The Symbaline - An Active Wine Glass Instrument with a Liquid Sloshing Vibrato Mechanism

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ABSTRACT

The Symbaline is an active instrument comprised of several partly-filled wine glasses excited by electromagnetic coils. This work describes an electromechanical system for incorporating frequency and amplitude modulation into the Symbaline's sound. A pendulum having a magnetic bob is suspended inside the liquid in the wine glass. The pendulum is put into oscillation by driving infra-sound signals through the coil. The pendulum's movement causes the liquid in the glass to slosh back and forth. Simultaneously, wine glass sounds are produced by driving audio-range signals through the coil, inducing vibrations in a small magnet attached to the glass's surface and exciting glass vibrations. As the glass vibrates, the sloshing liquid periodically changes the glass's resonance frequencies and dampens the glass, thus modulating both wine glass pitch and sound intensity.

Author Keywords

Augmented, Electromechanical, Water, Wine glass, Modulation

CCS Concepts

•**Hardware** → **Sound-based input / output;** *Electromechanical devices;* •**Applied computing** → *Sound and music computing;*

1. INTRODUCTION

Modulation effects are frequently used in both instrumental and vocal music. Modulation can affect a tone's pitch, amplitude, or both. Modulation production vary per instrument. In some instruments modulation effects may require external accessories or specific implementations such as an electric guitar's tremolo bar (*Whammy bar*) or involve large mechanical movements, such as Leslie speakers. While the terms *vibrato* and *tremolo* are used do describe different modulation types [20], the precise definitions may vary between disciplines. Therefore, this paper uses the explicit terms *frequency modulation* and *amplitude modulation*.

The Symbaline is an active wine glass instrument consisting of a set of partly-filled wine glasses actuated by an electromagnet. The Symbaline is played using an auxiliary musical instrument as an interface [2]. An overview of the Symbaline is given in Section 2.1. This paper presents the development of a modulation mechanism for the Symbaline based on existing studies of liquid sloshing in cylindrical cups, as discussed in Section 3. Figure 1 shows a block diagram of the mechanism. The mechanism consists of a pendulum with a magnetic bob submerged inside the water in a partly-filled wine glass. A low frequency signal ($\sim 3Hz$) is sent to the Symbaline's electromagnetic coil, placed in front of the pendulum, outside the glass. The induced magnetic field causes the pendulum to oscillate. The pendulum's movement creates a sloshing movement in the liquid. An audio-range signal in the glass's pitch is sent to the same coil, causing the wine glass itself to produce sounds via a small magnet attached to the glass's surface. The sloshing liquid both changes the glass resonance frequencies and dampens the glass vibrations, thus creating a modulation effect of both pitch and amplitude. Figure 2 shows the mechanism in mid-slosh position.

Sections 2-4 provide an overview of related works, modulation methods in musical instruments and liquid sloshing. The modulation mechanism is described in Section 5. Section 6 describes a characterization experiment of the modulation mechanism, where the glass was excited by input signals of different musical instruments, while being modulated by the mechanism. The complementary results are shown in Section 7.

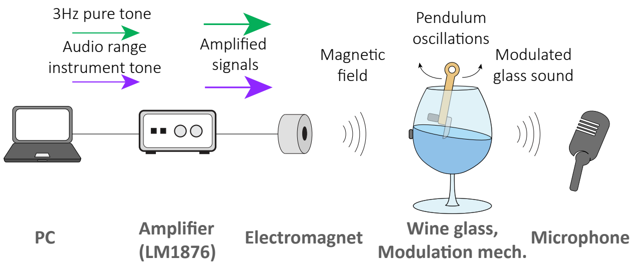

Figure 1: Block diagram of the modulation mechanism and experiment rig. The PC generates a low-frequency pure tone to activate the modulation mechanism and an audio-range tone sampled from a musical instrument to induce glass vibrations. Both signals are amplified and routed to the electromagnet. The electromagnet generates a magnetic field. The audio range field excites wine glass vibrations and the low frequency field puts the pendulum into oscillations, causing water sloshing. Wine glass sounds modulated by sloshing are captured by the microphone.

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Figure 2: The modulation mechanism in mid oscillation. The pendulum is excited by the electromagnet, placed left of the glass. The water is sloshing to the right, lowering the wine glass's pitch.

Figure 3: The Symbaline, tuned to a full octave, showing the wine glasses and electromagnets. The Symbaline is played by an amplified external musical instrument (not shown).

2. RELATED WORK

2.1 The Symbaline

The Symbaline, shown in Figure 3, [2] is an active instrument consisting of a set of partly-filled wine glasses. Each wine glass is actuated by an electromagnet, exciting a small magnet attached to the glass's surface. The electromagnetic actuation method is inspired by earlier augmented instruments such as the Magnetic Resonator Piano [10], the Electromagnetically Sustained Rhodes Piano [21] and the EMvibe [4]. These instruments use electromagnets to excite and augment sounds produced by strings, tines and bars.

The Symbaline is played by using an auxiliary musical instrument as an interface. This instrument, such as a classical guitar or a MIDI keyboard, produces an analog signal. The signal is sampled by an audio interface and processed with various audio effects and filters on a PC. The processed signal is then converted back to an analog signal, split, amplified, and sent to the electromagnets. The electromagnets generate magnetic fields which vibrate the magnets attached to the glasses, thus producing wine glass sounds.

The Symbaline's sound is created by two distinct sources: 1) The wine glasses' radiated sounds; 2) The input instrument's original sound, radiated by the input instrument itself or by an additional speaker. The glass sounds are characterized by the input signal's properties: decay and attack times, volume envelope and spectral content can all be modified to an extent by using different input signals, instruments and effects. The Symbaline is based on earlier prototypes which implement wine glass-string coupling by strictly mechanical means [1].

The previous Symbaline's implementation enables modulation by input signal processing. However, this implementation is limited in effect as input signals outside the glasses' resonance frequencies tend to produce dim and quiet sounds. In addition, modulation sometimes occurs due to arbitrarily occurring warble - an amplitude modulation effect caused by mild glass asymmetry. The asymmetry causes a frequency difference between the components of a mode doublet [19], adding a beating effect to the glass tone. Both modulation methods are limited in capabilities, raising the need for the modulation mechanism described in this work.

2.2 Musical Modulation Mechanisms

Modulation methods and mechanisms vary per instrument. In string instruments, the vibrating string's length is periodically changed by a rocking motion of the string-stopping finger. In wind instruments and singing, modulation is produced by periodically changing the air flow, the mouth piece pressure or similar techniques [11].

Some electric guitars are equipped with a dedicated modulation mechanism; a non-fixed bridge is rocked back and forth using a controlling lever to alter the vibrating string's length and tension [13]. The Floyd Rose bridge is a specific modulation mechanism for the electric guitar, capable of generating extreme pitch modulations [17]. A Leslie speaker is a device, originally intended to be used with the Hammond organ, in which the sound produced by a loudspeaker is directed through a rotating wooden drum or horn. The sound source's periodical movement away and towards the listener produces both amplitude and frequency modulation [14]. Similar principles of sound modulation by sound source rotations are found in the Corrugaphone (*Whirley tube*) [12] and the Bullroarer [16]. The vibraphone is a percussion instrument resembling a marimba with tubular resonators. The vibraphone is equipped with a unique mechanism: electrically rotating discs are placed at the top of the resonators, changing the bar-resonator coupling, thus creating amplitude modulation [5].

A simple method exists for wine glass modulation: *the tilt modulation method*. A partly filled wine glass is fixed in a tilted position, letting water extend to the lowered side. The glass is played by rubbing the rim in circular motions. As the nodes and anti-nodes revolve around the glass, the contribution of the 'higher' water level at one side of the glass fluctuates, resulting in frequency modulation [15]. As the Symbaline's wine glass excitation points are fixed, this method is inapplicable.

2.3 Liquids in Musical Instruments

Musical instruments utilize the flowing and wobbling properties of liquids in various manners. The waterphone consists of an enclosed steel bowl with protruding rods. Water wobbling inside the bowl create a mostly arbitrary change of resonance frequencies, modulating the sounds produced by the bowed rods or struck bowl [22]. The hydraulophones are a family of instrument, all consisting of water jets spouting out of a series of holes in a large pipe. The player blocks the holes, redirecting the jets towards sound producing mechanisms such as perforated disks or shafts [7]. The ancient Chinese instrument Yu xi (*Spouting bowl* or *Resonance bowl*) consists of a large metal bowl filled with water. When friction is properly applied to the handles, the bowl produces sounds accompanied by visible water spouts [18]. The Mocean is an installation in which water movements in a tank control organ pipe's sound production by image processing. The variable water pressure and movements create varied frequency and amplitude envelopes [8]. The WaterTouch is a water based interface capturing acoustic waves at frequencies outside the human hearing range formed in a water tank. The frequencies are shifted and acoustically radiated, producing audible sounds and music [6].

3. SLOSHING IN A CYLINDRICAL CUP

Sloshing is the movement of liquids inside containers such as tanks, pools and drinking glasses. While sloshing is often studied in the context of large-scale containers such as fuel tanks, Mayer and Krechetnikov [9] suggest an analytic model for the sloshing frequencies in cylindrical coffee cups:

$$\omega_{mn}^2 = \frac{g\epsilon_{mn}}{R}\tanh\left(\epsilon_{mn}\frac{H}{R}\right) \tag{1}$$

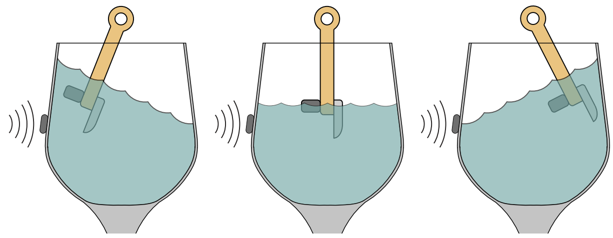
where H is the liquid's height, R is the cup's radius and g is the gravity acceleration. Here ϵ_{mn} is the nth root of the first derivative of the mth-order Bessel function of the first kind. For a typical cup, $R = 3.5cm$ and $H = 10cm$, the lowest sloshing frequency is $3.65Hz$.

As wine glasses differ from cylindrical cups by having curved bottom and walls, they are expected to demonstrate slightly different sloshing frequencies. Section 6.1 describes an experiment measuring wine glass sloshing frequencies.

4. WINE GLASS TONE MODULATION

Adding liquid to a wine glass has two distinct effects on the tone. First, the glass's resonance frequency is lowered due to the increased vibrating mass. Second, the liquid dampens the glass, decreasing the sound intensity. As the most dominant wine glass normal modes are characterized by larger displacement amplitudes near the top, both effects are more pronounced with higher initial liquid levels. Sloshing liquids in a wine glass can therefore be used to modulate the tone's pitch and intensity in a periodic fashion. The lowest resonant sloshing frequency involves the largest liquid displacement amplitudes. Therefore, it is the frequency used for sound modulation by the mechanism described here.

Figure 4 shows liquid sloshing in a wine glass with a period T at different time points. The glass's electromagnetic excitation point is shown to the left. At $t = 0$ (Figure 4a), a large liquid mass is raised near the excitation point. The raised liquid mass joins the glass's vibration, resulting in a lowered pitch and decreased sound intensity relative to the rest position. At $t = T/4$ (Figure 4b) the liquid is lowered to a horizontal position. As the glass's vibrations are smaller at the bottom, the liquid vibrations decrease, resulting in a raised pitch and increased sound intensity relative to $t = 0$. Time point $t = T/2$ (Figure 4c) is similar to point $t = 0$,



(a) $t = 0$. (b) $t = T/4$. (c) $t = T/2$.

Figure 4: Stages of sloshing. (a) The water is raised on the left side, near the excitation point, contributing to both pitch and sound intensity decrease. (b) The water is horizontal. In this stage both pitch and sound intensity are maximal. (c) The water is raised on the right side away from the excitation point. Much like at $t = 0$, both pitch and sound intensity decrease, resulting in a modulation period of $T/2$.

as the vibrating liquid mass is equally increased, causing lowered pitch and damping. Since time points $t = 0$ and $t = T/2$ are acoustically similar, sloshing at frequency f is expected to generate frequency and amplitude modulations at $2f$. Additional modulation components may be found in other frequencies, as described in Section 7.

5. LIQUID MODULATION MECHANISM

5.1 Pendulum

The modulation mechanism consists of a pendulum having a magnetic bob submerged inside the water in a partly-filled wine glass. The water has a resonant sloshing frequency of $\sim 3Hz$. The pendulum is activated by an electromagnet placed outside the glass. A low frequency pure tone signal at $\sim 3Hz$ is sent to the electromagnet. The pendulum responds in oscillations at the same frequency, generating a corresponding high amplitude liquid sloshing.

The pendulum, $60mm$ long, is made of 3D printed PLA plastic. A piece of sheet metal with a larger surface area acts like the blade of an oar: it is attached at the bottom of the pendulum, and is responsible for moving the liquid. A weak magnetic field, generated by the permanent magnets in the configuration, is present inside the glass. The pendulum's initial position in the glass is therefore near equilibrium. Figure 5 shows the pendulum suspended from its mounting rig with the magnetic bob and blade.

5.2 Signal Generation

The Symbaline's electromagnetic coils were previously developed for the sole purpose of wine glass sound excitation. Our novel modulation mechanism uses the original coils for simplicity. Each coil consists of 250 turns of 28AWG ($0.3mm$ diameter) magnetic wire around a ferrite core. A Neodymium magnet is attached at the back of the coil to increase the magnetic flux. The coil is driven by amplified $3 - 3.5Hz$ pure tones generated by a PC.

A standard audio amplifier circuit based on a LM1876 (20 Watt) integrated circuit was used for driving the coil. Signals for both pendulum and wine glass sound excitation were amplified. Like many audio amplifiers, the circuit incorporates a high-pass filter at the input stage, to block DC from previous stages and to attenuate infra-sound signals. This standard circuit is incompatible with our needs, as the pendulum is excited by infra-sound frequencies. Therefore, the amplifier was modified and its cutoff frequency was decreased to below $\sim 2Hz$.

Figure 5: Closeup of the modulation mechanism, showing the pendulum, magnetic bob, blade and external supports.

6. EXPERIMENT

6.1 Wine Glass Sloshing Resonance

A preliminary experiment was conducted to measure the sloshing resonance frequency of water filled wine glasses. The modulation mechanism was submerged inside a partly-filled wine glass. A frequency sweep of the excitation signal was performed over $1-8Hz$, capturing the sloshing on video. The water's sloshing resonance frequency was detected at $3.2Hz$ by video analysis. Casual observations of different glasses with varying water levels show similar sloshing resonant frequencies. Furthermore, pendulums of different lengths were used, showing a discernible effect of the pendulum's length on sloshing.

6.2 Modulation Mechanism Characterization

The experiment's block diagram is shown in Figure 1. A wine glass was fastened to a base, filled with water and fitted with a surface magnet. An electromagnetic coil was placed in front of the surface magnet. A pendulum, hanging from an external support, was submerged in the water. Two signals were sent to the coil simultaneously: 1) A signal at the sloshing resonant frequency, f_{pend}, used to put the pendulum into oscillation; 2) An audio-range signal, used to excite wine glass acoustic sounds. A microphone recorded the resulting wine glass sound which contained modulation caused by the sloshing.

The experiment was performed on two glasses: *Glass A* was tuned with water to B4 ($\sim 494Hz$) with $3.2Hz$ sloshing frequency and *Glass B* was tuned with water to G4 ($\sim 392Hz$) with $3.05Hz$ sloshing frequency. Each glass was excited by six audio-range signals. Each signal contained a recording of a single tone in the glass's pitch, produced by a different musical instrument: classical guitar, electric guitar, cello, piano, recorder and flute. Reference recordings were obtained by exciting the glasses with the same input signals, but without activating the pendulum. The supplemental file *Modulation_sample.wav* contains a recording of a wine glass excited by a classical guitar and a flute without modulation, followed by a recording with modulation for the same inputs.

7. RESULTS AND ANALYSIS

Let $f_{\mathrm{fund}}(t)$ be the fundamental frequency of a non modulated wine glass sound, generated by exciting the glass in audio frequency, without activating the pendulum. In a typical musical tone, $f_{\mathrm{fund}}(t)$ has some mild temporal changes over time t.

Let $G[t \cdot f_{\mathrm{fund}}(t)]$ be the fundamental frequency component of the non-modulated wine glass sound, which is a carrier wave having an attack-decay amplitude envelope.

Let us introduce frequency modulation to $G[t \cdot f_{\mathrm{fund}}(t)]$ by adding strong temporal changes to $f_{\mathrm{fund}}(t)$, so it becomes $f_{\mathrm{FM}}(t)$. The fundamental frequency component of the frequency modulated wine glass sound is now given by:

$$G_{\mathrm{FM}}(t) = G[t \cdot f_{\mathrm{FM}}(t)]. \quad (2)$$

Similarly, let us independently introduce amplitude modulation to $G[t \cdot f_{\mathrm{fund}}(t)]$ using a modulation amplitude envelope $a_{\mathrm{AM}}(t)$. The fundamental frequency component of the amplitude modulated wine glass sound is now given by:

$$G_{\mathrm{AM}}(t) = a_{\mathrm{AM}}(t) G[t \cdot f_{\mathrm{fund}}(t)]. \quad (3)$$

Praat (a software for speech and phonetics analysis) [3] and Matlab were used to extract $f_{\mathrm{FM}}(t)$ and $a_{\mathrm{AM}}(t)$ from each of the recordings obtained in the experiment. The extracted values were then examined in both the time and frequency domains.

7.1 Frequency Modulation

Figure 6a plots the frequency temporal changes, $f_{\mathrm{FM}}(t)$, of a glass sound generated by a classical guitar input tone with pendulum modulation. Figure 6b plots FFT$[f_{\mathrm{FM}}(t)]$. The temporal changes are apparent in the form of a peak at double the pendulum's frequency: $2f_{pend} = 6Hz$. The figures also show $f_{\mathrm{fund}}(t)$ and FFT$[f_{\mathrm{fund}}(t)]$, obtained from a glass sound excited by a classical guitar input tone *without* pendulum modulation, i.e., $G[t \cdot f_{\mathrm{fund}}(t)]$. The temporal changes of $f_{\mathrm{fund}}(t)$ are considerably lower. Figures 6c and 6d show analogous analysis for a wine glass sound generated by flute input tone. Similar frequency modulations at double the sloshing frequency were detected across most recordings, with a typical magnitude of 60 cents peak-to-peak (0.6 semitones).

7.2 Amplitude Modulation

Figure 7a plots the modulated envelope $a_{\mathrm{AM}}(t)$ of a glass sound generated by a classical guitar input tone with pendulum modulation. Figure 7b plots FFT$[a_{\mathrm{AM}}(t)]$. Amplitude modulation is visible at double the pendulum's frequency, $2f_{pend} = 6Hz$. The figures also show the amplitude envelope of $G[t \cdot f_{\mathrm{fund}}(t)]$, a glass sound generated by a classical guitar input tone *without* pendulum modulation, and the corresponding envelope's FFT. Figures 7c and 7d show analogous analysis for a wine glass sound generated by flute input tone.

Similar amplitude modulations at double the pendulum's frequency were detected in 11 out of 12 pendulum modulated tones. At a single recording (Flute input, *Glass A*, Figures 7c and 7d) amplitude modulation was detected at $\sim 3Hz$.

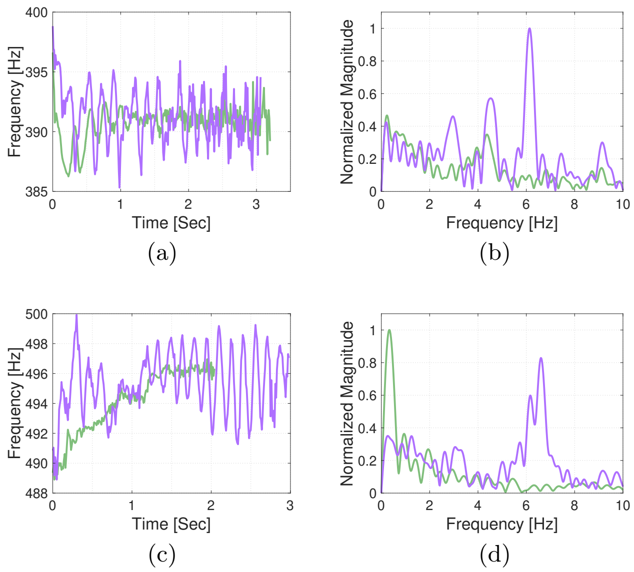


Figure 6: Frequency modulation of wine glass tones. (a) The wine glass is excited by a classical guitar tone and modulated by the pendulum, resulting in temporal changes of the fundamental frequency, $f_{\mathrm{FM}}(t)$ (*purple*), compared to the fundamental frequency of a non-modulated tone $f_{\mathrm{fund}}(t)$ (*green*). (b) FFT of both frequencies' temporal changes, showing strong frequency modulation at $6Hz$. (c), (d) Similar graphs showing the frequency modulation of a wine glass sound excited by a flute tone, with strong fundamental frequency modulation at $6.5Hz$.

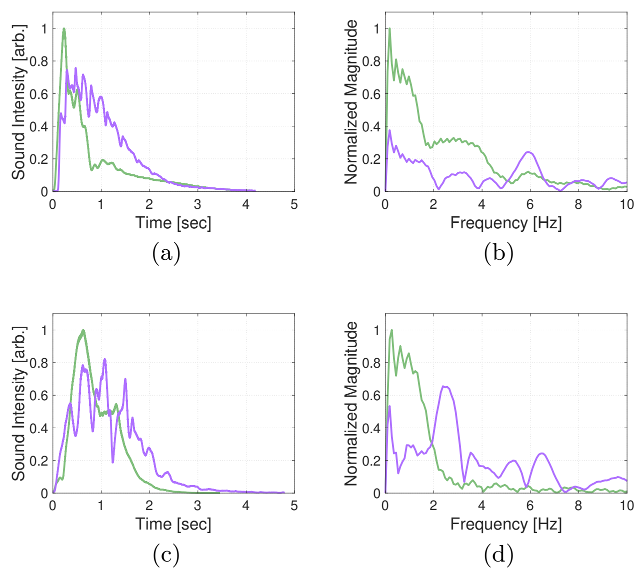


Figure 7: Amplitude modulation of wine glass tones. (a) The wine glass is excited by a classical guitar tone and modulated by the pendulum, resulting in amplitude modulation $a_{\mathrm{AM}}(t)$ (*purple*), compared to the envelope of a non-modulated tone $G[t \cdot f_{\mathrm{fund}}(t)]$ (*green*). (b). FFT of both amplitude envelopes, showing modulation at $6Hz$. (c), (d) Similar graphs showing the $\sim 3Hz$ amplitude modulation of a wine glass sound excited by a flute tone.

8. DISCUSSION AND OUTLOOK

A mechanism for mechanically modulating active wine glass sounds was presented, using automated water sloshing movements generated by electromagnets. While various automated electromechanical modulation mechanisms exist, such as the vibraphone's rotating discs, we are unaware of such mechanisms for wine glasses or similar instruments, nor of automated water sloshing based mechanisms.

The mechanism demonstrated both frequency and amplitude modulation on different glasses, through various input signals. For most input signals, the generated modulation frequency is double the sloshing frequency. Frequency doubling is caused by the approximate vertical symmetry of the wine glass and sloshing movement, making the raised liquid levels on both sides of the glass acoustically similar. Throughout a single pendulum oscillation period, the liquid raises twice, once per each side of the glass. Each time the liquid raises, both frequency and amplitude decrease, resulting in a doubled modulation frequency as discussed in section 4.

The pendulum modulation's frequency is limited: the sloshing frequency is determined by the glass geometry and water level, thus defining a specific modulation frequency per a given water-tuned glass. For the wine glasses and water levels typically used in the Symbaline, the modulation frequency was shown to be $\sim 6Hz$. This is unlike *the tilt modulation method*, where the modulation frequency is determined by the hand movement's velocity. Thus, the modulation is limited only by the player's dexterity. The *tilt modulation method* is applicable to an ordinary glass played by friction, but not to an active wine glass excited electromagnetically, as explained in section 2.2.

The pendulum modulation is also limited to generating precise periodic amplitude and frequency modulation. Expanding the mechanism with additional modulation types, such as the arbitrary modulation of the waterphone may be considered.

The mechanism presented here was developed for characterization purposes. The mechanism may be used as a modulation accessory for the Symbaline, although further development should be considered before incorporating it as an integral part of the instrument. The mechanism's support may be more elegant if fitted from inside the glass, rather than from an external apparatus. The required electric power may prove to be excessive when driving several mechanisms simultaneously, and require specialized power supply units. Furthermore, the low frequency currents generate noticeable heat in the electromagnetic coils. Both issues may be overcome by improving the mechanism's design.

9. ACKNOWLEDGMENTS

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