UNIVERSITY OF CALIFORNIA
Santa Barbara

# Forces of Nature: Software-Defined Ferrofluid Kinetic Sculpture

A Project submitted in partial satisfaction
of the requirements for the degree of

Master of Arts

in

Visual and Spatial Art
Media Arts & Technology

by

Paul Jacobs

Committee in Charge:

Professor JoAnn Kuchera Morin, Co-Chair

Professor Marko Peljhan, Co-Chair

Professor Matthew Wright

Professor Andres Cabrera

December 2015

The Project of
Paul Jacobs is approved:

Professor Matthew Wright

Professor Andres Cabrera

Professor Marko Peljhan, Committee Co-Chairperson

Professor JoAnn Kuchera Morin, Committee Co-Chairperson

December 2015

Forces of Nature: Software-Defined Ferrofluid Kinetic Sculpture

*To the troublemakers.*

# Acknowledgements

I would like to thank the members of my committee for their help in preparing my project and this document: JoAnn Kuchera-Morin, Marko Peljhan, Matthew Wright, and Andres Cabrera. In addition, I would like to thank my grandfather Jerome Jacobs and father Robert Jacobs, both for teaching me respect for science and engineering, and my grandmother, Doris Jacobs, for teaching me respect for art.

# Abstract

## Forces of Nature: Software-Defined Ferrofluid Kinetic Sculpture

Paul Jacobs

*Forces of Nature* is a reusable platform of custom-built hardware and software for creating software-defined kinetic sculpture. A two-dimensional array of high-energy electromagnets synchronized by a micro-controller project an animated electromagnetic field, visualized in ferrofluid.

Through interactions of water, ferrofluid, gravity, and the generated magnetic output field, *Forces of Nature* is capable of exhibiting a variety of visual patterns and expressive sequences of motion. These expressive units are recombined in pre-scripted sequences (timed to music or other performances) or directed in real time through a USB connection to a host machine as part of a live performance, in reaction to live sensor input from a viewer, scripted algorithmic design, or any number of potential inputs in combination.


Professor Marko Peljhan
Dissertation Committee Co-Chair

Professor JoAnn Kuchera Morin
Dissertation Committee Co-Chair

# Contents

# List of Figures

# List of Tables

# Chapter 1

# Introduction

Four fundamental forces shape our reality. The strong & weak nuclear forces work on a scale too small to detect with human senses. Gravity keeps us all on Earth but interactions with objects other than the planet happen on a scale larger than the reach of our sensory capabilities, except when observing the night sky, the movement of the moon across the sky, or the effects of its gravity on Earth's seas and oceans. Of all these forces, we postulate that only electromagnetism (EM) is observable on a human scale with the human sensory apparatus fully engaged. Electricity and the harnessing of electric potential are a core basis of modern society, making a clear difference in the lives of those who have access to technology making use of it. Even those without such access can see lightning, sparks, and other physical manifestations of electrical fields interacting with other substances, such as air. Magnetism is well understood by science, but even the powerful magnetic fields generated by an MRI machine are not directly visible to humans, as they do not interact with the atmosphere. The invisibility of magnetic fields lend them an aura of the mysterious - of a choreographer behind the scenes.

These ever-present magnetic fields can be made visible using a range of materials - a compass, box of iron filings, a candle flame, or as was chosen for this project, ferrofluid. After evaluating the alternatives, ferrofluid was determined to have the greatest potential for artistic expression (Fig. 1.1) of the available options for magnetic field visualization.

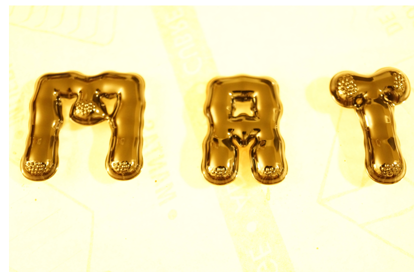

**Figure 1.1:** *MAT Logo-shaped Field Visualized* Paul Jacobs (2013) Ferrofluid, sheet plastic, magnets.

Ferrofluid has a variety of unique physical electromagnetic properties that can be taken advantage of to push the boundaries of artistic exploration and expand the capabilities of dynamic sculpture.

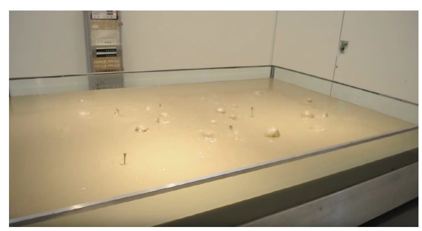

**Figure 1.2:** Rauschenberg, Robert. *Mud Muse* Rauschenberg, Robert (1971) Mud and Air. Moderna Museet / Museum of Modern Art Stockholm

Sculpture in solid form has been explored in great depth. Working with Ferrofluid and magnetic fields, though technically and practically quite challenging, makes new types of sculpture possible in liquid form with more dynamic behavior than previous liquid sculpture work, such as Robert Rauschenberg's Mud Muse (1971) [1] (Fig. 1.2).

Through the interaction of the viscosity of the suspension liquid or gas, the effects of gravity and inertia, and a constructed set of magnetic forces to project through the ferrofluid, it is possible to create a display with organic, intricately evolving patterns.

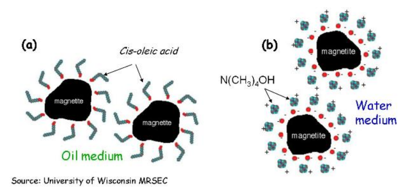


**Figure 1.3:** Surfactants help keep ferrofluid colloidal suspensions stable by keeping nanoscale magnetite particles separated.[18]

Ferrofluid is a colloidal suspension of nano-sized solid magnetic particles, each immersed in a surfactant bubble, floating in a carrier fluid (Fig. 1.3). Surfactants keep these particles separated in oil-based ferrofluid using a long chain polymer with a hydrophobic tail that tends to avoid other nanoparticles within the liquid medium. Water-based ferrofluids use electrostatic repulsion of charged surfactant molecules. [18]

Though the term is not precisely accurate, it can be considered analogous to a liquid magnet in its physical behavior. A true liquid magnet cannot exist under the currently accepted laws of physics, because magnetic materials lose their magnetic properties as they are heated past their Curie Temperature.[2] The

[1] "*Created in collaboration with Teledyne Corporation as part of A&T, [Mud Muse] consisted of a basin in which bubbles spurted to the surface of a viscous mass of mud with more or less energy depending on the degree of noise made by participants.*"[2]

[2] A material's Curie Temperature is the temperature at which it loses its permanent magnetic properties.

Curie Temperature is in all cases is below the melting temperature. "Heat a magnet even more [beyond its Curie Temperature] and it'll go through another phase transition from order to disorder – it will melt" [23]. A so-called magnet in liquid form would thus have to have been heated enough to have lost its magnetic properties.

Instead, ferrofluid's vast quantities of independent nano-scale magnetite particles (on the order of 10nm [18]), while solid at a small scale, behave as a liquid through their suspension in carrier fluid (e.g., mineral oil, in the case of the ferrofluid used in this project.) Each tiny particle is separated from the other particles in its own, magnetically independent bubble of surfactant, which remains attached to the magnetite at one end and at the other end has a means of repelling similar non-attached portions of other surfactant chains. This repulsion is prevents the magnets from touching or clogging as they flow past each-other.

When these particles are large enough to interfere with each-other, or when Brownian Motion is insufficient to keep particles from settling, the resulting substance is not ferrofluid, but Magnetorheological (MR) Fluid. MR fluid is essentially the same as ferrofluid, except that MR fluid may lack a surfactant, and the particle size. MR fluid will sometimes form solid structures in external magnetic fields, or when left to sit for extended periods [19]. Ferrofluid is noted for its property of remaining a fluid, even down at very small scales and when exposed to strong external magnetic fields. These properties cause it to render itself into shapes that visualize an externally imposed magnetic field in three dimensions, in a fluid and constantly moving fashion.

This project is a proof of concept - both a re-usable platform for controlling and generating an animated magnetic field, and an implementation of a work of ferrofluid art using this system.

The history of electromagnetic art using ferrofluids will be discussed, as well as the design and methodology of the system implementation through each of several iterations: *Forces of Nature* and its predecessor, *Fluidic Space.* The hardware was created to give as much control over ferrofluid (and create as much beauty) as possible - which required construction of hardware not commercially available in its final form to generate the magnetic field, as well as custom software to control the hardware.

# Chapter 2

# Previous Work

Electromagnetic art using ferrofluids is a relatively new field, with much potential untapped. A world of fascinating questions and experiments remain to be answered and performed.

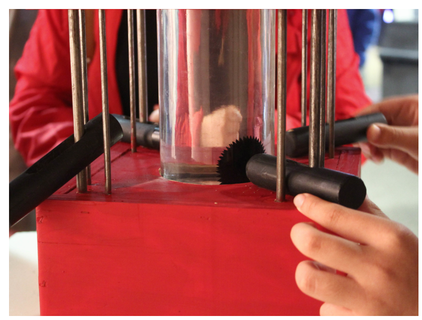

**Figure 2.1:** *Ferrofluid Display* Lee Anne Steers (2014)

Kinetic fluid sculpture itself is not an innovation requiring ferrofluid, as can be seen in Robert Rauschberg's Mud Muse [24] (Fig. 1.2) - a kinetic fluid sculpture with no apparent ferrofluid or magnetic fields involved.

The standard museum display [29] with ferrofluid and water in an enclosed vessel, along with permanent magnets for the viewer to manipulate (Fig. 2.1), is fascinating to play with, creating complex patterns and rhythms of movement in response to strategies of moving the magnet - however much more can be done.

Most museum displays and ferrofluid videos observed by the author involve ferrofluid suspended in clear liquid. The higher end of this type of display shows great expressive potential in using just a single magnet, manipulated by hand, such as this demonstration by Casey Hughes of CZFerro (Fig. 2.2).

**Figure 2.2:** *Prototype Glass Ferrofluid Display* Casey Hughes (2013) [8]

Perhaps due to technical issues soon to be discussed, relatively few artists have worked in this medium successfully. Only one artist is truly well known for it - Sachiko Kodama.

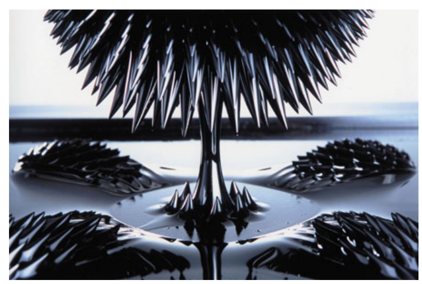

**Figure 2.3:** *Protrude, Flow.* Sachiko Kodama (2001) [17].

One of her early ferrofluid works, *Protrude, Flow* (Fig. 2.3), an open-air gallery piece featuring several fixed position electromagnets, remains one of if not the most well-known ferrofluid art work. citepKodama:2001tz.

Her follow up, Morpho Towers / Two Standing Spirals is an installation that "consists of two ferrofluid sculptures that moves synthetically to music. The two spiral towers stand on a large plate holding ferrofluid. When the music starts, the magnetic field around the tower is strengthened. Spikes of ferrofluid are formed at the bottom of the plate and move up, trembling and rotating around the edge of the iron spiral"(Fig. 2.4) [16].

It is one of the more impressive demonstrations of the innate beauty inherent in the mechanics of magnetic field interaction.

**Figure 2.4:** *Morpho Towers / Two Standing Spirals* Sachiko Kodama (2007).

UCSB College of Creative Studies student Zach Rubin created an open-air ferrofluid display with 8 electromagnets (Fig. 2.5). Its magnets were spaced far enough apart to have non-interacting magnetic fields, excluding the central electromagnet's interaction with the permanent magnet above it [26].

**Figure 2.5:** *FerroFluid Fountain* Zach Rubin (2010)

Fabian Oefner has done some interesting work with Ferrofluid. His work showcases the organic-looking irregular forms that ferrofluid takes. He uses its natural pattern-forming qualities as line boundaries in a spectacular arrangement of watercolor compositions titled *Millefiori* (Fig. 2.6) [22].

**Figure 2.6:** *Millefiori* Fabian Oefner (2013)

Magnetic fields through ferrofluid may comprise a form of performance art, causing the fluid to dance, evade, scurry, gather, flock, hover, or disperse - all in service of artistic expression. Unfortunately, precise human control of the position of even two strong permanent magnets becomes much less feasible as the distance between those magnets decreases, due to the dramatic increase in force drawing their respective magnetic fields into alignment. The field strength varies with the inverse square of the distance from the source - all else equal, it will be 25% of the strength from 2cm away that it is at 1cm.

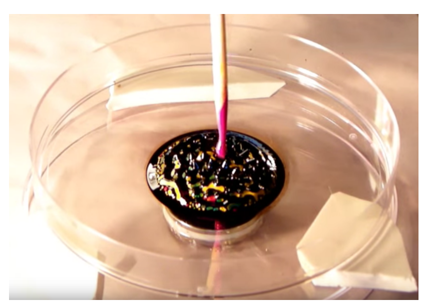

**Figure 2.7:** *Fun With Ferrofluids* Neil Jenkins (2013)

Neil Jenkins followed up with a similar work and captured it on video (Fig 2.7). His work is more three dimensional, but also uses watercolors with ferrofluid as a guiding material structure.[15]

YouTube user Xman posted a video (Fig. 2.8) of a composition created using the interaction of ferrofluid, soap bubbles, and what appears to be watercolor or food coloring. The way magnetism is used to coax the ferrofluid through channels created at the intersections of the bubbles is quite unique [30].

**Figure 2.8:** *Ferrofluid and soap bubbles* Xman (2014)

An artist group known as Chemical Bullion has created a video showing these pattern-forming attributes of ferrofluid in what must be a fairly heavy magnetic field, as they have caused it to form not only lines but actual vertical strips (Fig. 2.9) of ferrofluid in response to its magnetic environment [3].

**Figure 2.9:** *Ferrofluid - Strip Form* Chemical Bullion (2014)

Martin Frey developed a project, *SnOIL* [1] (Fig. 2.10). *SnOIL* is a computer-controlled 12x12 grid of electromagnets, which was used as a display screen to play the game Snake [27] with each pixel either showing a flat area under normal circum-

[1]SnOil is short for Snake Oil

stances, or a bunched up area of more dense ferrofluid under the influence of magnetism [6].

However, the magnets and/or power system that SnOil uses are not powerful enough to create noticeable spikes, or intersecting magnetic field volumes in the ferrofluid. Two adjacent activated pixels on this display appear as two completely separate, squared blobs, with no spikes and no possibility of building up other shapes.

**Figure 2.10:** *SnOIL* Martin Frey (2006)

# Chapter 3

# Methodology

## 3.1 System Design

Having looked through the described prior work, many projects made clear strides in expanding the range of ferrofluid-based art. However, all known ferrofluid displays were "unitaskers", i.e. created and built to display a single set of shapes or animations. Given the difficulty in building such a piece, for that effort to be required for each and every display built, even every prototype display, seemed more effort than necessary.

This is particularly the case when compared to the software-driven art experience, where progress can be locked in place and built upon using tools such as version control and deterministic compilation. Changing a text file defining an algorithm, and letting it rebuild and regenerate a visual image or animation is incredibly predictable and solid compared to balancing a physical electromagnetic, mechanical, and chemical system that had to be operating perfectly for the output to be observed turned out to be more difficult that previously imagined.

Though creating hardware to display a given piece seemed a requirement, other hardware for creating EM fields in the visual spectrum - LCD displays, for example, have grown to be more flexible over time. The concept of a single-point light source eventually developed into digitally controllable screens. Individual electromagnets, it was clear, could similarly be arranged and controlled to form a software defined magnetic field which ferrofluid could respond to.

The goal was to create a piece of hardware that would be as expressive as possible, a more flexible, open platform for experimentation that could be driven by software, and could thus be indirectly controlled by human interaction. Rather than only allowing adjustment over a small fixed set of variable controls for a couple of electromagnets, a wide variety of content could be played upon this screen by integrating different patterns in timing and/or intensity [1] of field strength across the different magnets in the grid, and over time.

It was intriguing to discover that a general purpose ferrofluid experimentation platform did not yet exist. It was decided to build iterations toward a modular system, which could be reconfigured to be used in multiple displays. If correctly implemented this could lend a stability to experiment and develop new electromag-

[1] Variation of magnetic field intensity is discussed as future work, such variation is not implemented in the iterations of Forces of Nature discussed here.

netic field configurations and patterns without having to re-build the hardware, micro-controller software, network control data protocol, and client software from scratch each time a new display was desired.

Thus the primary objective of this project was to build a hardware-software system to reduce the required tasks in creating an attractive interactive ferrofluid display to one of software development, for a wide class of ferrofluid use cases, as well as to create such a display using this system.

**Figure 3.1:** *Fluidic Space Forces of Nature v0.1* Paul Jacobs (2013) UCSB MAT 2013 End of Year Show.

It must be noted that this paper discusses very different iterations of the same project - the first was displayed at the UCSB Media Art Technology Program (MAT) End of Year Show in 2013 (Fig. 3.1) made with rebuilt transformers as electromagnets, while the second was displayed at the MAT End of Year Show in 2014 (Fig. 3.2), used commercial electromagnets and had a custom-built enclosure.

**Figure 3.2:** *Forces of Nature v1.0* Paul Jacobs (2014) UCSB MAT 2014 End of Year Show.

Many lessons learned during the first iteration lead to changes in the second iteration - most of which turned out to be positive. Each iteration's solution to various challenges will be discussed in the context of the various system components.

Three major system components are necessary for this to work: the Display, the Magnetic Field Generation System (MFG), and the Control System (Fig. 3.3).

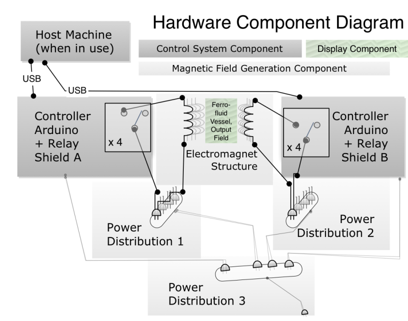


**Figure 3.3:** Major hardware components as implemented in first iteration.

The Display is what the audience actually sees - this includes the Vessel, the Ferrofluid, and the Suspension Liquid (SL). Behind (or in some cases below) the Display will be the MFG system, providing the magnetic field to be projected through the ferrofluid to give it shape and movement.

The MFG system includes the electromagnets themselves, the supporting structure and environment of those magnets, cooling, and wiring to connect to the Control System. Finally, the Display may include Lighting, which helps increase the visibility of fine detail produced by the system.

Supporting and channeling the power of the Magnetic Field Generation System into the proper expression of the artist's intent is the Control System, comprised of one or more Arduino microcontrollers, a connected piece of hardware capable of switching the power going into the MFG system for each active electromagnet, and the related wiring. The Control System may be driven by a Host Machine which may in turn be driven by some combination of human interaction, a higher-level scripted set of movements, sensors, feedback, and software of varying complexity to integrate these and other inputs.

## 3.2 Display

### 3.2.1 Ferrofluid

Ferrofluid was attempted to be manufactured as part of this project, as well as experiments into modifying professionally made ferrofluid in various ways. First, in attempting to create ferrofluid, using magnetic laser printer toner and vegetable oil, it was found that the particles were far too large to maintain their independence under magnetic fields, and they did not return to a liquid state as true ferrofluid does. Magnetic laser printer toner with Isopropyl Alcohol did not appear to be an improvement. Each produced MR fluid rather than true ferrofluid.

Experiments with MR Fluid, often the result of failed attempts to produce homemade ferrofluid, were disappointing for several reasons. First, though MR fluid was able to react to magnetic fields by generally bunching up in areas of high field density, it is not fluid enough to show the detailed contours of the magnetic field shape - in other words, MR fluid does not produce spikes. This is because its particles get caught up in each-other's magnetic domains, rather than aligning exclusively to external magnetic fields. This prevents them from flowing freely enough to spike, as in Matty Metlitz's Ferrofluid Experiments: "None of these [MR fluid] mixtures produced spikes when exposed to a magnet" [20].

The other reason MR fluid was not a suitable candidate for inclusion in this project is that it settles over time and can become solid in a strong enough magnetic field, while ferrofluid does not - due to whether the particles are small enough to remain suspended from the effects of Brownian Motion[19].

MR fluid particles are large enough that they can interfere with each-other's magnetic fields and become bound to one another, while true Ferrofluid has small enough particles, isolated in surfactant bubbles within the carrier fluid, that they will not bind to one another, instead aligning to the exterior magnetic field in a physical configuration to mirror the shape of the magnetic field. If the field were to be removed, the ferrofluid will lose its shape and coalesce back into a pool.

Once the need was established, working with commercially produced ferrofluid produced much more interesting results. Most importantly, under a strong enough magnetic field, this fluid would produce spikes.

Wanting to distinguish this display from others seen in videos and museums, various attempts were made to produce ferrofluid in some other color, yet with identical or very similar behavior. Over and over again, however, liquid dyes and pigments (specifically, replacement pigment ink, and replacement dye-based ink, respectively, for an Epson R1900 printer), powders (powdered pigments), and other coloring agents (Fig. 3.4) that were tested did not tend to remain evenly distributed in the fluid, and thus did not produce a usable ferrofluid in another color, as the magnetically reactive ferrofluid would come to the surface, uncontaminated by whatever substance had been attempted to be mixed in.

**Figure 3.4:** Coloring agents used to mix with ferrofluid: liquid dyes, several colors of iron oxide powder, others.

Recognizing that the issue involved the magnetic re-activity of the additive, the addition of Iron Oxide powder was tried as well, in a wide variety of colors. Most colors either had the same problem of not remaining distributed widely enough under magnetic fields to have changed the color of the liquid as a whole (though the effect was fairly interesting in creating non-uniform coloration), or it affected the fluid in a way that compromised its overall effect, such as dampening the spiking behavior. The ferrofluid's initial color of deep black limited the range of resulting colors producible by mixing in coloring agents.

In the end, only one coloring agent was found to be useful in changing ferrofluid color without unreasonably limiting its behavior - red iron oxide. When a sufficient quantity of red iron oxide was mixed in, the ferrofluid would react normally, but took on a dark chocolate color, rather than the typical glossy black. Though an interesting result primarily for the volume of failed results using other oxides (all of which were significantly less magnetically reactive) this was not a significant enough change to merit further research.

**Figure 3.5:** CZFerro has successfully created blue and gold colored ferrofluid.

It is worth noting that after these series of experiments in this area had concluded, another group succeeded [21] in creating colored ferrofluid. Concept Zero (Casey Hughes and Nicky Nada) has created both gold and blue (Fig. 3.5) ferrofluid for their displays. The exact composition of their fluid remains a trade secret, but it is now clear that other colors (besides the chocolate color produced with red iron oxide) are possible in magnetic fluid displays.

It is also of note that the colloidal arrangement created with non-iron-oxide-based coloring agents generated beautiful results when working with magnetic fields (Fig. 3.6) - but as my aim was to create a general purpose system, for this project it was decided to stick with the more well-known visual traits of standard ferrofluid, rather than expecting users of my system to be comfortable working with a coloring layer exposed only in the absence of external magnetic stimulation.

After testing the ease of modifying the color of the ferrofluid and experimenting with changing the behavior of the ferrofluid, many trials were performed, building on what was recognized in the difference between how the fluid reacted to iron oxide powders vs. other additives. Not all unsuccessful trials had results recorded. However, interesting behavior was suspected if bismuth, the most naturally diamagnetic element [7], were to be added, so bismuth needles were added to the fluid. It was discovered that in magnetic fields, these needles appeared to be anchored to the surface of the ferrofluid, forming a prickly texture.

**Figure 3.6:** Experiments mixing FF with both magnetic and non-magnetic coloring agents show potential for interesting future work.

This suggests the possibility of non-smooth surfaces dynamically generated with smooth magnetic fields. Other shapes of bismuth particles may be instrumental in creating other interesting surface textures. However, given the general nature of the tool being designed, and not wanting to stretch the definition of ferrofluid in this first encounter with it, such adventures were left for future work.

### 3.2.2 Fluid Vessel, Suspension Liquid (vs. Open-Air Displays)

As demonstrated by the body of art created with it, ferrofluid is quite visually compelling, though its beauty is often concentrated into a fairly small area, and the intricate details can be best observed from very short distances. Thus, it is desirable to allow the audience to get as close as possible to get a good view.

The minimum components in making a ferrofluid display are ferrofluid, magnets, and a barrier in between them. To avoid spills in the absence of a magnetic field, walls around the side of the barrier are necessary. With an open container such as a petri dish, an open-air based ferrofluid display can be compelling, and has the advantage of allowing the audience to get closest to the action, as in *Mud Muse* (Fig. 1.2). An air-buffered display can also react more quickly than a water-based one, due to air having less density than any suspension liquid option.

Air also has less optical distortion - but an open-air display also creates the risk of staining of the viewer, particularly if they are close up. Measures should be considered to protect them - asking them not to bring magnets or to reach into the display, for example. These displays can be difficult to keep working properly over time, as part, but not all of the ferrofluid evaporates, changing its behavior and the appearance of what is left. On the other hand, with wide flat containers one starts to discover the beauty that thin-film ferrofluid presents, as shown in the work of such artists as Fabian Oefner. Given the emphasis on re-usability in this project, however, a closed container was decided upon to prevent evaporation.

In initial research with closed containers, ferrofluid was put into a sealed transparent container with air, and manipulated with a permanent magnet. It was hoped that this would be the best of both worlds. Instead it was discovered, as noted above, how easily ferrofluid would permanently stain any surface the fluid touched. In one experiment, after a few short minutes of exploration, an opaque black container with no way to see inside was the result. Experiments with coatings and other surfaces have not so far found a solution for this issue with a sealed ferrofluid-air container.

Contact between the ferrofluid and the container surface can be minimized by using a suspension liquid that does not mix with the ferrofluid, such as distilled water. I have found that for sealed containers, use of this buffer liquid seems to be necessary to maintain display quality - container transparency in particular.

Experiments with other potential buffer fluids such as Canola Oil, 91% Isopropyl Alcohol, distilled water, and mixtures of the three lead me to initially[2]

[2] Pure distilled water was used as solution liquid for the first and second iterations, while the third iteration uses 65% Isopropyl Alcohol, 35% distilled water.

find that pure distilled water was the best option for display purposes, of those tested, due to either dissolution of the ferrofluid into the suspension liquid, or its viscosity significantly impairing the reaction speed of the ferrofluid, or lack of full-spectrum, distortion-free transparency.

A modular system seemed like a wise option, to allow components to be upgraded or repaired as necessary, as well as to assist in adapting to future needs. Thus, the magnetic field generation system was built as separate piece from the fluid display vessel and is intentionally removable.

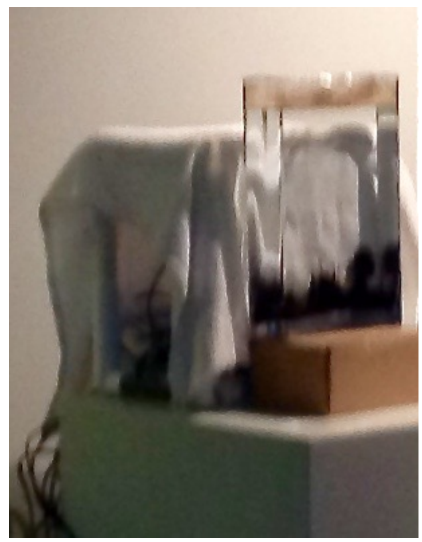

**Figure 3.7:** *Fluidic Space (Forces Of Nature v0.1)* Paul Jacobs (2013)

In addition, for reasons already discussed, a water-based, sealed ferrofluid system was chosen for this project. It would be sub-optimal for such a re-usable system to dry out over the course of several days or permanently turn opaque after a short period of use.

To include the interaction of gravity to the expressive potential, to best make use of the buffer fluid, and to allow for the audience to see the work from a greater distance; a vertical arrangement was selected. A horizontal arrangement was another option considered, where the magnetic field projection would have been arranged along a flat plane with the ferrofluid above. The modularity of the system allows for a future horizontal container to utilize the same magnetic field generation hardware currently in use.

For the first iteration a vessel of 8" W x 12" H x 3" D (filled to a fluid height of 10") was used along with a magnetic projection system designed to create a field in an 8" W x 10" H area, which was placed directly behind it, without any direct connection. (Fig. 3.7) The coupling between the two was an issue during display at times.

To remedy this, the second iteration vessel was built with the magnet and ferrofluid area integrated into a single container of size 8.5 W x 10.5 H x 3 D. This integrated area was split into a fluid vessel of approximately 2 depth, the plastic dividing panel of $\frac{1}{8}$" width, and a 1" section containing the magnets on a removable panel (Fig. 3.8).

**Figure 3.8:** *Forces Of Nature v1.0* Paul Jacobs (2014)

To be sufficiently powerful, the magnetic projection needs either to be adjacent to the vessel, as in the first iteration

(Fig. 3.1), or to be even closer, needs to have a space inside of the vessel, as in the second iteration.

Glass containers seem to be somewhat more resilient to staining than plastic, however they are much less resistant to cracking and breaking, particularly at the small thicknesses necessary to create a reasonably portable and transparent display case. Glass was chosen as a separate container for the first iteration, but its opacity was less than ideal, as it had an irregular curvature across the surface, distorting the field of view into the work.

The second iteration used plastic instead, and was, in theory, able to be much smaller for a similar level of stability. However, using plastic in the second version proved to be a significant weakness - weeks of experimentation failed to produce a truly waterproof vessel, the plastic was not resistant to the heat generated by the electromagnets during the EOYS presenting the second iteration publicly, and staining was a more significant issue than with glass.

Waterproofing proved to be surprisingly difficult. In the second iteration it required seven separate attempts to seal the panels together before it would hold for the show, and while it did, the warping caused by the heat of the magnets as well as the passage of time allowed the waterproofing (or ferrofluid-proofing, at least) to fail within a week following the show.

In retrospect, working with ferrofluid required dealing with a set of difficulties beyond what was initially expected. Two primary issues arose: First was the uncanny ability of ferrofluid to permanently stain nearly any surface, including plastic or glass enclosures one might have hoped to use as displays — in fact this issue has never been fully resolved: wherever the ferrofluid rests for an extended period, stains result. The second issue had to do with ferrofluid being able to penetrate membranes and containers even where water could not. For example, latex gloves are not always successful in keeping ferrofluid from staining fingers underneath.

The second iteration of my project, though managing to stay intact for the duration of MAT's End of Year Show in 2013, slowly began to leak ferrofluid and then water roughly one week after the show, or about two weeks after being filled with water and ferrofluid. It appears that the ferrofluid may have reacted with the binding adhesive, creating a path for it to flow out.

Further work in waterproofing and ferrofluid-proofing are clearly required. One option for avoiding the staining of ferrofluid on containers was thought to be to apply a hydrophobic and oleo-phobic coating to the interior of the vessel. This may be helpful in future work and if developed, may be used seamlessly with the rest of this modular system, so long as it fits the proper dimensions to match the projected magnetic field.

Careful selection of the suspension liquid, vessel material, and what treatment, if any, to apply to the vessel are necessary to minimize staining and visual obstruction and maximize the visual quality of the work [28].

Lighting is another issue. In the first iteration it was left to ambient lighting, but in the second an LED strip able to change color by remote control was integrated by including it in the enclosure, with the light directed inward. Setting the strip to shine bright white light into the fluid significantly improved the viewers' ability to clearly see the shapes generated by the work. To properly see the spike detail, there must be good lighting at the proper angle to emphasize the shapes formed in the magnetic field. The lighting must not point directly at the viewer, but must be bright enough to reflect clearly off of the glossy black surface of the ferrofluid.

## 3.3 Magnetic Field Generation System

### 3.3.1 Electromagnet Composition

The task of generating a reasonably powerful, animated, digitally controllable electromagnetic field can be more challenging than it first appears. There are many issues that must be taken into account in creating this field.

Generally, an electromagnet is depicted as a simple coil of wire around an iron core, driven by a constant DC voltage source. Each winding of the coil has the same shape and size and contributes an identical portion of electromagnetic energy to the field (Fig. 3.9).

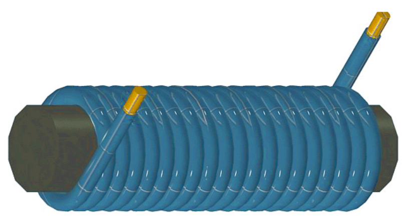

**Figure 3.9:** Conceptual Illustration of Electromagnet [4]

The overall effect produces a positive magnetic pole at one end, a negative pole at the other, with the intensity and direction controlled by the amperage flowing through the electromagnet, which is controlled directly by the voltage applied to the inputs (assuming power source output limitations are high enough).

Initially, an example commercial electromagnet (Fig. 3.10) was ordered, which took the form of a metal cylinder with wiring attached. It was labeled to take 12V and claimed to use 0.84A to lift 90lbs. Experiments in testing this using 12V power sources (rated to deliver 1A or more) showed it to be woefully insignificant in drawing in ferrofluid from a distance of more than a few centimeters.

**Figure 3.10:** Commercial electromagnet rejected in first iteration, used in second iteration (90lbs DC 12V holding electromagnet lift solenoid [1])

So, the voltage was increased beyond its design limits to 24V. At 24V and with very little distance between the magnet and a vessel, the field was having a moderate effect on the ferrofluid, beginning to produce spikes, but that was already doubling the rated voltage to get a middling effect. It could be increased further, but the wires attached to the magnets did not appear designed to handle high voltages and there was concern about the interior wiring, which would most likely be thinner than the exposed and presumably more insulated wire. It was too costly,

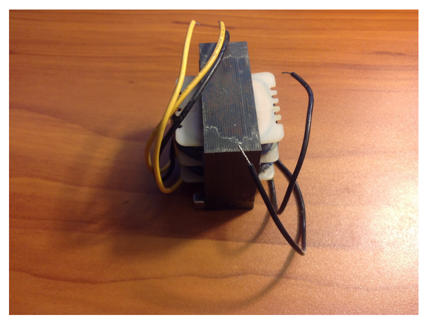

**Figure 3.11:** Transformer as purchased, before being re-built as electromagnet.

and too risky to use the commercial magnets for the first iteration. This lead to experiments with home-built electromagnets.

Home built electromagnets, in addition to offering a possibly less expensive alternative, allowed consideration of non-traditional wiring arrangements, such as a star-shaped rather than circular coil. Though experiments using magnetic field visualizing film did show that uniquely shaped fields were produced, a coil composed of dozens or hundreds of copies of the same shape seemed impossible to produce without some kind of machine to do so. For manual construction, circular coil shapes seemed to be the optimal starting point.

As it turned out however, even with a circular coil, manually winding a coil around an iron core did not prove to produce a strong enough field to work with. Potential issues include the uniformity of the windings, as well as the quantity and tightness, and the resistance of the wire itself. Looking at electronic parts available in the area, a transformer seemed to be the best available solution. Though contained in a field-enclosing figure-8-shaped iron structure (Fig. 3.11), it was essentially two large coils around the core of that structure. By removing one edge of the iron structure I produced an air gap

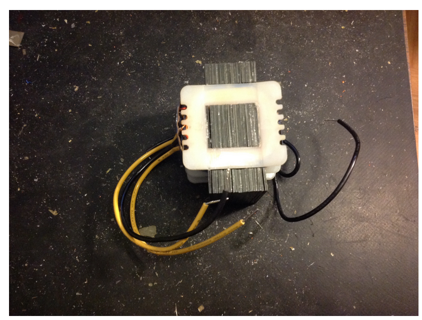

**Figure 3.12:** Electromagnet after being re-built from transformer.

in the contained magnetic field where the field would radiate from one end of the now E-shaped iron core (Fig. 3.12).

Both sides of the transformer were made to work in concert by reversing the polarity on one side, when wiring them in series,[3] thus both sets of windings were used to produce the field. This initially caused some concern due to one side of the transformer being intentionally designed with far more windings designed for a lower voltage, and thus likely to be using thinner wire with lower tolerance to high voltage. Most of these transformers were designed to convert 110VAC to 12VDC or 24VDC, so voltages considerably higher than that presented potential risks.

However, electromagnets designed to exert considerably higher strength fields were orders of magnitude more expensive, more bulky, and were not available by rebuilding locally sourced, reasonably priced transformers. So the first iteration was created with these rebuilt transformers. When the E-shaped iron core (Fig. 3.12) had a field generated within it by power flowing through the windings, a field was created in the open space, and was transmitted through the vessel and the ferrofluid. The construction process was similar to that described in the Instructable by Rocketman221 (2011) [25].

[3] This was observed to produce the strongest response from a test ferrofluid vessel.

The second iteration, Forces of Nature v1.0, used commercial electromagnets (Fig. 3.10) due to spacing concerns, a belief that extra voltage/amperage could make up for the missing power in commercial magnets, and under the assumption that they would be more able to handle excess power than the rebuilt transformers. The second iteration had safety as an explicit goal, where it could be left unattended without concern that it would melt in the absence of supervision and potential manual shutdown.

There were no rated voltage limits for the home built magnets, though the magnetic power circuits were far exceeding the rated voltage of one side of the transformers. This caused concern because in early testing, part of a bridge wire had vaporized under heavy electrical load, showing the necessity of sufficient power capacity in the wiring.

### 3.3.2 Electromagnet Grid Layout and Thermal Issues

Both standard rectilinear as well as hexagonal grid arrangements were considered. A hexagonal grid would allow for tighter packing of magnets, at the expense of the ability to move ferrofluid in 90 degree increments as a rectilinear grid provides for. Though 60 degree increments would have been desirable for some cases, given that computer monitors and software arrays have settled into arrangements more suitable for display in rectilinear grids, they were selected for this project.

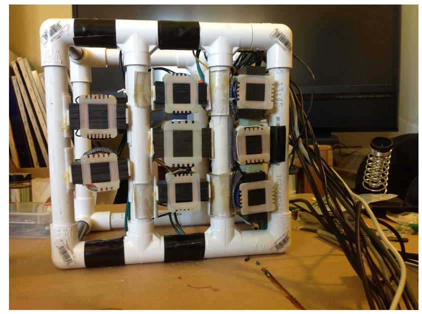

**Figure 3.13:** Electromagnets in support structure for *Fluidic Space / Forces of Nature v0.1*

Though initially a grid of 3x3 magnets was planned for, due to the initial controller hardware being limited to 8 relays and the extended time it took to disassemble a transformer and rebuild it into a magnet, the first iteration was built with 8 magnets (Fig. 3.13), though in public showings only three have been clearly fully active. **Fluidic Space**, the version featured in the 2013 EOYS (using homemade magnets) had issues with vertical movement, due to excess spacing between magnets relative to the strength and width of the generated field.

In that show it moved horizontally only, with the three bottom magnets being strong enough to draw ferrofluid into them. An open-air arrangement was used with a cloth to cover the magnet array and provide a background for viewing the ferrofluid against, but the heat generated during the show proved to be far beyond what was anticipated during testing and construction. The temperature measured over 150 degrees Celsius at one point, prompting shutdown of the system periodically to keep it from overheating.

Because of the heating issues, it wasn't practical to completely hide the MFG unit (Fig. 3.1), thus the visual appearance of the exposed magnet grid in the first iteration could not be safely concealed. This prompted a desire for a more visually appealing MFG system for the second iteration.

In later experimentation, the spacing issue was partially remedied by rotating the structure 90 degrees, so that vertically adjacent magnets were next to each-other. For a single column it was extremely effective, and ended up producing some of the most beautiful footage (Fig. 3.16) captured during this project [9].

There were several issues with the electromagnet setup for the first iteration: It was far too bulky to be made attractive or made to fit into a compact display. Individual magnets had no means of anchoring themselves and had to be clamped in place by compressing other materials against them.

There was no real heat management, though its portable design was well ventilated, which turned out to be more important than realized. The project had to be turned off periodically during the first show to avoid melting the solid plastic structure that held it in place, as the heat generated by it was excessive.

In the second iteration, I tried another tack. Attributing the heating issues to the rebuilt magnets and their off-label usage, the commercially made electromagnets were assumed likely to be more heat-efficient than those that could be produced by rebuilding transformers.

A set of electromagnets was ordered, to be arranged into a grid, and it was decided to build an enclosure for that grid along with a simple fan-based cooling system. These magnets would be attached with screws using holes designed for that purpose drilled into the magnet housing. These could be mounted much more closely together than the first iteration's magnets with a simple back-plate to attach the screws to.

These magnets turned out to be fairly weak when used as directed. It was attempted to make up for the weakness of the magnets by overfeeding them voltage. Though only a partially satisfactory solution, it caused enough overheating that the cooling system was insufficient. During the show, after only 90 minutes, the ferrofluid no longer produced spikes, dramatically reducing the visual quality of the display. This appears to be either because the ferrofluid's magnetite particles [5]) had approached their Curie point, or because of some unknown heat-induced ferrofluid degradation.

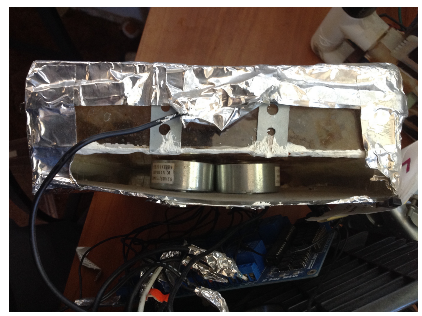

**Figure 3.14:** Electromagnets' excessive heat warped support structure during exhibition of *Forces of Nature v1.0*, increasing the distance between magnets and ferrofluid vessel.

Despite an open air path and a cooling fan blowing directly on the magnets throughout the show, by the end of the show, in addition to the spiking issue, after four hours on display the heat resistant acrylic sheet had warped and bent from the intense heat, straining the rest of the enclosure and weakening the effect of the magnets near the center, particularly those in the top row, as they were now spaced farther from the fluid vessel (Fig. 3.14). In retrospect it was fortunate that a leak in the ferrofluid vessel did not develop during the show.

Optimizing magnetic field strength turned out to be largely about striking a workable balance between maximizing power input and managing the resulting heat. Despite using up to triple the designed voltage in some cases, in the author's opinion the field strength continued to feel as if it were never quite enough. It is clear this project needs significant improvement in cooling efficiency for future revisions, such as active cooling (using a compression cycle) or a detachable set of magnets that can be swapped out for a pre-cooled set when temperatures get too high.

### 3.3.3 Lighting

The first iteration did not address lighting, but was installed in a well-lit area. Despite this, it was difficult to make out the smaller shapes created in the vessel. The second iteration attempted to improve the visibility of the ferrofluid and the shapes it would take up by integrating an LED lighting strip around the sides and top of fluid vessel. This allowed much more detailed shapes to be seen by the audience, and was clearly an improvement over the previous iteration.

## 3.4 Control System Hardware

### 3.4.1 Magnetic Field Controller Hardware

When working with individual magnets, it is easy enough to attach a power source to the electromagnet manually and then control it by switching the upstream power on and off. However, this does not suffice to achieve the level of automated control targeted in this project. Using a separate power strip for each magnet, individual control is possible - but only feasible for two or three magnets. The precision timing required to coordinate ferrofluid movement smoothly between more than one electromagnet proved to be too difficult of a task to perform manually.

The solution to controlling multiple magnets in a coordinated performance is to put the magnets under digital control, and then in some cases to give that control back to a human at a higher level, through software. Software customization and pattern triggering would allow for higher resolution control than a person could attain using bare electrical switches.

For the first iteration, an Arduino Uno was used with a SeedStudio RelayShield, which allowed up to four electronically isolated circuits to be switched on and off under digital control. The electrical isolation was a necessity, as the voltage levels (≈24V) required to generate the field were more than enough to destroy the controller hardware, which was designed to operate at 5V.

Each of the 8 electromagnets was connected with an individually addressable relay on one of two Relay Shield + Arduino sets; with each set handling 4 electromagnet circuits (Fig. 3.15).

Note that each magnet has its own independent power source and isolated circuit, so electrical failures that the controller survives will not cascade, and each magnet will always be driven at full power regardless of how many other magnets are active.

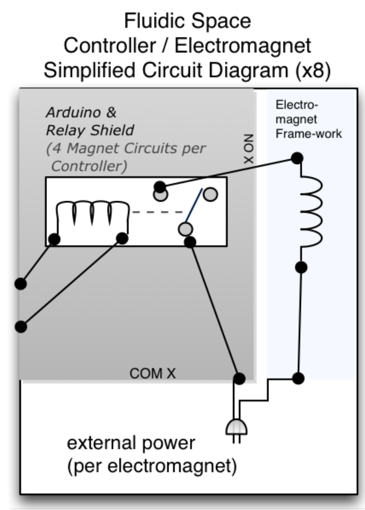


**Figure 3.15:** A schematic diagram of the circuit driving each electromagnet, including the Relay Shield's contribution.

Coordinating the work of these two Arduinos required either for them to communicate with each other or with a third machine controlling the system. Though this third machine could theoretically be an Arduino or other microcontroller, the Arduino models did not have sufficient built-in hardware to connect to two other Arduinos as well as a host machine.

While this could have been remedied by attaching communications hardware and adding driver software to the Arduinos, using a Mac OSX machine was much more simple and reliable, and was the configuration used for the first show. The downside of this arrangement was that two open USB ports were required on the host machine to fully drive the project (Fig. 3.3).

For the second iteration, I used a single controller connected to a separate hardware relay board with 16 relays. This eliminated the issue of having to drive multiple controller boards to use 8 magnets, also eliminating the related issue of keeping multiple controller boards properly synchronized.

### 3.4.2 Power Distribution Hardware

Converting line-level 120V power into what is required to drive these magnets and controller boards was a significant task in and of itself, given the requirement for individual power sources per magnet.

In the first iteration, typical magnet power after conversion averaged 20V at 2A. Due to financial limitations, a uniform set of identical power sources for each magnet were not available. Some magnets were driven at up to 24V, others were as low as 18V. In the second iteration, typical magnet power was 24V at 2A, ranging from 19V to 31.5V.

Due to the issues of limited portability due to weight and volume, as well as the excess of wiring necessitated by using a separate power source per magnet, there was strong incentive to find ways to use fewer power sources. In addition to the sheer bulk and weight of accommodating the power bricks and the power strips they plugged into, each power source had a cord which had to reach the relay board on one side, and the MFG array on the other. Because of the power levels involved, they could not be bundled into a ribbon cable without risk of shorting or overheating the wiring.

Another option would have been a simple parallel wiring arrangement for groups of magnets, thus allowing multiple magnets to share a single power source. This solution would not have required complex routing circuitry, but would have cut the available power in half when using two magnets in the same group, by 2/3rds if using 3 magnets in the same group, etc.

However, because power levels far beyond the design specs of the electromagnets (and original transformers for the rebuilt ones) were required just to maintain an acceptable field, I decided not to further limit power by requiring multiple magnets to share power sources and settled on giving each magnet its own power source. This also simplified the software design and removed what may have been seemingly arbitrary limitations from the artists perspective. With this arrangement a logical control system arises, without need to discuss details of implementation to explain, for example why magnet 3 and 7 can't reach full power at the same time. Instead, each magnet has an unchanging range of power levels that could be applied to it at any given time, rather than having half the power available if another magnet sharing its power source is in use simultaneously.

Though the design I had chosen for power distribution (one power source per magnet) is the most straightforward to implement and understand, it is also the most bulky, heavy, power consuming, and heat-generating of the options (Fig. 3.3). However the heat in this case is generated away from the Display, and does not approach the heat levels measured in the MFG. Passive ventilation has proven sufficient to cool the power sources in each iteration thus-far.

Using custom circuitry, future work could reduce generation requirements to one power source per simultaneously operating magnet by routing the next unused power source to the desired magnet as needed. While this would work in theory, time and budget prohibited its use in this project, and it would inevitably introduce some latency in switching a power source from one magnet to another prior to powering it on.

### 3.4.3 Hardware Modularity

Magnets in the first iteration were hard-wired, but in later iterations a more flexible approach was used, where a given magnet could be connected to a given relay and thus power source without soldering. This has proven invaluable in accelerating the process of research and development.

## 3.5 Control System Software

### 3.5.1 Controller Software

After building the hardware connection between the relays and the Arduino, initial testing involved working with the Arduino firmware itself to create simple patterns and displays. This was useful, but prevented significant complexity or dynamic behavior from being reasonably efficient to create. Though many interesting pseudo-random field patterns were developed which could be run entirely on the Arduino hardware platform; updating these patterns (or other controller-resident software generating these patterns) required a host machine to edit, recompile, and overwrite the firmware on the Arduino.

### 3.5.2 Controller to Host Serial Protocol

As the project evolved, a simple low-overhead driver program was created to run on the controller hardware, which would listen continuously over a serial USB link for low-level instructions from a host machine, and control the magnets accordingly.

The protocol used between the Arduino and the Host machine is a simple character-based (8-bit) protocol, each instruction was comprised of a single character (Table 3.1).

| Operand | Meaning | Operand | Meaning |
|---|---|---|---|
| 1 | Toggle Magnet 1 | A | Turn On Magnet 1 |
| 2 | Toggle Magnet 2 | B | Turn On Magnet 2 |
| 3 | Toggle Magnet 3 | C | Turn On Magnet 3 |
| 4 | Toggle Magnet 4 | D | Turn On Magnet 4 |
| 5 | Toggle Magnet 5 | E | Turn On Magnet 5 |
| 6 | Toggle Magnet 6 | F | Turn On Magnet 6 |
| 7 | Toggle Magnet 7 | G | Turn On Magnet 7 |
| 8 | Toggle Magnet 8 | H | Turn On Magnet 8 |
| 9 | Toggle Magnet 9 | I | Turn On Magnet 9 |
| 0 | Turn Off All Magnets | n | Pause 10ms |
| a | Turn Off Magnet 1 | N | Pause 50ms |
| b | Turn Off Magnet 2 | p | Pause 100ms |
| c | Turn Off Magnet 3 | s | Pause 500ms |
| d | Turn Off Magnet 4 | - | Pause 1000ms |
| e | Turn Off Magnet 5 | S | Pause 2000ms |
| f | Turn Off Magnet 6 | ? | Print Magnet State |
| g | Turn Off Magnet 7 | | |
| h | Turn Off Magnet 8 | | |
| i | Turn Off Magnet 9 | | |

**Table 3.1:** Serial Protocol Operands, Protocol v1.1

This minimized communication delay between software triggering and magnetic field generation, helped minimize parsing complexity on the controller side, simplified generation complexity on the host side, and enabled simple live human performances without any host software, other than a serial port terminal.

Using this terminal as an interactive mode was assisted by including an instruction to return the current state of the magnet array for debugging purposes. The system also allowed for dynamic control by a ferrofluid performance artist, working with a palette of previously-composed programmed short sequences of magnet instructions [10].

This protocol also allowed for more complex, automated software control of the magnet array such as responding to audience members interacting through sensors, as well as enabling the building and sending of large-scale fixed or pseudo-random sequences. The ability to build larger scale sequences in particular, greatly accelerated research into building functional patterns of magnet control, including ideal impulse length and adjacent magnet field production overlap timings, for example. With this protocol, more interactive, synchronized, and complex displays can be created by using this hardware as a peripheral to a system with much more processing and sensing capacity, to create interactivity or feedback. In addition, host software can be developed and improved more quickly and efficiently than controller software, as any programming language able to communicate with a virtual USB serial port can be used to control the magnet array.

### 3.5.3 Host Software, Magnetic Field Pattern Development

To fully realize the vision of a software-controlled ferrofluid display, code was created on the host side to use the protocol to control the systems magnetic field and animation.

**Figure 3.16:** *First Vertical Motion Test* Paul Jacobs (2013)

This magnet control protocol, along with companion software on the Host machine, helped build up a series of patterns showing increasingly interesting behavior, and lead to the first successful vertical movement observed in this project - a surprisingly difficult feat. By testing and iterating a set of timing and magnet trigger patterns was found that would work together to accomplish a task that had proven impossible before that: to move ferrofluid vertically upward (Fig. 3.16) [9].

Previously, with controller-board pattern composition, timing values were required to be manually estimated and typed in advance without the driver program, and attempts to successfully grab the ferrofluid from a lower magnet to a higher one consistently failed due to timing issues.

When the lower magnet released too early or the upper magnet engaged too late, most of the fluid would be dropped to the base pool of fluid. If the lower magnet released too late or if the upper magnet engaged too early, much or all of the ferrofluid would be stuck in the lower magnets field and would not be drawn upward with enough force to move it to the higher magnet, leaving it to drift slowly downward instead.

Further, though the lower magnet had to be initially powered to impart an upward inertial impulse to the ferrofluid, the lower magnetic field had to be disabled as closely as possible to the moment that half of the captured ferrofluid had passed the center of the magnet, or its field would slow the upward momentum of the fluid.

At the same time the lower magnet shuts off, the upper magnet must engage, adding to the existing momentum to pull the ferrofluid further upward. The ability to fling the fluid up to the second level of magnets is a tiny but critical building block in composing an interesting display. Even working with just one magnet, tiny variations in the timing of the pulse can lead to wide variations in ferrofluid behavior (Fig. 3.17) [11].

Software written in perl was created on the host machine to use the protocol to drive the ferrofluid system as an external peripheral to the host machine, sending streams of timing and control data in real time to create visual effects. The host machine may, in determining the proper stream of timing and control data to send to Forces of Nature, process input other peripherals such as a LEAP motion sensor to allow interactive control, or a camera system to provide input to a dynamic feedback system monitoring the movement of the ferrofluid, and controlling the ferrofluid display using that information - such as building up all available ferrofluid on a given second level magnet and then immediately moving it side-to-side once the camera detects a relatively steady state has been reached.

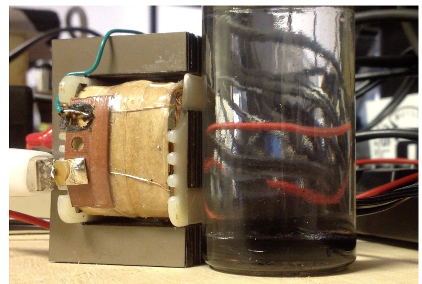

**Figure 3.17:** Single Magnet, Varying Pulse Timing Research Setup

Though this same process of iterative development is necessary in developing timing patterns on the host machine, the significantly faster development cycle makes it possible to find reliably working sequences to create this and many other visual effects which could be recombined to show longer sequences.

To better analyze the control mechanism provided by the system, several of these mid-level sequences or "gestures" will be discussed. To understand these sequences, it will be necessary to refer to the Serial Protocol Operands table (Table 3.1) and the table showing the magnet numbering arrangement for the second iteration, as used in the most recent public exhibition of Forces of Nature, at MAT's 2014 End of Year Show (Table 3.2).

| | |
|---|---|
| 5 | 1 |
| 6 | 2 |
| 7 | 3 |
| 8 | 4 |

**Table 3.2:** Magnet Numbering Arrangement for 2014 End of Year Show. Magnet 1 is also Magnet A, 2 is B, etc.

Several named gestures were used in the show. A set of gestures were created to be used as a higher level language, some of which directly translate to lower level instructions.

Some gestures are simple: 'wait' will simply transmit an 's', causing a pause of 500ms. A 'clear' simply sends "0pp", which will shut off all magnets at the first operand, and then pause for 20ms before running any further instructions, to allow any ferrofluid clinging to upper magnets to detach and begin to fall. 'fillRightPauseDrop' sends "abcdABCDSSSSSSabcd", which first turns off the right side in case any were previously on, then turns on the whole right side, waits 12 seconds with the fluid in the energized magnetic field, and then drops them all at once.

A more complex example is ‘rise1’, which sends “HDNhdGCNgcS.” This powers up the bottom two magnets, leaves them energized for 50ms, turns them back off, and then powers up the two magnets above that for an additional 50ms, before turning those off and pausing for two seconds.

The full source code to the host machine control software used in MAT’s 2014 End of Year Show is included (Listing 3.5.3). These gestures and several more are included. At a higher level, this program is essentially a “Sculptural Jukebox”, playing back predefined animated sequences either in a particular scripted order or in completely random order, with random perturbations in sequencing.

Though this program is merely pseudo-random, including sensor input or input from a computer vision system processing the output of a camera could enable true interactivity and feedback of the real word implementation of the system back into its controlling software.

---

**Listing 3.1:** SculpturalJukebox.pl - 2014 EOYS Host Machine Code

```
#!/usr/bin/perl

# Set up the serial port
use Device::SerialPort;

# Set up the leap - not yet implemented
#use Device::Leap;

my $port = Device::SerialPort->new("/dev/tty.usbmodem1421");
```

```
$port->baudrate(115200); # you may change this value
$port->databits(8); # but not this and the two following
$port->parity("none");
$port->stopbits(1);

# now catch gremlins at start
my $tEnd = time()+5; # 2 seconds in future
while (time()< $tEnd) { # end latest after 2 seconds
  my $c = $port->lookfor(); # char or nothing
  next if $c eq ""; # restart if noting
  last;
}
while (1) { # and all the rest of the gremlins as they come in one piece
  my $c = $port->lookfor(); # get the next one
  last if $c eq ""; # or we're done
}
print "Writing..";

%run = (
    "flingUpFromBot" => "HDNhd",
    "wind"           => "ABCDEFGHSSSSSabcdSSSABCDefghS",
    "fillBoth"       => "8
         s87s76s65s54ssSss43s32s21s1ss8s87s76s65s5sSss4s43s32s21s1sss8s87s76s65s5ssSs4s43s32s21s1sss",
    "fillRightPauseDrop" => "abcdABCDSSSSSSabcd",
    "fillLeftPauseDrop" =>  "efghEFGHSSSSSSfghSefgh",
    "clear"          =>  "0pp",

    "topRightTurn"   =>  "abcdABCDSSSbcdEaSFeSBfSCbSSScFSfSSS",

    "wait"           =>  "s",
    "wait1"          =>  "ss",
    "wait6"          =>  "SSS",

    "rise0" =>  "48nnnnn48ss48nnnnn48ss348nnnnn48ss3748nnnnn48ss748nnnnn48ss0",
    "rise1"          => "HDNhdGCNgcS",

    "allOn"          =>  "ABCDEFGH",
    "allOff"         =>  "0",
    "allLeftOn"      =>  "EFGH",
    "allLeftOff"     =>  "efgh",
    "allRightOn"     =>  "ABCD",
    "allRightOff"    =>  "abcd",

    );

while(1) {
  if (rand(10)<3) {

    foreach(qw/
    wind
    topRightTurn
    flingUpFromBot
    wait1
    fillRightPauseDrop
    clear
    fillLeftPauseDrop
    clear
    rise1
    wait1
    rise0
    clear
    flingUpFromBot
    clear
    allOn
    wait1
```

```
    allLeftOff
    allRightOn
    wait1
    allLeftOn
    allRightOff
    wait1
    allLeftOff
    allRightOn
    clear
    allLeftOn
    wait1
    allRightOff
    wait1
    allLeftOff
    allRightOn
    wait1
    allOff
    fillRightPauseDrop
    fillLeftPauseDrop
    clear
        /) {
        next if (rand(20)<4);
        $port->write($run{$_}) if (length $run{$_});
        print "$_\n";
        sleep(5) unless /wait/;

    $port->write($run{clear});

    }
} elsif (rand(10)<8) {
    @sequences = values %run;
    $port->write($sequences[rand(scalar @sequences)]);
    $port->write($run{clear});
}

}

END {
    $port->write($run{clear});
}
```

# Chapter 4

# Results

**Figure 4.1:** *Fluidic Space Forces of Nature v0.1* Paul Jacobs (2013)

## 4.1 Forces of Nature v0.1 (2013)

Various results were found from working with subsequent iterations of the project. *Fluidic Space*, the first iteration (Fig. 4.1), was built using knowledge gained from experimentation with individual magnets and smaller ferrofluid vessels. Control hardware and software were only introduced later on, as construction of the hardware they depended upon took much more time than planned for. The home-built magnets required an average of 8 hours each to construct, with the potential for mistakes requiring the purchase of a new transformer and starting its conversion from scratch.

The power system's weight and its short tether to the circuitry involved in the controller board made moving the first iteration system awkward. The fact that the controller board had another, shorter tether to the large, heavy magnet grid made moving the system difficult without breaking one of the dozens of necessary wire connections. Three separate power strips were required to distribute enough power to the 10 separate power transformers necessary (8 magnet power sources, one controller board power source, one host computer power source) to use the first iteration system.

In addition, the visual appearance of *Fluidic Space* left much to be desired in terms of polish and professionalism. Thus it is considered to also be version 0.1 of this work, *Forces of Nature*.


**Figure 4.2:** *Forces of Nature v1.0* Paul Jacobs (2014)

## 4.2 Forces of Nature v1.0 (2014)

The second iteration of this work is version 1.0 of *Forces of Nature*, (Fig 4.2) the title for the work as shown at the 2014 MAT End of Year Show.[1] Design goals for the second iteration included improving the appearance, designing and

[1]This title, *Forces of Nature*, will be used for future versions of this system.

building a custom enclosure for the system, adding integrated lighting, increasing portability and reliability, increasing the number of working electromagnets, and reducing the size of the visible functional components. The size reduction was accomplished by integrating the magnets into the custom enclosure and trailing wires from the attached relay board down to the control and power distribution components hidden in the podium below. Waterproofing and cooling issues were central in the second iteration. Both were addressed, but insufficiently so, with the heat build-up causing the ferrofluid to lose its spiking ability 90 minutes into the show, and showing visible warping of the magnet support plate after 4 hours. In addition, the enclosure which had seemed to be fully waterproof began leaking water and then ferrofluid 2 weeks following the show.

# Chapter 5

# Conclusions

This project was the beginning of a programmable hardware-software platform for making a wide variety of magnetic field-related art. The system can be extended and evolved by building upon the software control protocol, by using it with various types of hardware, or by using the same hardware in different configurations, such as to power an open-air horizontal ferrofluid display.

It started with a simple concept: The hardware and software creates the field, the ferrofluid makes it visible. Research and development of a software-defined magnetic field generator was surprisingly difficult, providing many more opportunities for learning along the way than expected. Obtaining a reasonably powerful electromagnet, at a reasonable price, that could operate within listed operating voltage limits, proved to be impossible. Raising power beyond those limits inevitably generated excess heat, which caused other issues in turn. Each iteration had its own balance of compromises made to address these issues.

Ferrofluid itself was extremely difficult to work with, staining everything it touches, jumping unpredictably in the presence of magnetic fields, and finding its way through materials that are non-porous to water.

The commercial magnets did not reach a power level found to be expressively satisfactory after the previous year's magnets had demonstrated such strength (but at prohibitively high thermal cost), and after observing the heat problems they still presented, the home-built magnets are most attractive to use again in future iterations.

Even taking into account all the difficulties, this project has been successful in opening the door to software-defined ferrofluid art. Future developments in programmable ferrofluid displays can build upon what has been learned and developed here. Modularity in terms of separable magnetic field generation from power and control systems has proven to increase development efficiency dramatically, and the programmable nature of the platform will spur new displays as time goes on.

# Chapter 6

# Future Work

## 6.1 Magnetic Field Generation

Increasing the number of magnets and corresponding control systems as well as increasing the precision at which the magnets are driven are both likely to be fruitful areas of further study. In particular, using a high-voltage-tolerant transistor array to drive the electromagnets is a tempting avenue of exploration. In addition, other arrangements of magnets would be worth exploring and could be controlled through a similar control protocol. Adding magnets to the side of displays, or on opposing sides of a vessel, would be an interesting start to a new application of this platform. Experiments using novel magnet arrangements may lead to development of more interesting magnetic field shapes than have been observed thus-far.

## 6.2 Modifying Ferrofluid

Many other decisions made for the two iterations of this project, as well as the series of experiments leading up to the first iteration, point in directions worthy of further examination. Concept Zero's success in creating colored ferrofluids rekindles the desire to experiment with other coloring agents including metals. Behavioral and textural modification seemed to embody the most potential for future work when adding needles of bismuth to the ferrofluid. Other consistencies of bismuth appear to be worthy of experimentation. It seems feasible as well that an anti-ferrofluid could in theory be created using bismuth, the most strongly diamagnetic naturally occurring material, in place of magnetite, a very strong magnetic material. Since these are opposite properties and interesting behavior has already been observed using bismuth in magnetic fields, further research is warranted in this area.

## 6.3 Alternative Magnetic Visualization Media

Another consideration is that other substances might be used in place of ferrofluid. This field generator as well as the seed of the protocol it currently uses could develop into something capable of affecting other magnetically responsive substances, such as candle flames or MR fluid.

## 6.4 Power Distribution

The weight of the power distribution system was found to be quite cumbersome. For future work a hybrid system is suggested, with fewer power sources at higher amperage, or with variable power simulated or implemented using PWM or transistor-based control, respectively, rather than the simple relay-based control implemented here. With more sophisticated circuitry, power to a given electromagnet could be activated and routed when and only when its going to be turned on. For lower power situations power could be divided between multiple magnets to further reduce power source requirements, at the cost of display quality and capabilities. Research into more complex power distribution as well as the effect of lower power display timing and display qualities may be worth pursuing.

## 6.5 Cooling

Some suggested possibilities for stronger cooling in future work are:

- Add dry ice crushed into small particles into the magnet chamber, with the resulting vapor being dispersed into the air either at a distance from the project, or near the floor for effect.

- The above, but with the addition of a non-circulating, non-conductive fluid such as mineral oil, to spread out the effect of the dry ice's cooling.

- Install a fluid circulation cooling system comparable to those used in high-performance custom built computer systems.

- Add a thermally conductive plate to the back of the magnets and install an active phase-change cooling system onto that.

- Create a removable magnet module that can be cooled in advance for limited term performances.

## 6.6 System Modularity

In future iterations, several of these MFG modules could be tiled and controlled by a single host machine to create larger fields in a 2D arrangement. For example, four of these systems could generate a field with twice the width and height but at the same resolution, or three systems could be used on three sides of a larger vessel, etc.

Host software could be built to take this into account and communicate with multiple instances of the system simultaneously to create larger scale displays.

## 6.7 Interactivity and Feedback

On the software side there is significant future work available in the area of interactivity as well as feedback, which were not demonstrated in this project.

Due to hardware issues, less time was spent on software for this project than would have been ideal. Building upon the low-level protocol with more complex software than the described "sculptural jukebox" approach would allow low-level (magnet control and timing) and mid-level gestures (preprogrammed sequences in low-level protocol, such as "allLeftOn" or 'EFGH') to be controlled from a higher level algorithm involving input from sensors such as a LEAP device or a camera focused on the display itself.

## 6.8 Expressive Potential in Live Performance

Forces of Nature's protocol is designed to be composed in simple text strings. A live performance interface could integrate sensor inputs as well as a higher level host-machine-based textual interface to trigger sequences, ongoing actions such as beat pulses that can be added to signals generated by the user, or other similar tools for expression as they evolve.

# Bibliography


[1] *90lbs DC 12V Holding Electromagnet Lift Solenoid* [n.d.].
**URL:** *http://www.amazon.com/gp/product/B008JLWRYY*

[2] Albu, C. [2011], 'Five Degrees of Separation between Art and New Media', *Artnodes* **0**(11).

[3] Chemical Bouillon [2014], 'Ferrofluid - Strip form'.
**URL:** *https://www.youtube.com/watch?v=jOpdIRWbZrw*

[4] *Electromagnet* [n.d.].
**URL:** *https://en.wikipedia.org/wiki/Electromagnet*

[5] FerroTec [n.d.], 'EFH Series Ferrofluid Material Safety Data Sheet'.
**URL:** *https://ferrofluid.ferrotec.com/downloads/efhmsds.pdf*

[6] Frey, M. [2006], 'SnOil'.

[7] Hammond, C R [2005], *CRC Handbook of Chemistry and Physics*, A Ready-Reference of Chemical and Physical Data, 95th edn, CRC Press.

[8] Hughes, C. [2013], 'Glass ferrofluid display prototype'.

[9] Jacobs, P. [2013*a*], 'First Vertical Motion Test'.
**URL:** *https://vimeo.com/67732086*

[10] Jacobs, P. [2013*b*], 'Forces of Nature v0.5 Performance Demo'.
**URL:** *https://vimeo.com/148948608*

[11] Jacobs, P. [2013*c*], 'Magnet Timing Research 2'.
**URL:** *https://vimeo.com/148925450*

[12] Jacobs, P. [2015*a*], 'Forces of Nature v1.8 - 3rd Level'.
**URL:** *https://vimeo.com/150742112*

[13] Jacobs, P. [2015*b*], 'Forces of Nature v1.8 - Dandelion'.
**URL:** *https://vimeo.com/150742806*

[14] Jacobs, P. [2015*c*], 'Forces of Nature v1.8 - LilDLion'.
**URL:** *https://vimeo.com/150743993*

[15] Jenkins, N. [2013], 'Fun With Ferrofluids'.
**URL:** *https://www.youtube.com/watch?v=AVzSJJNDOkc*

[16] Kodama, S. and Miyajima, Y. [2007], 'Morpho Towor / Two Standing Spirals'.
**URL:** *http://sachikokodama.com/text/works/morphoTwo/morphotwo2.html*

[17] Kodama, S. and Takeno, M. [2001], 'Protrude, Flow'.

[18] KoserLab [n.d.], 'What is a Ferrofluid'.
**URL:** *https://sites.google.com/site/koserlab/outreach/what-is-a-ferrofluid*

[19] *Magnetorheological Fluid* [n.d.].
**URL:** *https://en.wikipedia.org/wiki/Magnetorheological_fluid*

[20] Metlitz, M. [2014], 'Ferrofluid Sketch Model'.
**URL:** *http://web.mit.edu/2.744/studentSubmissions/sketchModels/jedimasters/metlitzm/*

[21] Nada, N. and Hughes, C. [2014], 'Colored Ferrofluids'.
**URL:** *http://www.czferro.com/buy/?category=Colored+Ferrofluids*

[22] Oefner, F. [2012], 'Millefiori'.

[23] *Q & A: Heating Magnets* [2015].
**URL:** *https://van.physics.illinois.edu/qa/listing.php?id=2744*

[24] Rauschenburg, R. [1971], 'Mud Muse'.

[25] rocketman221 [2011], 'Strong Electromagnet From An Old Transformer'.
**URL:** *http://www.instructables.com/id/Strong-Electromagnet-From-An-Old-Transformer/*

[26] Rubin, Z. [2010], 'FerroFluid Fountain!'.
**URL:** *https://vimeo.com/9711771*

[27] *Snake_(video_game)* [n.d.].
**URL:** *https://en.wikipedia.org/wiki/Snake_(video_game)*

[28] Stankovic, D. [2012], ‘What kind of suspension liquid should be used with ferrofluid (so it does not stain the glass)?’.
**URL:** *http://chemistry.stackexchange.com/questions/409/what-kind-of-suspension-liquid-should-be-used-with-ferrofluid-so-it-does-not-st*

[29] Steers, L. A. [n.d.], ‘Ferrofluid Display - Lee Anne Steers’.
**URL:** *http://leeannesteers.com/Ferrofluid-Display*

[30] Xman [n.d.], ‘Ferrofluid and soap bubbles HD’.
**URL:** *https://www.youtube.com/watch?v=9wTGKpq3Ugk*

# Appendix A

# Forces of Nature v1.8

## A.1 Introduction

Due in part to consequences of staining and difficulty in waterproofing, a relatively small proportion of interesting results from the first and second iteration were properly documented. Recognizing this, as well as desiring a more professional looking finish to the work, a third iteration of this project was designed and built, with an emphasis on combining the most successful elements of previous iterations, as well as evolving modularity and re-usability toward overcoming difficulties of documentation and reliability. It is felt that, as of publication time, this version still has some work to be completed, thus the iteration described is tagged as Forces of Nature version 1.8.

**Figure A.1:** *Forces of Nature v1.8* Paul Jacobs (2015) Case

## A.2 Methodology

Electromagnets used in the third iteration were the same custom-built type described and used in the first iteration, as those clearly were more powerful. The arrangement used was a blend of the first two iterations, as a 3x3 grid was chosen

(Fig. A.2), but with no spacing in between the magnets in the module. Instead of attempting to cool the system over a long period, the magnet module is removable and designed to be frozen prior to public performances to allow for heat build-up.

Wiring between magnets and controller board has been made significantly more flexible through the use of a set of 1/8" DC power plugs, with a similar set of plugs connecting the controller board to the power sources for each magnet as well as one for the board itself and one for the internal lighting system. A detachable USB cable is the only other required connection to operate Forces of Nature v1.8. Magnet and controller wiring is entirely internal to the device, hidden behind a wooden or mirrored panel placed in between the MFG and the Display vessel. The MFG is elevated by 1 inch so as to more effectively project a field to lift the ferrofluid into interesting animated patterns, avoiding projection of the field into solid glass where it cannot be used artistically.

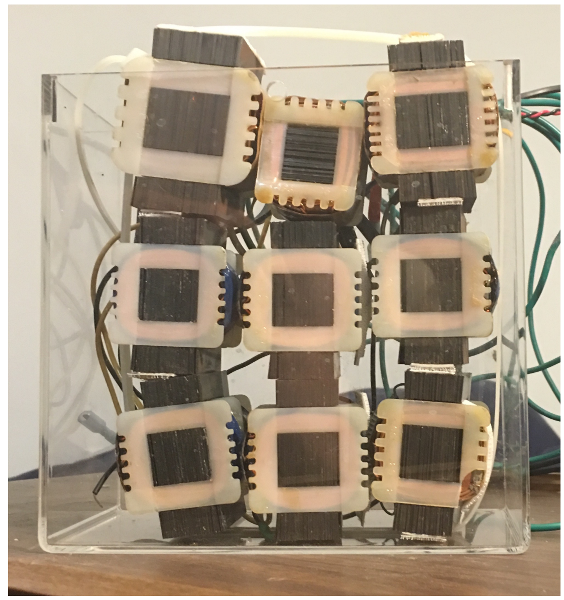

**Figure A.2:** *Forces of Nature v1.8* Paul Jacobs (2015) Prototype Magnet Module Arrangement

The core innovation in this iteration was the custom-built wooden case (Fig. A.1), which was designed to cleanly enclose a separately replaceable module for the Display, with embedded lighting in the enclosing compartment. The MFG module which is now enclosed in it's own removable plastic assembly; and the control system is hidden behind the MFG, connected between it and the outside world. Power and cables are connected to a series of plugs that extend out through a hole in the back of the wooden case, the USB cable connects through that same opening.

Refinements were made to the Solution Liquid, which in this iteration is 65% isopropyl alcohol, 35% distilled water. Other mixtures and ingredients were tested, this solution struck the best balance between dealing with staining and maximizing the time before the ferrofluid is dissolved into the solution liquid with only magnetite particles remaining.

## A.3 Results

Staining of the container remains a serious issue, to the extent that Display modules have to be produced in advance of a given showing and never used prior. Even with these precautions, staining causes difficulty in properly seeing the shapes formed by the ferrofluid. It is hoped that by working with other artists who have been more successful in developing Solution Liquids for permanent displays, this project may be advanced further.

A major improvement in this iteration is that some fairly interesting behavior has been captured on video for this Appendix. Design documents for the case as well as photos and video links documenting this revision follow. Videos featuring particularly patterns such as dandelion-shapes as seen in (Fig. A.3) can be viewed at [12], [13], and [14].

**Figure A.3:** *Forces of Nature v1.8* Paul Jacobs (2015) Close-Up