predictable polyrhythmic pattern. However, the dynamic complexity of the robots causes a different and unpredictable pattern to emerge. One possibility is when one robot plays double strokes and the other plays single strokes. Since the timing of the double strokes is mainly dependent on the stiffness of the springs, the emergent pattern would be completely unpredictable at different tempi.

An example of such behaviour is illustrated in Figure +7. In this case, ZRob 1 is playing a quadruple metre and ZRob 2 is playing a compound metre with the same tempo. The control configurations such as frequency, bias and amplitude, make ZRob 2 play double strokes. The rebounding strokes have their own timing according to the stiffness of the gripper. The resultant pattern would be unpredictable, as shown in the third circle in Figure +7. Performing such a complex pattern is extremely hard for human drummers since the coordination between the arms is biophysically constrained [3, 11].

While the chaotic dynamics of the robots create unpredictable behaviour, the system is not fully controllable and the performance of the robots is constrained by the chaotic dynamics. This is due to the fact that the robots are underactuated and one motor is used for each 2-DoF arm. However, unpredictability is what we look for in this context. Generally, there is a trade-off between flexibility and controllability. When we build robots for a specific task, it is important to have a controllable system that meets the precision and accuracy requirements for the task. On the other hand, the application of musical robots is not necessarily optimizing musical tasks. In our case, rhythmic exploration is at the heart of our investigation. We tried to look for new possibilities for creative expression by developing a robotic system with complex dynamics.

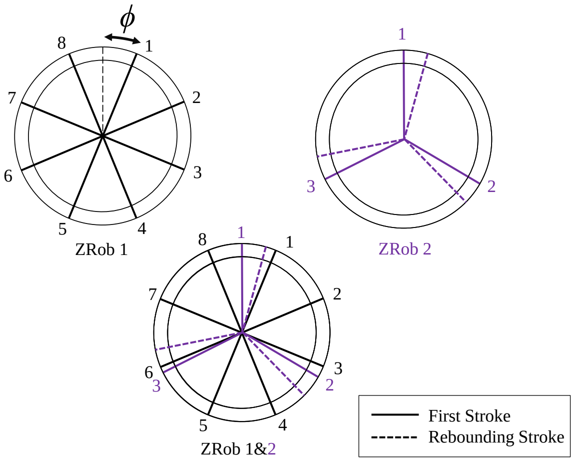


Figure 7: A representation of polyrhythmic pattern performed by the robots. The black lines indicate the strokes played by ZRob 1 and the purple lines indicate the strokes played by ZRob 2. Both robots play with the same tempo but with different meters, ZRob 1 plays a simple metre and ZRob 2 plays a compound rhythm.

7. CONCLUSION

In this paper, we introduced the new prototypes of our drumming robotic system ZRob, and described the new possibilities that a chaotic dynamical system can create for musical expression. In the future, we aim to empower the system by using machine learning algorithms to learn the dynamics and track the external rhythms for playing with others (humans and machines). We also aim to expand the control modes of the robots and designing other periodic trajectories can create new possibilities.

8. ACKNOWLEDGMENTS

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