The Design of AA-RO, an Abstract Robotic Object, and the Development of a Method to Create and Evaluate its Expressive Motion

Carlo ter Woord

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Thesis Supervision:

Edwin van der Heide & Rob Saunders

Abstract

In this study, we both designed and developed an abstract robotic object, and we have created a method to systematically explore and evaluate its potential for locomotion and gestures. The rectangular-shaped abstract robotic object named AA-RO contains three actuators, each with a custom gear mechanism, that allows various rotatory movements. The developed evaluation method uses three experimental approaches, each containing specific procedures using animation techniques to generate motion. We used personal observations to assess the resulting movements by their locomotive and gestural qualities. To structure and reflect upon these observations we have used qualitative mapping and visualizations techniques. Our results show that our method effectively develops rudimentary locomotive movements. The method seems to be less effective in realizing, and thereby revealing, recognizable gestures. It remains to be seen whether this is due to the used method or inherent to the robot's qualities. From an artistic perspective, the developed evaluation method could contribute to discovering the movement potential of an abstract robotic object containing linear or rotary actuators.

1. Introduction

This paper is written from the perspective of a designer/artist with the thoughts of better understanding his way of working with the medium of robotics. Why the interest in robotics as a medium? Why the interest in movement? How does one work with a robot as a medium? And how does one find novel ways of working with a robot?

The first encounters of working with robots as a medium were during the final years as a bachelor design student. There was the urge of creating something that could function on its own, something that did not require any direct input in being able to exist. With the ability to move lifelike and with its own autonomy. During this time, and in a process of tinkering, the interest in robotics developed. The experience of the interplay between artist and robot through its development process, creating the interplay between human and machine, is what initiated this research interest.

From an artistic perspective this medium offers something that can't be compared with other mediums, like Kac & Antunez Roca (1997) state, robots can be merged with different technologies, and therefore transcend the property as a category of objects scattered in the environment. In recent years the technology to develop robots has become more and more accessible and easier to use. Microcontrollers and computers have become smaller and more efficient and actuators have been made easier to control. With the introduction of consumer 3D printers, it became easier to develop a capable robot, making robotics a more accessible medium (Penny, 2016). For an artist working with robots these technologies are essential tools similar to sculptors using pliable materials to create form and painters using paint and brushes on canvas (Kac & Antunez Roca, 1997).

This research started with seeing the Heider & Simmel experiment (Heider & Simmel, 1944). What intrigued the most was that by animating purely simple abstract two-dimensional forms, communication arose through movement. Also, the vehicle thought experiments by Braitenberg (1984), in which he presents ideas of simple control mechanisms in movable objects that are able to present complex behavior sparked a curiosity.

This curiosity was the introduction to the study of abstract and non-humanoid robotics. Rather than striving for practical applications or human replication efforts, it investigates the underlying question of what robots are, what shape they can take and how such machines move and behave.

The main interest is the process of working with an abstract robot as a medium, developing its shape and generating movement by assessing this work methodology in a qualitative manner. This has led to the process of developing an abstract robot and raised the following research question:

> *Given a suitable abstract robot object, what methods allow us to systematically explore and evaluate the potential for expressive motion?*

To answer the research question, an abstract robot was developed, based on a geometric shape that is without anthropomorphic or zoo-morphic properties, named AA-RO (Abstract Autonomous – Robotic Object). We created a method to explore and assess its movement and gestural qualities. In this paper we discuss related work, the development process of AA-RO, present our method of work and our results followed by a discussion and conclusion.

2. Related work

We discuss relevant works on approaches towards abstract, non-anthropomorphic and zoomorphic robots and we compare methods for evaluating such robotic designs on their motion and behavior.

The Senster by Edward Ihnatowicz, is a large robotic sculpture made out of steel welded pipes that interacts with its audience by following them around through lively movement. Using microphones to detect sound and sensors to detect movement (Zivanovic , 2005). Another example is Petit Mal by Simon Penny, an abstract robotic artwork at human scale, that was built with the intention to be engaged with by humans and perceived as an intelligent being, with a physical appearance that had no anthropomorphic or zoomorphic characteristics. By means of sensory input the interaction between Petit Mal and viewer was described by Penny as 'a dance' (Penny, 2016).

When we look at these works, they all have been developed through an artistic vision wherein Ihnatowicz and Penny developed their robotic artifact from a certain desire for interaction, and movement. The Senster's shape was inspired by natural phenomenon, whereas the shape of Petit Mal was developed to have no direct anthropomorphic or zoomorphic characteristics but could still be perceived as intelligent. These works differ in their mobility and scale. Petit Mal can move itself by means of two motorized wheels, and is sized at human scale, the Senster maintains a fixed position whereby only the mechanical parts can move, without changing its orientation. What is interesting about these works is that the they are only able to communicate through their motion.

Another example is The Tiller Girls by Louis-Philippe Demers, a robotic performance consisting out of so called 'machine performers' based on a robot used to study gaits in AI research. Demers explores the behavior of these machine performers through their mechanical embodiment in a theatrical setting, without the use of computer modeling. Presenting autonomous machine behavior to be perceived by its audience (Demers, 2016). Demers states that using the word 'machine performer', rather than robot, is to have a non-anthropomorphic representation equivalent to an anthropomorphic one, allowing to look beyond just 'the machine' and also at the movement qualities and behavior it exhibits, mechanical or lifelike.

The Greeting Machine (Anderson-Bashan, et al., 2018) is an abstract robotic object, consisting of a large spherical shape and a small ball that performed two types of gestures regarding opening encounters. Using animation principles, they developed a total of eight 'approach' and 'avoid' gestures which were divided into a straight and an animated motion in which the small ball was either visible or not. These gestures were evaluated using an in person qualitive assessment. Their results indicated that their abstract robotic object is effective in opening encounters and that minimal short movements are already enough to induce a positive or negative response. They argue that using an abstract shaped robot enhances the focus towards movement characteristics.

The Tiller Girls and The Greeting Machine are both at a smaller scale compared to Petit Mal or the Senster. The Greeting Machine, like the Senster can't change its orientation where Petit Mal and The Tiller Girls are able to move more freely and displace themselves through physical space. The Greeting Machine looks neutral and does not show any direct visible mechanical components, which is precisely what the other works do. In the case of AA-RO we also strive for a neutral design without directly visible mechanical components.

While these works all may have a different appearance and mechanical quality, they have a strong common denominator. Due to their abstract appearance, they can only communicate through their movements. The design leads to the movement and therefore also emphasizes the movement qualities of the design due to that no direct recognizable anthropomorphic features are visible. This is also the goal of our abstract robotic object, AA-RO in which we solely rely on its movement by abstracting the form as much as possible.

From a mobility standpoint we want AA-RO to be able to displace itself freely through physical space. Modular robotics approaches offer such mobility. A modular robot consists of smaller individual robots that, when put together, can form a new whole. The individual parts often contain one actuator that allows one degree-of-freedom. When these parts are put together in a configuration it provides more degrees-of-freedom and new movement abilities. To make these new configurations possible, geometric primitives are often used as the main shape for the robot containing the actuator. These principles are best demonstrated in the works by (Liang, Qian, Luo, & Lam, 2020; Zykov, Chan, & Lipson , 2007; Spröwitz, Moeckel, Vespignani, Bonardi, & Ijspeert, 2014).

We are not particularly interested in the modular aspect itself, but how their mechanical structure offers movement by using primitive shapes. Our goal is not to peruse practical or technical applications as suggested in these works, we are interested in what this mechanical functionality has to offer when considering the potential for motion. Similarly, as previous works mentioned here, these modular designs use of primarily primitive, abstract shapes with non-anthropomorphic and zoo-morphic qualities.

Evaluating the movement of an abstract robotic object is a challenging task. This is because it is influenced by various factors such as the context in which this robot is placed and the spatial and physical influences that come into play.

A method that that is often used is Labanotation. It is used to capture and analyze human movement, used in dance but also robotics. The system contains symbols representing the direction, the duration, the dynamic quality and part of the body executing the movement. Bianchini et al. (2016) state that such a system is effective for general notation and movement descriptions regarding humans, but does not go beyond these aspects. Looking at non-anthropomorphic moving objects, Bianchini et al. propose a method to analyze and implement behavior. Using behavior rather than movement to describe not only the motion itself, but also the psychological aspects of movement like animacy and agency. To shape and implement movement, they suggest working with three orders of constraints. The first order looks at the possible movements that can be achieved given the mechanical construction of the robot. The second order looks at the physical and psychological constraints that influence the movement. The third connects to the behavioral aspects that an observer may project.

Levillain & Lepart (2019) developed a non-humanlike robot, containing of two small motors connected by a flexible rod. Using a simple qualitative assessment 20 participants rated six developed movement sequences that varied in speed and amplitude using oscillating patterns. To rank these sequences five motion descriptors were developed that would be most or least representative, such as: active, effort, regularity, discomfort and expressiveness. Their results indicated that movement containing low speed and high amplitude described as expressive, while it was not described as most active.

Another example of such an analysis is the work by Harris & Sharlin (2011) in which they developed 'The Stem' a 'formless' robot without utility, consisting of a wooden lath driven by three motors. They developed organic and mechanical movements with a duration of 45 seconds that were evaluated in two parts by participants on these two conditions. First, participants would observe and reflect on the robot's movement, in the second part they were asked to rate the motions based on movement descriptions using a Likert-scale and compared as histograms. Their results indicate that there is a relation between speed and direction of movement generating affective response when interacting with the robot.

Venture & Kulić (2019) give an overview of different evaluation methods that fit specific movements or morphologies of a robot. Their review proposes that to generate movement for robots without anthropomorphic or zoomorphic features hand-crafted animation offers a good solution. They state that currently the evaluation of movement, relies on observation, interpretation and qualitative assessment. The body of work regarding these methods and analysis is still emerging.

These works have in common that they all try to achieve a similar goal: propose useful descriptions to achieve insightful movement analysis. In addition, these works employ a form of visualization that attempts to provide visual insight in a qualitative manner. We believe such visualization is very useful and insightful in addition to observations as they could offer a new perspective. As these examples use different descriptions to describe 'movement', clear definitions should be given upfront to comprehend a proposed analysis.

3. Designing and developing an abstract autonomous robotic object: AA-RO

3.1 Finding the shape

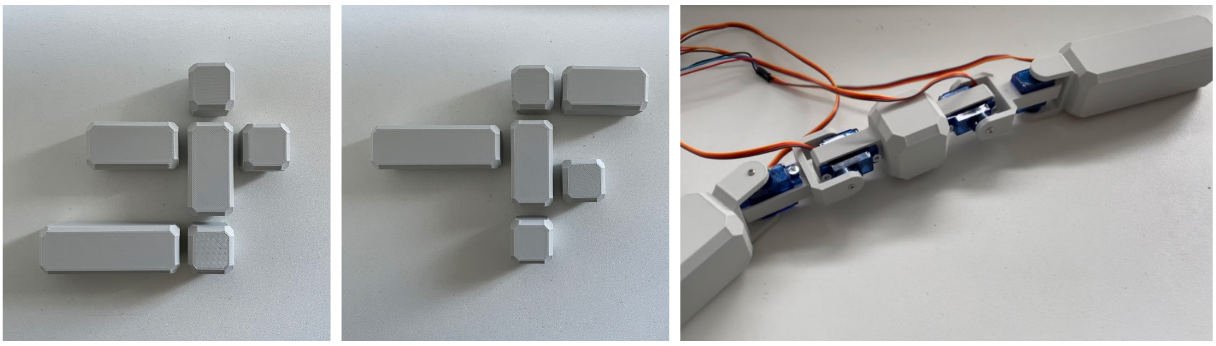

Figure 1. – Small 3D printed scale models and chain-like moving prototype

Taking inspiration from the works mentioned in our related works, and come to an interesting shape, we aimed to create an abstract robot that has a geometric shape by taking the cube as our starting point for AA-RO's shape. Initial explorations were small 3D printed scale models (Figure 1) in which we combined the shapes to see what configurations would be possible. Initially it felt like the right direction to work towards a chain-like shaped robot. During the exploration we felt that it still had too much of a 'recognizable' shape. There was a tendency to identify parts in a configuration as 'body' 'arms' or 'legs'. We wanted to avoid a shape that could be addressed as zoo-morphic or direct anthropomorphic features.

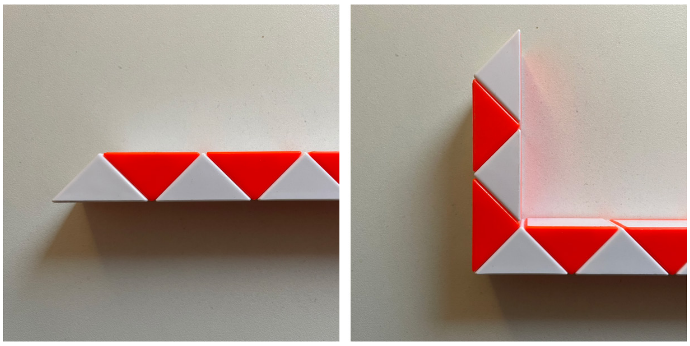

Figure 2. – 'Cube Snake'

We found our answer in a child's toy, a so-called 'Cube Snake', consisting of a series of triangle-like block shapes strained together (Figure 2). The shape allows various configurations in which each joint can be rotated around its axis to create a new shape. We applied this joint idea to our cube configuration that started to mitigate the anthropomorphic projections on the shape (Figure 3).

A small movable prototype was designed using 3D printed parts and small servos. The prototype itself showed a promising direction for the robot. However, we learned from this prototype that rotation, with this shape alone, would not be enough to generate motion to make the shape move. We decided that a flatter shape would work better, as it would offer

Figure 3. – 'Cube Snake' joint applied to scale model

less continuous surface contact when the shape rotated, while maintaining the rectangular character. A new prototype was built and tested, which resulted in the final shape for our robot, AA-RO (Figure 4). We have tried a different shape configuration during the development phase of AA-RO. Both the left triangular actuators were mirrored towards the right side. Due to it causing mechanical complications, we have placed AA-RO in its current configuration (Figure 4).

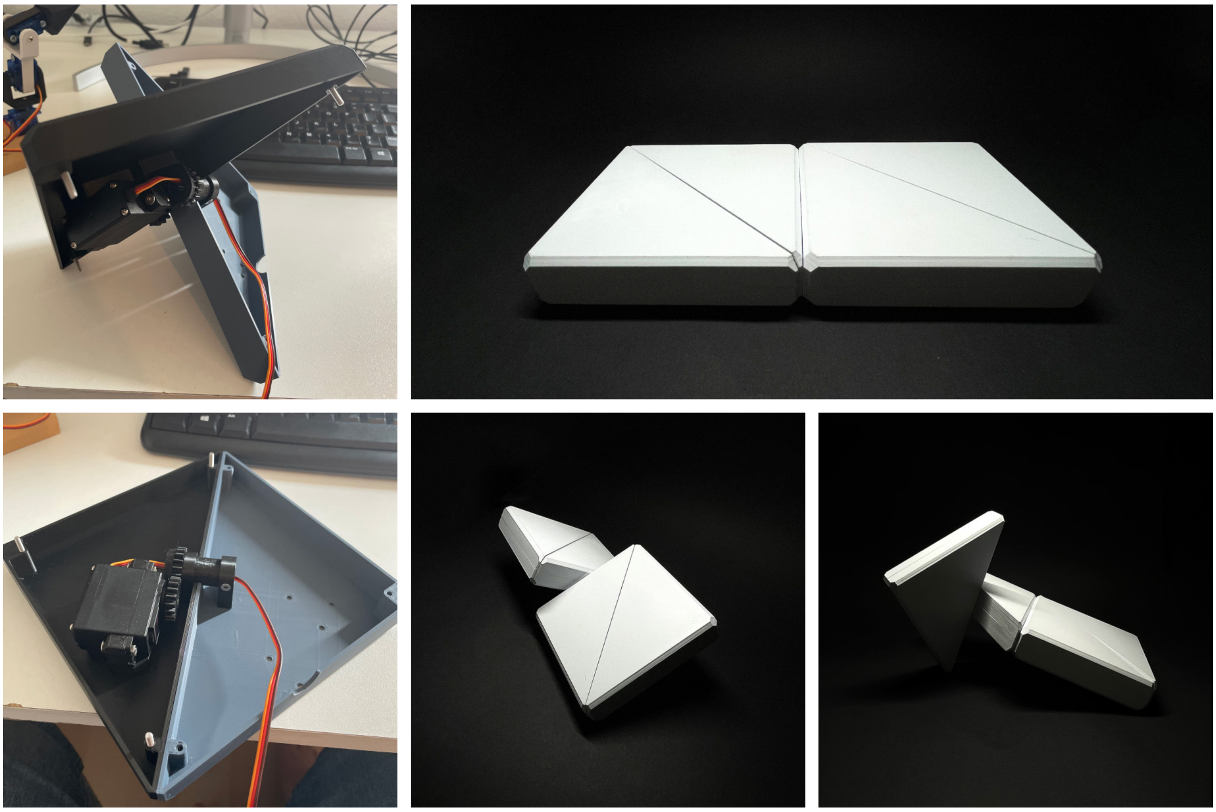

Figure 4. – Final prototype (left) and final robot shape (right).

3.2 Mechanical design

The body of AA-RO consists of eight covers and a custom 1-to-1 gearing system (Figure 5), 3D printed on a Prusa Mini+ in a neutrally colored PLA/PHA material by colorFabb. The robot contains three low-cost TD-8120MG metal-geared digital servos (PWM). A Raspberry Pi Zero W, as its onboard computer for the locomotion control connected to a PCA9685 servo controller over i2C. The hardware is powered by a two cell 18650 battery pack, each cell containing 3500 mAh delivering up to 10A at 3.7V. We convert the voltage to 5V logic using a custom level converter PCB, allowing us to run our configuration of hardware in a clean 5V output. The outer shells of AA-RO are used as a support frame to mount the hardware. Using the shells as support frames, because of the added mounting points, it allowed us to replace parts more convenient when necessary.

With our gearing system that allows the mechanical rotation of the robot (Figure 5), we created an effective way to route the cables through the gearing system itself. The cables can move freely without getting coiled up, which enabled us avoid the use of sliprings, as our rotation is limited and does not exceed ± 180 degrees. It kept the scale of the robot as compact as possible.

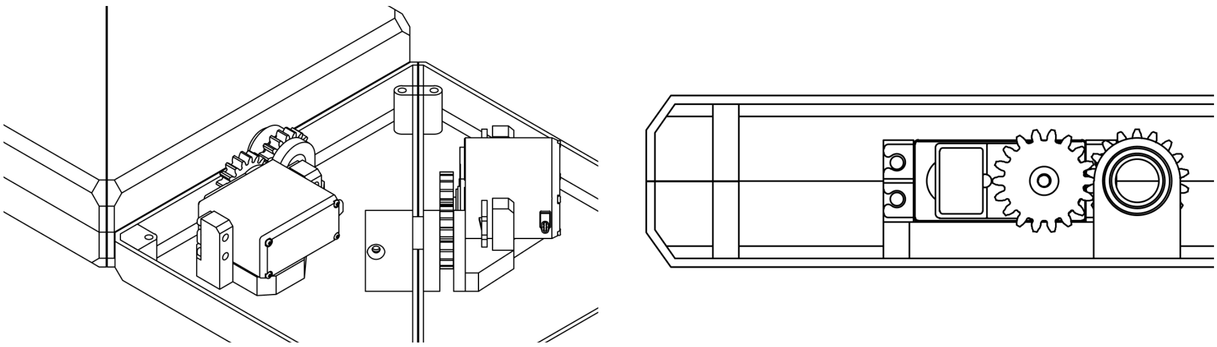

Figure 5. – Mechanical Design of Actuator

3.3 Controlling AA-RO

To work with abstract robots, in our case AA-RO, there are many strategies and ways to generate movement. From elaborate self-learning or evolutionary algorithms (Sims, 1994) using machine learning (Oudeyer, Kaplan, Hafner, & Whyte, 2005) principles, working with sensory-motor loops (Braitenberg, 1984; Brooks, 1991), or by using manual RC controllers.

In this case we have been working with a semi-automated controller, in which the input was provided by human interaction with the controller. Due to having an artistic background and familiarity with working various animation software, we developed our own custom animation software that allows working with AA-RO easier for non-programmers. Our developed controller is suitable for live performing and 'pre-recorded' animation reels.

To control AA-RO, we created a simple setup in which we make use of two computers. In which the main computer communicates over a shared network to the internal computer of the robot. We use a OSC server running on the robot to receive data from an OSC control interface. We developed an interactive MAX/MSP animation controller patch to work with the robot to generate and control its movement (Figure 6). The software consists of an animation timeline in seconds. We can draw in an animation using linear lines and curves to determine the motion. The OSC server converts the received data and sends it to the PCA9685 servo controller over i2C. Using both protocols allowed us a robust way to control the hardware but still can extend or replace the hardware if needed.

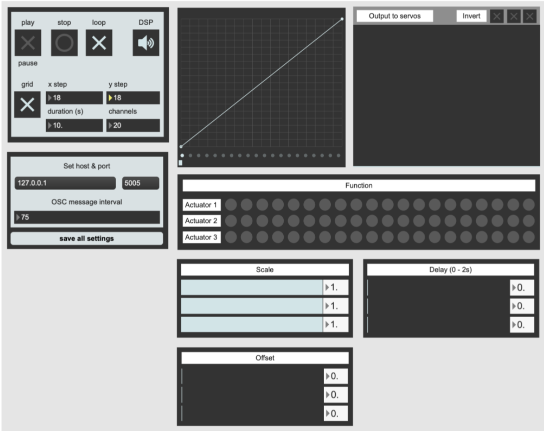

Figure 6. – Animation controller MAX/MSP patch (interface)

For the control interface, we took an animation approach similarly in work by Ribeiro & Paiva (2019). Taking inspiration from how animators work with traditional animation software and personal experiences with such workflows, we developed the interface in a similar way.

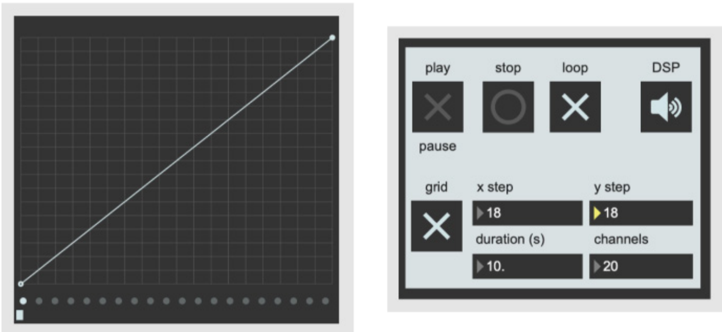

Figure 7. – Animation timeline (left) & Play, Stop, Loop & Grid (right)

We are using a scalable x and y plot for our animation timeline in which animation lines and curves can be drawn (Figure 7). The x-axis is translated into time in seconds, and the y-axis is translated into degrees of rotation that ranges from 0 to 180 degrees. The timeline can be changed by adjusting the grid step size and time in seconds. It is set to a 10-second timeline by default, with 18 degrees of rotation per second. The timeline consists of separate channels. In each channel, an individual animation can be drawn and stored. A default of 20 channels is set, each containing an individual timeline, but can be extended to any desired amount.

Each timeline can be played, paused and stopped at any given moment (Figure 7). In addition, a timeline can be looped indefinitely, until it is paused or stopped. To note here: pausing is different from stopping, when a timeline is paused and played again, it continues from the last position where it was paused. Stopping in this case resets the motion playback position back to the start of the timeline.

To route a particular timeline to an actuator or multiple actuators we have an array of buttons in which each row resembles an actuator, and each column resembles a timeline.

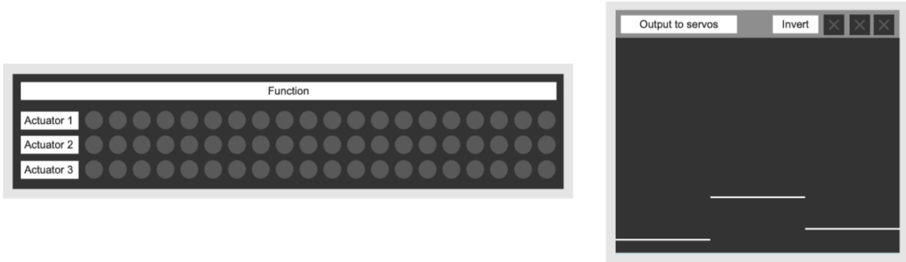

Figure 8. – Animation router for each actuator (left) & Actuator monitor (right)

We can easily route timelines to multiple or single actuators at once, that allows for an intuitive way of working (Figure 8). In addition, we have a monitor that shows the output of each actuator to see how the actuator executes the motion timeline it is been given. Finally, we added a feature to invert the animation's starting point to either the 0- or 180-degrees, making it easy to use the same developed motion but starting from the opposite direction (Figure 8).

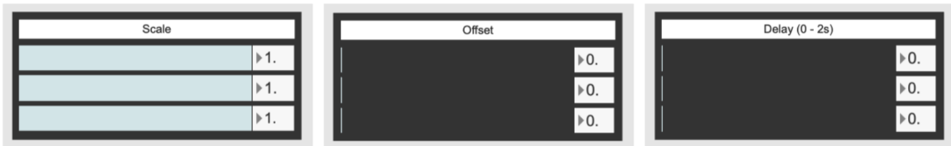

Figure 9. – Actuator parameters, scale, offset and delay (0-2 seconds)

Included are three parameters we can change for each actuator (Figure 9). First, we have the ability to delay the start of a motion between a range of 0 to 2 seconds. It allows to varying the execution rates and synchronous and asynchronous playback of movement. The second parameter allows for adjusting the range of the motion. The execution of the motion stays as drawn in the timeline, but can vary in the range of degrees. For example, instead of going to 0 to 180 degrees, having it to go from 0 to 35 degrees. Finally, we can add an offset to the starting position of an actuator. For instance, having an actuator start from 90 degrees instead of 0. To note here, it also limits the range of the animation. If an actuator is offset to 90 degrees upfront it is only able to reach the positions between 90 to 180 degrees.

The rate at which we send the OSC message data is set to a default interval of 75 milliseconds. However, it can be changed to any preferred interval, taking into account the clock speeds of the onboard computer. This rate also influences the rate of rotation, lower intervals result in smooth motion, where a higher interval creates a stutter motion.

4. Method & Results

We explore different approaches to achieve expressive movements for an abstract robot using our developed control interface. Each approach inherits a focus that is based on predefined limitations.

We need a meaningful way to group types of movements together to give our explorations structure. We take inspiration from our human fundamental ways of movement (Lubans, Morgan, Cliff, Barnett, & Okely, 2010), we name the following two main categories, Locomotion and Gestures. In order to have a clear understanding of what we mean by gesture or locomotion, we describe them like the following.

Locomotion includes movements that cause displacement in various ways through one or more actuators. It is distinguished by being moved from its starting position during or as a result of a movement. These movements will be more directly described as falling, standing up, turning, tumbling, rolling, forward, backward, to the left, to the right.

A gesture is a movement that conveys or emphasizes an idea or feeling through the body. Such a movement is distinguished by little or no physical displacement, by means of one or more actuators. It is also distinguished by the fact that it requires little movement to express something.

We describe gestures as a means of expression, as in this study we are not particularly interested in the psychological and social aspects. Describing the specific characteristics beforehand in recognizable terminology is much more difficult. Therefore, these characteristics and denominations would emerge while working with AA-RO rather than using a preconceived denomination structure. Using these two categories will help us to structure what we interpret and is helping us to understand AA-RO movements better.

Our methodology consists of smaller approaches used to generate expressive motion in AA-RO. Each approach inherits a specific focus by limiting our options in how we approach the generation of motion. It is essential to start from a rudimentary approach and evolve each approach based on what has been previously observed.

In addition to our categories, we add an additional structure to our explorations. We divide our explorations into two focus parts, single movements and repetitive movements. Under single movements we study an animation performed once, and with repetitive movements we study an animation performed repeatedly. We use this structure in each of our developed approaches wherein each contains an individual modification that can affect a movement. We work with the following modifications (Table 1).

Actuator range (0–±180 degrees)	Delay (0-2 seconds)	Duration of a repetitive movement (0-60 seconds)	Zero position (Starting position)

Table 1. – Adjustable features to modify movements

Due to the nature of these adjustable features, there is a chance of creating an unforeseen combinatorial explosion, meaning that by introducing such adjustment to an approach it can create a rapid growth of complexity that could result in endless possibilities. We are very much aware that AA-RO carries a plethora of possibilities and ways to generate motion that can be studied. We have made the decision to limit ourselves in what we can do with AA-RO, to keep the scale of our explorations manageable, we limit ourselves to only one modification for each predefined approach.

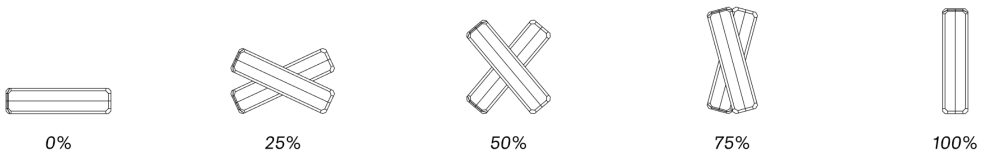

Figure 10. – Actuator position stages, expressed as percentages

In all our approaches we use percentages to express our actuator positions. In (Figure 10) you can see a visual representation of the position an actuator can reach. This is due to the nature of cheaper servo's, even after calibration they are not all able to reach its 180 degrees of rotation. To ensure we keep our test conditions for each explored animation the same, AA-RO will be reset to its base (center position) on its evaluation setting (Figure 11). If an animation requires a different base condition, we indicate this in the results section under the approach in which it is used.

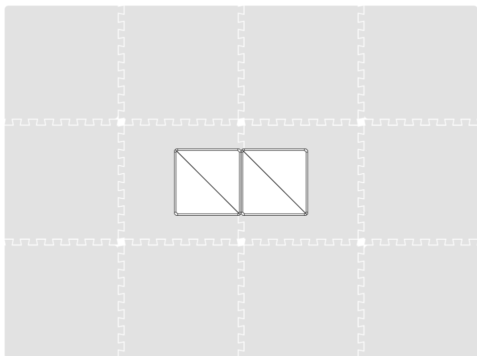

Figure 11. – AA-RO's base (center position) on its movement platform in the evaluation setting (top view).

We evaluate each exploration through systematic observations. During the execution of the experiments, we pay attention to the qualities of the movement and how it fits into one of the categories, compared to other movements.

Each approach is documented through video, these videos will be used in addition to the observations notes during execution for our analysis. To note here, the videos are without sound to focus only on movement on playback. In the following sections, we explain our approaches and present our findings.

4.1 Approach 1 – Less is more, a single actuator exploration

To understand the capabilities of AA-RO, we need a simple way to generate movements to find out what AA-RO does after an actuator moves. We want to work in a rudimentary way as we can only assume what AA-RO can do. Therefore, in this first approach, we only use each actuator individually without using them in combination or relation with each other.

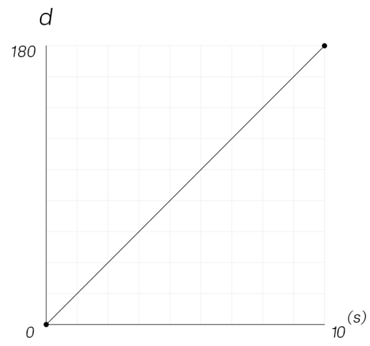

*Figure 12. – Linear animation, degrees of rotation are expressed as **d**, with a duration of 10 seconds*

First, we will generate movement by only using a linear animation without using curves or easing (Figure 12). The linear animation will be performed by each actuator individually will be put through the four position stages, 25%, 50%, 75% and 100% (Figure 10).

By limiting ourselves to a linear animation at the four position stages, we expect that the length of a particular animation, and the duration of a particular animation that is performed, will play a role in interpreting the movement. A single movement will take the time of a single animation of 10 seconds. A repetitive movement will take the time of a single animation of 10 seconds repeated for a duration of a maximum 60 seconds. If we do not see anything new happening during that time-frame we have the ability to stop earlier. After each animation is performed, AA-RO will be 'reset' and put back to its base position on its movement platform. In this approach, AA-RO's starting configuration is flat (Figure 13).

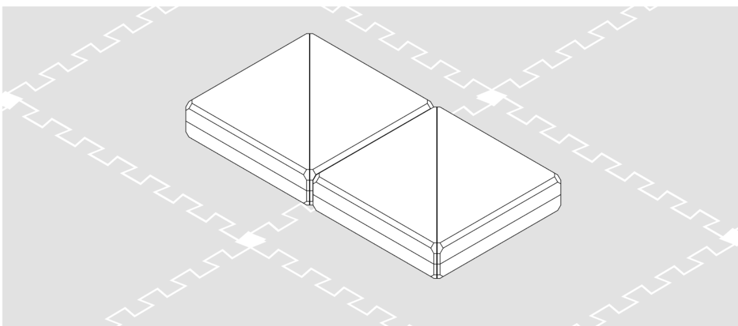

Figure 13. – AA-RO's starting position (Flat)

We expect in this case that AA-RO will present rotating movements, or motion that inherit qualities of displacement.

4.2 Approach 2 – Actuated pairs

Our first approach focuses on generating an understanding of AA-RO's capabilities by limiting the input for the robot. In our second approach we build on top of the first approach. However, instead of only using one actuator, we are now using all three actuators, which enables us to use the actuators in combination with each other to perform animations involving two actuators at a time.

To generate movement in this approach, we will be working with the same limited restrictions regarding the generation of animation, the linear animation at the four stages mentioned in the first approach (Figure 12). We can make the following pair configurations (Table 2).

Configuration	1	2	3
Actuator 1	X		X
Actuator 2	X	X	
Actuator 3		X	X

Table 2. – Possible configuration pairs, X indicates which actuator is active

We restrict ourselves to work with the same durations for both the single movements and repetitive movements. Here again, a single movement takes 10 seconds the same as the animation duration. And the repetitive movement takes the same animation duration of 10 seconds, repeated for a duration of 60 seconds. We still utilize the flat starting configuration as in our first approach (Figure 13).

We expect that using more than one actuator at a time will allow us to steer in a direction where we have possibly more control over the motion output. We believe that a rolling or thumbling motion could be achieved and present different types displacements that could be achieved with a single actuator. We are especially interested in only using a linear animation, like in our first approach, in which case we could possibly achieve more elaborate gestures or displacements, while keeping the animation input the same.

4.3 Approach 3 – Out of sync, adding a delay

In our third approach, we use the same linear animation as in the previous two approaches combined with the actuation pairs from the second approach with the addition of a delay.

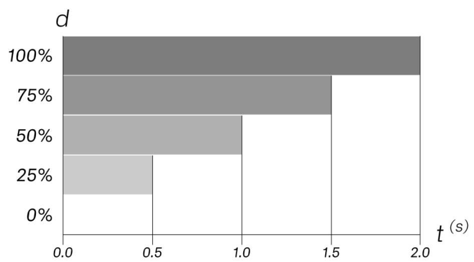

*Figure 14. – Delays, expressed as **d** in percentages, and **t** expressed time in seconds.*

With a delay, we can add time before the actual animation starts. Our delay has a maximum of 2 seconds. We use the same four stages principle and percentages to describe the amount of delay used (Figure 14). We will be using the same 10 and 60 second durations for single and repetitive movements with the addition of the delayed time. Here we also test every actuator at the four position stages. If we see a need for adjusting the base position of AA-RO, to allow more space to perform its motion more efficient, we make use of the following base positions (Figure 15). If such adjustments are made, we mention it in the results of this approach.

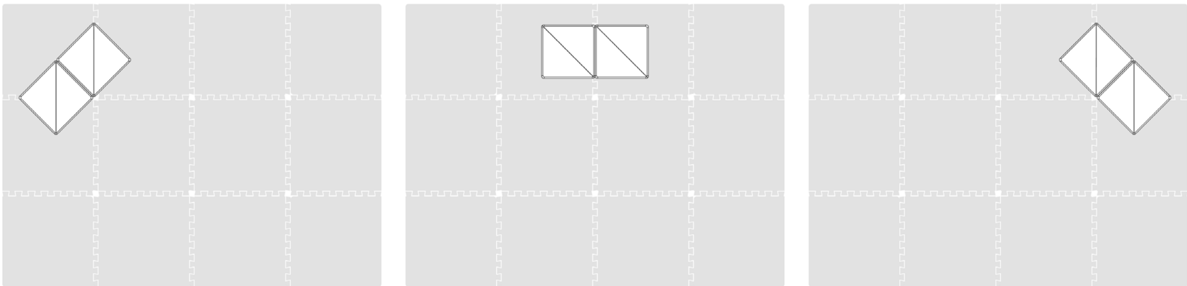

Figure 15. – Additional base positions

We want to understand the effect of the additional delay and what it does to the actuated pairs approach. As we believe the additional delay could create a secondary motion due to the momentum, that is being generated by the actuator, in the pair that is delayed. Wherein the weight, that is displaced within the robot, might result in a different motion quality that is controlled and only possible through physics.

4.4 Findings

There has been a total of 2,5 hours of recorded material of AA-RO moving. For each approach we made a selection of our findings based on how unique or common a motion is. How they compared based on its motion qualities to other movements and if there was a clear notion of a gesture or displacement. Each approach contains videos that present the results discussed in each section. In our analysis the material was analyzed without audio, to prevent any influence on our assessment. To make our findings more readable we will abbreviate actuators 1, 2 and 3 by A1, A2 and A3 (Figure 16). We have added a glossary (See Appendix) for terminology used to describe aspects in our results. In each section we first present our key findings by providing examples in video format.

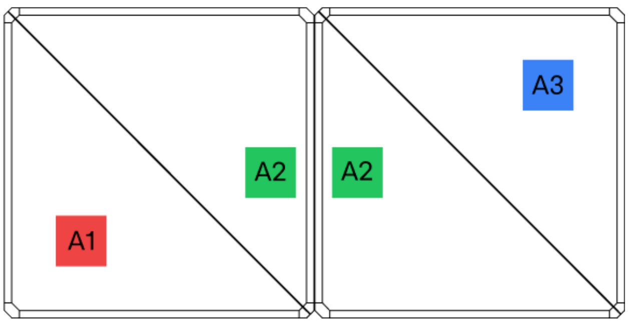

Figure 16. – Actuator positions AA-RO

By means of our observations, we developed a set of descriptors to more systematically describe the quality of a motion (Table 3). These are used to assess the quality of movement. They give an impression of what qualities are particularly present when it comes to gestures or locomotion and are visualized in the results section.

Landing (Drop)	Movement	Energy	Displacement	Control over motion
Hard	Fast	High	Restrained	In control
Soft	Slow	Low	Free	Helplessness

Table 3. – Motion quality descriptors.

We also introduce qualitive analysis maps of the results. They contain all movements observed and are mapped based on their movement category fit. We use these visualizations to communicate meaning rather than exact datapoints. This to provide a visual interpretation of our observations to better illustrate our results (Figure 17).

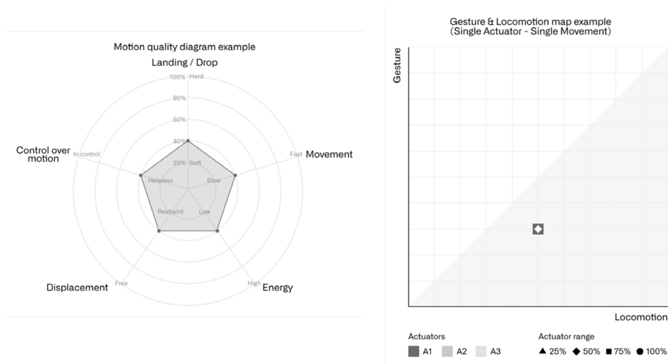

Figure 17. – Motion qualities diagram & Mapping example

4.4.1 Approach 1 – Less is more, a single actuator exploration

Our findings showed that AA-RO could not move without changing its orientation for single and repetitive movements in each actuator. We realized that it is fundamental to how AA-RO is designed. We noticed that many forms and types of movement already emerge by just applying a linear animation.

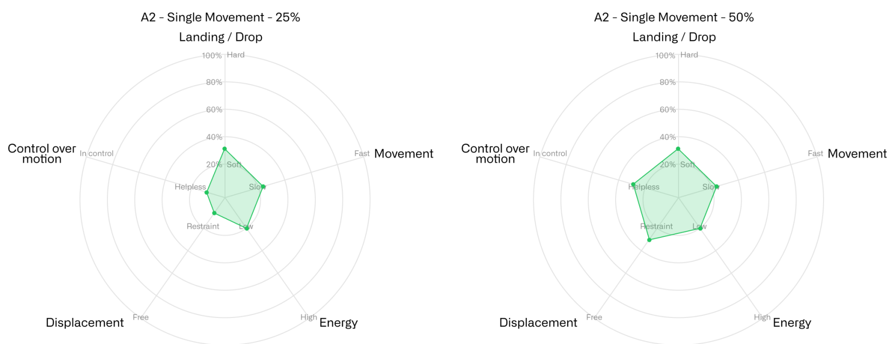

Figure 18. – Motion qualities A2 at 25% & 50% actuation range (Single Movement)

All tested actuators on single movement inherited many precursors that could lead to a gesture. It revealed potential gestures, in particular A2. For instance, it presents a motion that could become a ‘nodding’ gesture. This motion is present between the positions of 25% and 50% (Clip 1). In both positions there is a notion of a soft landing and relatively low energy in performing the motion (Figure 18). In our assessment, it would need more emphasis in its movement to become a recognizable gesture. We believe that by introducing an additional fast-retracting movement such a gesture could be achieved. We believe an animation, to generate a gesture, needs to be more designed.

We found that A1 and A3 inherit a more instrumental quality, as they mainly realize displacement, in the form of a dragging like motion. A1 can lift AA-RO more at an angle towards the left, A3 drags the non-moving parts across the ground (Clip 2 & Clip 3). Both inherit moderate amounts of energy and control over its motion, allowing to move comparatively free (Figure 19). The movements applied to A1 are mostly mirrored in A3, while A2 moves are unique compared to A1 & A3 in both single and repetitive movements.

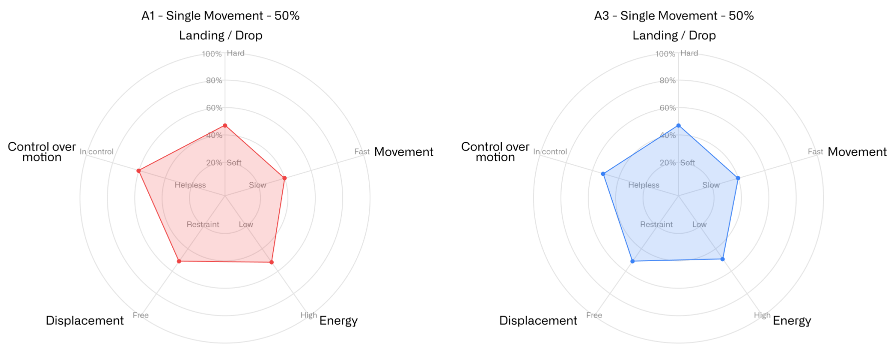

Figure 19. – Motion qualities A1 & A3 at 50% actuation range (Single Movement)

When we look at all three actuators in a higher actuation range noticeable variation in motion quality emerge. While they maintain their qualities seen at previous actuation stages the motion becomes more elaborate or presents something completely new.

A1 at its full actuation range (100%) (Figure 20), is able to produce a small hop forward in single and repetitive movements at the full actuation range (100%). First, it lifts itself upwards, making itself stand up. Then, when it returns to its zero-position, it lifts itself forwards, generating a small hop (Clip 4). AA-RO is able to move freely, in control of its motion and landing softly on its side.

A2 at its full actuation range (100%) (Figure 20), lifts itself upwards from its center in a single movement. After it almost reaches its entire range, it rests on its left side. When it resets itself to its zero-position, it pushes itself and falls forwards (Clip 5). Interesting to note here is that the motion quality stayed fairly consistent as seen earlier at 50% actuation range (Figure 18) but increased its harsher quality by dropping fairly hard on the ground.

A3 at its full actuation range (100%) (Figure 20), lifts itself forwards in a single movement. In a dragging motion it is able to move forwards. When it reaches its full range, it returns to its zero-position by lifting itself up in the opposite direction, when it reaches its tipping point it drops down (Clip 6). Here the scale of the motion quality has been increased but retains more of the features visible in a lower actuation range (50%).

Based on our expectations, AA-RO did present forms of displacement, like dragging itself towards the left and right direction. Again, both were somewhat expected given the configurations we tested. The slight hop forwards and putting itself on its side, as a result of secondary movement, presented in both single and repetitive movements, were unexpected.

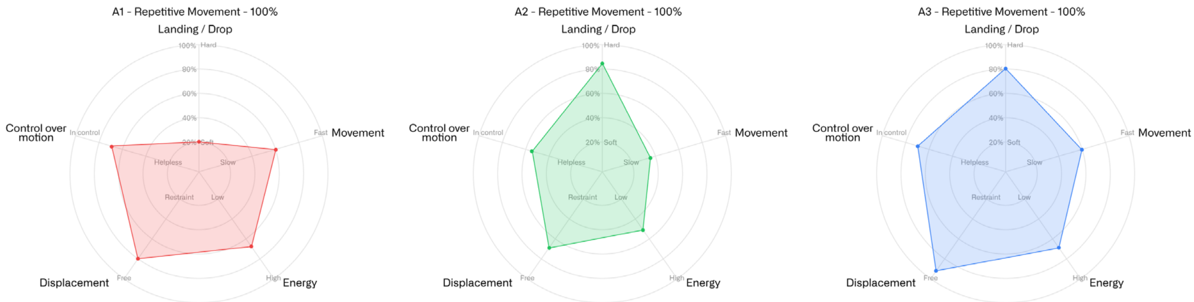

Figure 20. – Motion qualities A1, A2 & A3 at 100% actuation range (Single Movement)

Seeing all results side by side it is striking that especially in the 25% and 50% range qualities of a gesture are visible in single movements. This quality decreases when these movements are repeated. We see that in both single and repetitive movements the quality of a gesture is particularly visible in A2 compared to A1 & A3 with locomotive characteristics (Figure 21).

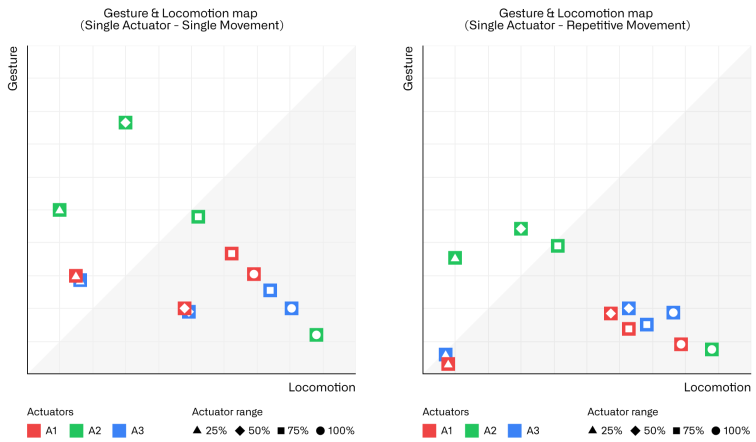

Figure 21. – Gesture & Locomotion map for single actuator in single and repetitive movement

We believe the two most important variables that caused these movements are the weight differences between actuators and how our software operates. A1 contains the hardware that delivers the power to the robot (Figure 22). The placement of the batteries in this situation may have provided the necessary weight, which, during movement, provides a balance that makes AA-RO easier to rest on its side, standing straight.

Our software does not consider the physical time it takes for the actuator to return to its zero position. The time of a repetition in software is probably not precisely synchronized with the actuator itself, which might have been of influence on the results.

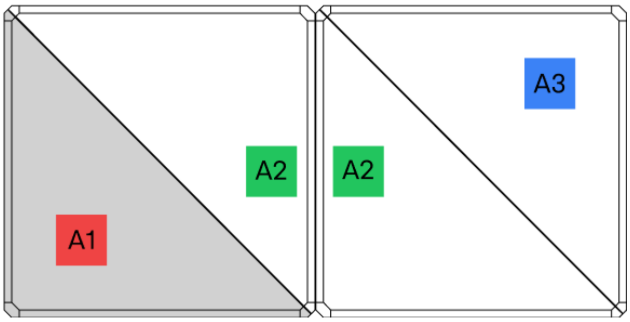

Figure 22. – Actuator containing the most weight (battery compartment)

4.4.2 Approach 2 – Actuated Pairs

Our initial expectations were met regarding the generation of more intricate movements causing displacement using only the same linear animation as our first approach. We did not observe any distinct gestures. We noticed that the actuator range at 25% does not add any significant displacement or noticeable gestures for both the single or repetitive movements (Figure 23). In repetitive movements we also start to see clustering to happen in locomotion-based movements.

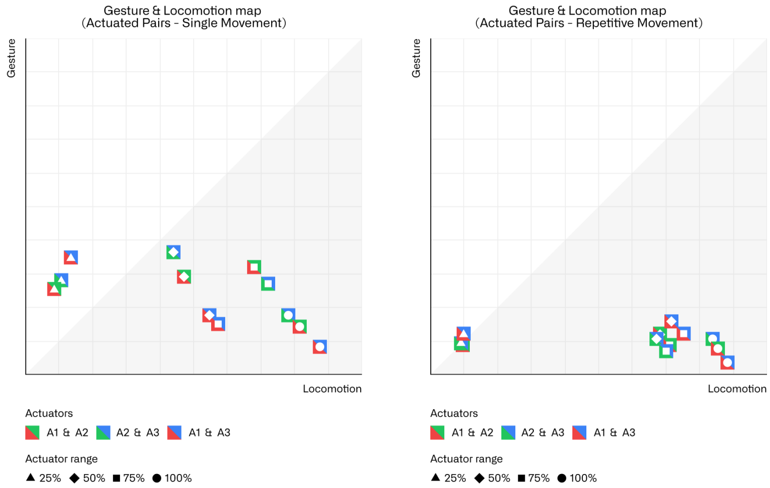

Figure 23 – Gesture & Locomotion map for actuated pairs in single and repetitive movement

As mentioned in the results of our first approach, the ability for AA-RO to put itself on its side is also present when actuators are paired. It mainly occurs at an actuation range of 100%, which in most examples involves A1. For instance, the small hop forwards are still present in A1 & A3 at 100% actuation range (Clip 7 & Clip 8). It lifts itself moves forward by using the inertia from the actuators resting to its zero-position, generating the hop while staying straight up on its side, tumbles forward and lifts itself again.

It is able to do this with some consistency as a repetitive movement, however, it sometimes gets stuck at a position where it only 'tries' to lift itself upward repeatedly. It loses some of its consistency resulting in a less controlled motion, resulting in less presence of displacement compared to a single movement (Figure 24).

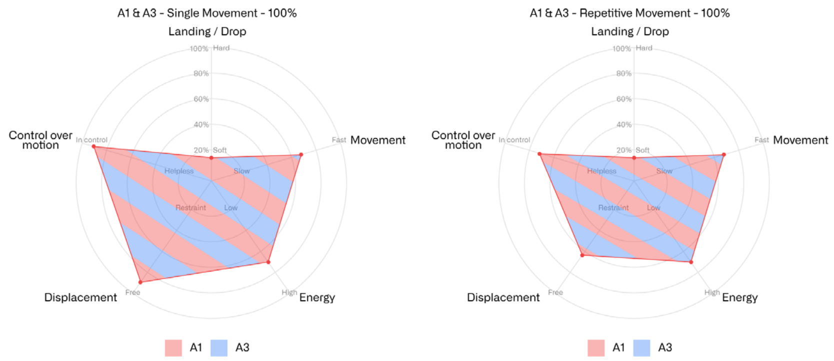

Figure 24. - Motion qualities A1 & A3 at 100% actuation range (Single & Repetive Movement)

As mentioned in the results of our first approach, the ability for AA-RO to put itself on its side is also present when actuators are paired. It mainly occurs at an actuation range of 100%, which in most examples involves A1. For instance, the small hop forwards are still present in A1 & A3 at 100% actuation range (Clip 7 & Clip 8). It lifts itself moves forward by using the inertia from the actuators resting to its zero-position, generating the hop while staying straight up on its side, tumbles forward and lifts itself again.

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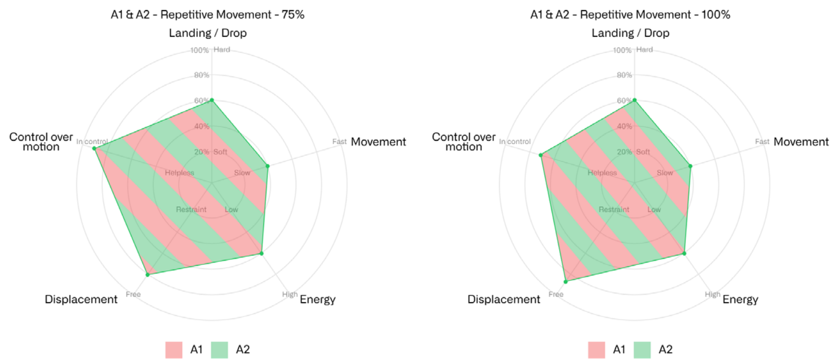

Figure 25. - Motion qualities A1 & A2 at 75% & 100% actuation range (Repetitive Movement)

We observed that this balance and imbalance added variation to how AA-RO performed its movement. For example, in A1 & A2 at an actuation range of 75% and 100% in a repetitive movement, one of the corners of the shell of A2 is being used as a pivot, creating a point of balance. In contrast, the other moving actuator then causes an imbalance to make it displace (Clip 7 & Clip 9). The motion quality is relatively slow and low in energy while its moving, due to this pivoting behavior, the motion feels in control while dropping frequently causing it to displace freely (Figure 25).

At 100%, A1 & A2 compromises control over the movement, which resulted in a complex displacement. Here again, A2 is being used as a pivot to move forwards, using it for balance. At the same time, while the actuator returns to zero-position, it can stand straight up, similarly seen as in the single actuator approach (Clip 4 & Clip 9). A1 & A2 were almost able to have AA-RO perform a full rolling like motion, then losing its balance, while performing, causing it to fall backwards.

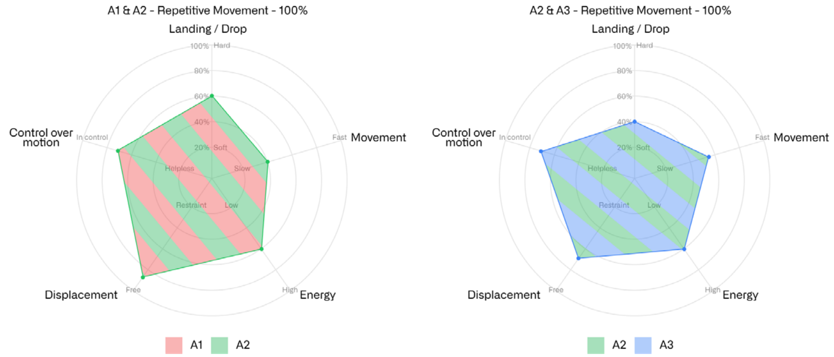

Figure 26. – Motion qualities A1 & A2 and A2 & A3 compared at 100% actuation range (Repettive Movement)

When we compared A1 & A2 to A2 & A3 at 100% it presented a different motion. While expecting a mirrored variant of A2 & A3, the character of the motion changed (Figure 26). A2 & A3 move upwards, almost standing, putting AA-RO on its side, then losing its balance and drops forwards, causing it to tumble back and forth when repeated. When both actuators are returning to their zero-positions, they can make AA-RO stand on its side. Something we have already witnessed in our single actuator explorations (Clip 10).

By introducing the additional actuator, new variations on movements were presented. Similarly, in our first approach, weight plays a role in how it alters the movement. As in some explorations, we expected AA-RO to move towards the right but moved towards the left. In repetitive movements, we saw that AA-RO could rotate in a quarter arc from its base position towards the left in pair A2 & A3 (Clip 11).

4.4.3 Approach 3 – Out of sync, adding a delay

Both individual actuators in a pair result in different movement outcome when a delay is applied. (Figure 27) is showing the slight differences in actuation range at each delay in single movement. In every increment of a delay the movements shift slightly towards the bottom right, indicating an increase of locomotion.

In most of our single movements, a delay at 25% resulted in the general direction of what motion quality AA-RO would present with increased delay time. Similar to our second approach, we see that at 25% actuation range there is no great increase in gesture quality for both single and repetitive movements (Figure 27 & Figure 30).

Regarding the actuated pairs we initially thought that actuators A1 & A2 could be directly mirrored to A2 & A3 and present similar motion in the opposite direction, based on what we had seen in our single movements with the delay ranges applied. However, in some instances in our repetitive movements, the character of the motion changed a lot.

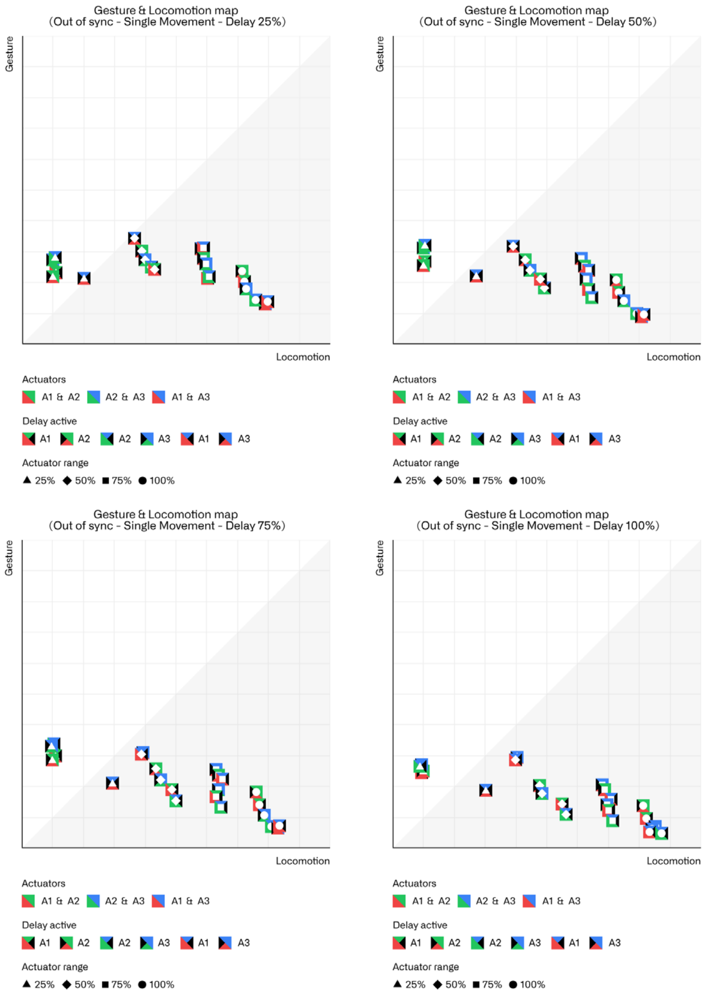

Figure 27. – Gesture & Locomotion map for actuated pairs with delay in single movement

A1 & A2, when the delay is put on A1 at 50%, move towards the left in almost a straight line using a two-step motion, lifting itself upwards and then dropping back down (Clip 12). The quality of motion, while being able to displace itself looks less in control. In contrast, A2 & A3 at 50% actuator range with a delay of 50% put on A3 results in AA-RO rotating in a quarter arc towards the upper left back of the platform (Clip 13). In contrast to A1 & A2 the motion appears freer and in control of how it moves and is perceived as more efficient (Figure 28).

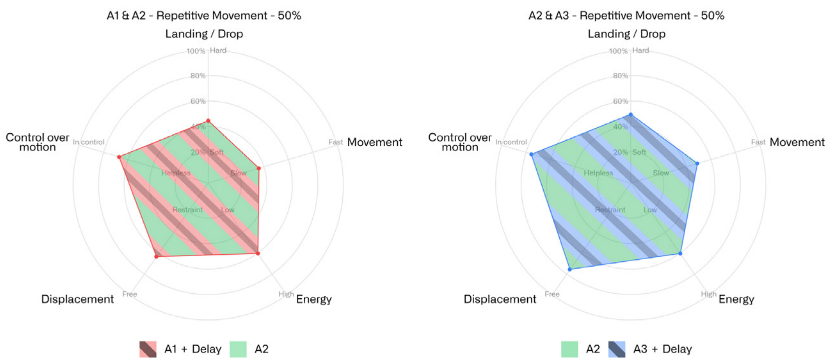

Figure 28. – Motion qualities A1 & A2 and A2 & A3 compared at 50% actuation range (Repetitive Movement)

Most movements at A2 & A3, when repeated at every delay and actuation range, resulted in rotating in an arc displacing itself towards the left. While A1 & A2 result in displacement towards the left in a straight line or at a slight arc, it can also move towards the front (Clip 14).

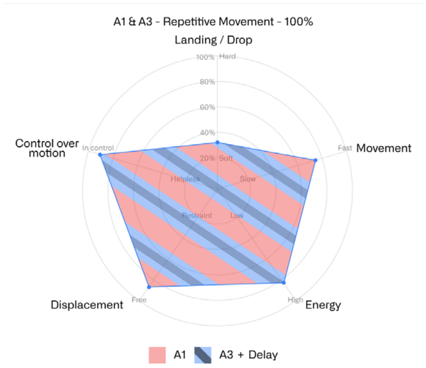

Figure 29. – Motion quality A1 & A3 at 100% actuation range (Repetitive Movement)

AA-RO did show unexpected motion when A1 & A3 at 100% with A3 at a delay of 25% actuation range presented a hop forward and transitioned in a forward rolling like motion where AA-RO lands on its side with its backside towards the front (Figure 29) (Clip 15). The movement seems fast and very controlled which increased the energy of the motion.

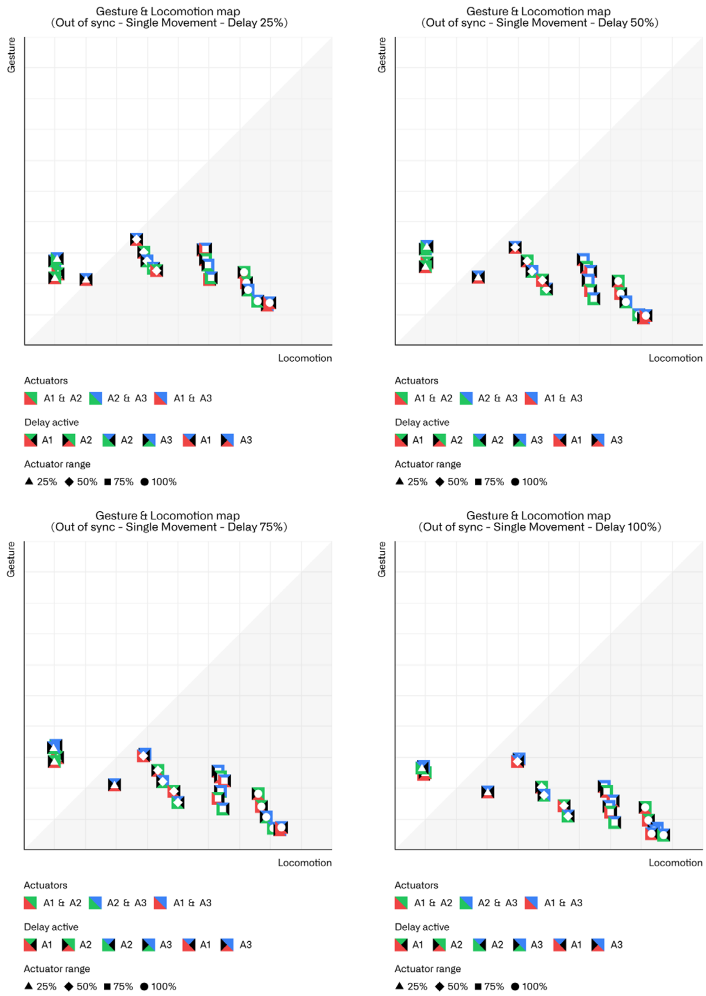

Figure 30. – Gesture & Locomotion map for actuated pairs with delay in repetitive movement

Adding a delay did increase the reading complexity of a motion. For example, at a longer delay of 75% and 100%, movements at an actuation range of 75% and 100% became very hard to read and evaluate, especially in the repetitive movements (Figure 30). In all these movements there was a high displacement present but they differed in their control over the motion.

The delay caused more variation between movements, causing a great increment in locomotive qualities in both single and repetitive movements. Long delays alter the behavior of the motion causing longer distances in displacement. We believe that a delay could help in developing recognizable gestures. When a short delay is applied, the motion does not change drastically but adds emphasis to the motion. Both are exciting aspects that could be explored further where the motion is more designed.

5. Results (Summary)

From our experiments we learned that AA-RO always changes its orientation while moving. Our tested approaches did not present recognizable gestures. Each approach contributed to the movement language of AA-RO. Each approach contained distinctive locomotion types: lifting, dragging, pushing, falling, tumbling, hopping and a rolling like motion. With these locomotive movements AA-RO can displace itself towards the left, right, front and back direction. Applying a single linear animation in single and repetitive movements to AA-RO, using one of our approaches, is able to produce complex motions.

In some of our experiments, the motion became rather complex and was harder to read. It mostly happened around the 75% & 100% range of an actuator in pair configuration. Delays with a duration above 50% contributed to this complication. AA-RO's weight distribution contributes to the animation performance, causing AA-RO to move mainly towards the left in our explorations. Our software influenced the animation execution in physical space. It does not consider the time for a servo to return to its zero position.

6. Discussion

Our findings suggest that our method offers an intriguing outcome to learn how an abstract robotic object can move. Especially when we do not know what to expect. It offered insights into how, in the case of AA-RO, it is able to displace itself in various ways. Unfortunately, our approach teaches us less about how AA-RO might express itself through gestures.

Our work has been systematically analyzed through observations and qualitative mapping, providing us with relational connections between movements. It allowed us to clarify how a movement could be qualified in one of our movement categories. Instead of explicitly judging a movement by solely locomotive or gestural qualities alone, it provided us insight into what qualities a movement possessed in itself. Gestural qualities appeared to be present in repetitive movements, movements with more than one actuator, or movements where a delay was applied. In this case much depends on the context of seeing a moving robot. The visualization techniques we used are suitable for assessing movement qualities at a general level.

We are aware that our method of analysis has its limitations. For example, when assessing the locomotive qualities, it would have been useful to determine the exact positions of the actuators to see if there was a pattern to the exact position information, which could be used to force movements. Our current actuators did not have this functionality and were not of the highest quality, which may have affected the results since not all actuators could achieve the full mechanical rotation of 180 degrees after calibration.

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Concerning assessing gestures, qualitative analysis through mapping alone is not sufficient. Mapping can help learn how to describe a gesture, but participants will be needed to come to such conclusions as to judge a gesture as recognizable. It would then also move the study in a social direction, which was not the intention of this study.

More emphasis must be given to the movement to achieve a gesture. A linear animation alone could not achieve this. Therefore, a new approach must be developed to design animations that lead to gestural movements. In a follow-up study, one could look at how we could apply our findings regarding our movement generation approaches, with adjustments in a new approach.

While both our method and the robot influence each other, it remains challenging to pinpoint whether it is due to the shape of AA-RO or the method used that has resulted in few gestures. In the current design the orientation of AA-RO is changing with every movement, causing stationary movements, in which the robot maintains its position and the same orientation, impossible to achieve. In the development of AA-RO we did not realize this, it only came to our attention during the execution of our experiments. Our current method only uses linear animation to generate movement. The adjust-ments in our approaches did not change the linear animation, it only changed the execution of the movement, so we do not know whether a designed animation could have changed this.

Our current assumption is that it is more the method than the form that is the problem, since we still believe that the design of AA-RO can exhibit gestures. Various strategies will have to be developed and tested to provide a more accurate understanding of this question. We propose to further develop the method, based on our current study's selection of movements, which contained the most gestural qualities. One could then focus on generating gestures containing an emotional character like: joy, surprise, confusion or fear. Participants would then evaluate how they perceived such gestures and rate them on their motion qualities. Similar to the approach in work by (Anderson-Bashan, et al., 2018).

In the scope of the current study, we have made limited use of the functionalities of our software. Our software is sophisticated and has extensive animation functionalities. Therefore, classical animation techniques such as easing (slow-in and slow-out), arcs, peaks and valleys can be applied in our suggested approach (Johnston & Thomas, 1995). From an artistic perspective, the method provides a sound basis for fundamentally generating movements that could be used in movement compositions. Here the robot becomes more of a performer than a moving object. Our software is capable of being used as an instrument for live performance.

Evaluating our robot has brought various insights into how movement works regarding this specific shape using linear animation. Our abstract robotic shape allows for rich movements to be achieved by doing very little regarding the generation of movement. One of the essential aspects of working with AA-RO in physical space are the unexpected moments. Revealing aspects which one could not have anticipated beforehand. Only by working with the robot one can anticipate on its peculiarities to achieve new forms of motion.

The current shape of AA-RO remains interesting to work with. The simple shapes in the design already allow for many forms of movement. The design could be even more interesting if we are able to change the configuration through different rotation positions without changing it mechanically. Our work has given us insight in the potential of working with abstract geometric shapes for a robot design. It removes any familiarity and possible expectations of a robotic form and its possibilities concerning movement. Regarding movement for a new robot, we envision a beam-like shape with similar mechanical properties like AA-RO, to be compared to our current design.

7. Conclusion

In this study we developed an abstract robotic object called AA-RO, for which we created a method of work containing three simple approaches that allowed us to systematically explore and evaluate the potential for expressive motion in our robot. Our results indicate that AA-RO possesses many movement qualities regarding locomotion. It shows indicators of possible presences of gestures. The current method did not present the emergence of clearly recognizable gestures in AA-RO we previously expected. We believe that such gestures can be more easily achieved by using more elaborate and designed animations. We have seen that by only applying a simple linear animation in either a single or repetitive movement, rich types of locomotion already emerge. From an artistic perspective, we see opportunities to further explore this way of working, where our approach of movement development can be applied to AA-RO as a performer through movement compositions.

8. Future work

From a practical perspective, we would develop the mechanical design of the robot to be stronger and replace the internal mechanical plastic parts with more durable material, like PETG, Carbon fiber or Acetal/Delrin, as there was more maintenance during the study than initially expected. CNC machining techniques could result in even more durable parts, instead of 3D printing. In addition, we would implement different servos that allow for 270 or 360 degrees of rotation in both directions. Creating possibilities to rotate the actuators in which AA-RO can be explored in different configurations.

In the scope of this study, we decided not to focus on social interactions with AA-RO and using participants for external evaluation. We believe this could be an exciting area of research. At the time of writing, there appeared to be a knowledge gap in regard to studies that use non-anthropomorphic and non-zoomorphic robots (Venture & Kulić, 2019). We propose similar methods for motion generation focusing on emotional qualities. From a movement generation perspective, it would be interesting to see what types of computational models could generate motion for AA-RO. For example, using an evolu-tionary algorithm that aims to develop various characters for AA-RO using goaloriented movements like crawling.

In future work it would be interesting to develop strategies that allow for a more designed approach towards generating movement. Our study limited itself to using a single linear animation. We think that using this study as a starting point could offer novel ways of generating expressive motion that could lead to more gesture or robot character-based explorations, something we were not able to achieve in this study due to time limitations.

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Appendix

Glossary

Method

Well-considered way of acting to achieve a certain goal, used as an umbrella term containing all used approaches.

Approach

A set of procedures to execute to generate motion.

Actuator

A device that can set something in motion.

Dragging

A motion in which non-moving parts are carried towards a particular direction.

Displacement

Moving through space in any particular way from its starting position.

Delay

A momentary pause before something starts moving, in our case between 0 and 2 seconds.

Easing

Making something move more gradually or carefully.

Slow In & Slow Out

An animation term in which movement starts slowly, accelerates and stops slowly. A tool that can be used to generate more natural, non-constant, motion.

Falling

A motion in which gravity makes it fall in a particular direction without the robot catching itself.

Gesture

A motion that indicates or expresses an idea or attitude used as a form of non-verbal communication.

Hopping

A motion that is a small or tiny jump in a particular direction.

Inversion

Reversing the previously used order.

Lifting

A motion which carries non-moving parts upwards at a constant rate.

Locomotion
A type of displacement.

Movement
The act of moving.

Motion
The process of moving in a particular way.

Pivot
A central point on the robot turns.

Range
The reach that a motor has between two positions, in our case between 0 and ±170 degrees.

Rolling
A motion that inherits a repetition of tumbling in a particular direction.

Servo
A small motor that can be controlled using pulse-width-modulation using digital signals.

Speed
How fast the robot is moving, a rate at which it covers distance.

Slack
The sagging or loosening of a moving part caused by stress on the part.

Tumbling
A motion that the robot catches itself upon almost falling in a particular direction.

Videos

Approach 1 – Less is more, a single actuator exploration

Clip 1: https://www.youtube.com/watch?v=4W9m_COd0Lw

Clip 2: https://www.youtube.com/watch?v=oSJyKbU3gbM

Clip 3: https://www.youtube.com/watch?v=MCj8-hTf678

Clip 4: https://www.youtube.com/watch?v=PEUDv-YFzZU

Clip 5: https://www.youtube.com/watch?v=qYmjQSg_9qQ

Clip 6: https://www.youtube.com/watch?v=3bez23W9oSY

Approach 2 – Actuated pairs

Clip 7: https://www.youtube.com/watch?v=sUm9taMo6KM

Clip 8: https://www.youtube.com/watch?v=PPPMCdgo1h8

Clip 9: https://www.youtube.com/watch?v=tHNSzjwD9Io

Clip 10: https://www.youtube.com/watch?v=H_C24WbzAYc

Clip 11: https://www.youtube.com/watch?v=6KXc46eiHqo

Approach 3 – Out of sync, adding a delay

Clip 12: https://www.youtube.com/watch?v=TAodJK-wSz8

Clip 13: https://www.youtube.com/watch?v=dtITw4bdre0

Clip 14: https://www.youtube.com/watch?v=ZWmP16sUpNk

Clip 15: https://www.youtube.com/watch?v=zSLarp9eXGg