Computer Mediated Expression in Paint

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ABSTRACT

In this thesis, we present a design and implementation of a framework for computer mediated expression. The computer's role in mediation is dual—both for enabling new forms of creative work as well as enabling creative work for populations for which it is not currently accessible, with the latter being the main focus of the work. The system consists of input, processing, and output stages. Simplicity of integration and modularity are the primary design goals which inform the architecture for the processing stage as well as the need for the interface layers to be universal and simple. Several input modalities have been realized and tested, including wearable IMU, airflow, and eye-tracking. One primary output modality has been constructed in the form of a robotic multi-color airbrush. Several evaluations were performed to assess the system's usability from a user's perspective as well as that of a developer. A survey was also conducted to evaluate the potential impact on the general public's perception of ability in the context of disability, particularly with respect to self-expression with paint.

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Chapter 1

Motivation & Overview

"We must humanize technology before it dehumanizes us"— Oliver Sacks

1.1. Motivation

Positive Psychology[1] describes a framework that gives rise to a model of five primary elements of psychological well-being (PERMA): Positive emotions, Engagement, Relationships, Meaning, and Accomplishment. Self-expression can at one time contribute to all of these elements. Painting, in particular is an adept practice for capturing each category with profound impact.

Studies show that making visual art improves the subjective well-being of patients in across all aspects of the Positive Psychology PERMA model[2].

- **Positive Emotions**
  Art making promotes enjoyment of the sensuality of color and texture. The recursive process of creating an image continuously heightens one's pleasure.

- **Engagement**
  Art-making is described as enriching the mental life of its practitioners, enhancing self-worth and social identity.

- **Relationship**
  Practitioners tend to experience an increase in the value of connections with their immediate family, the world outside, and the home itself.

- **Meaning**
  Art-making protects an individual's identities and creates opportunities for validation.

- **Accomplishment**

  Art making continually presents new challenges, encouraging playful experimentation and renewed ambitions.

For these reasons, and others as elaborated on in subsequent sections, painting, an essential form of self expression, is a perfect candidate for increasing resiliency, especially for people living with mental or physical disabilities. Yet, painting remains inaccessible to large sections of such populations. Technology can improve accessibility and open amazing new worlds of creativity to everyone, especially those with limited expressiveness otherwise.

In his work at the Media Lab titled 'Expressive Gesture Controller for an Individual with Quadriplegia[3]', Adam Boulanger presents the construction and deployment of a performative head-mounted continuous input device which is designed to be assistive for a person with quadriplegia. With the device, a quadriplegic individual was able to author and perform a musical composition.

Boulanger's work spanned several years, and tackled many design and implementation challenges. In the conclusion of his paper Boulanger writes:

> *"[The user] is physically limited in his ability to conduct expressive movement. This belies the fact that he is an expressive person. Knowledge of expression without the sufficient structure to allow an individual to apply that knowledge is replete in the general population. To move in the direction where our technologies are prosthetics to enable expressive and creative work from ubiquitous platforms, distributed throughout a population of would-be artists, we must investigate the abstraction of creative processes and how to adapt these abstractions (in the form of mapping and parameter assignments) for as many works and as many individuals as possible."*

Boulanger's conclusion is an inspiration to this work, and in particular we attempt to move towards realization of the goals it sets, as applied to the domain of painting.

With respect to self expression in paint, the population might be categorized generally into three groups: painters, those who are capable of but do not paint, and those who are physically incapable of painting due to a disability. This grouping could also be thought of as a continuum, representing ranges of abilities and inclinations to paint. Without arguing that people should want to paint, one could easily argue that people should be able to choose to paint. As will be shown throughout this work, there are two gaps in this categorization, one is the ability gap as perceived by the individual, and the other is the ability as perceived by society. The main goal of this thesis work is the development of technology that enables painting for populations for which it is not accessible while also moving towards an elimination of the notion that there are individuals who cannot paint.

Beyond the psychological well-being benefits, there are many benefits in assisted physical and occupational therapy, similarly to Biogaming[4] solutions which show promise in enhancing physical therapy effectiveness. Additionally, the diagnosis and tracking of neurological/muscular conditions such as post-stroke muscle control[5] issues, ALS progression, etc. also show promise for the prospect of integrating expressive technologies.

1.2. Structure

We present a design and implementation of an end-to-end system integrating sensors, processing, and actuators to create a system for painting which is accessible and expandable.

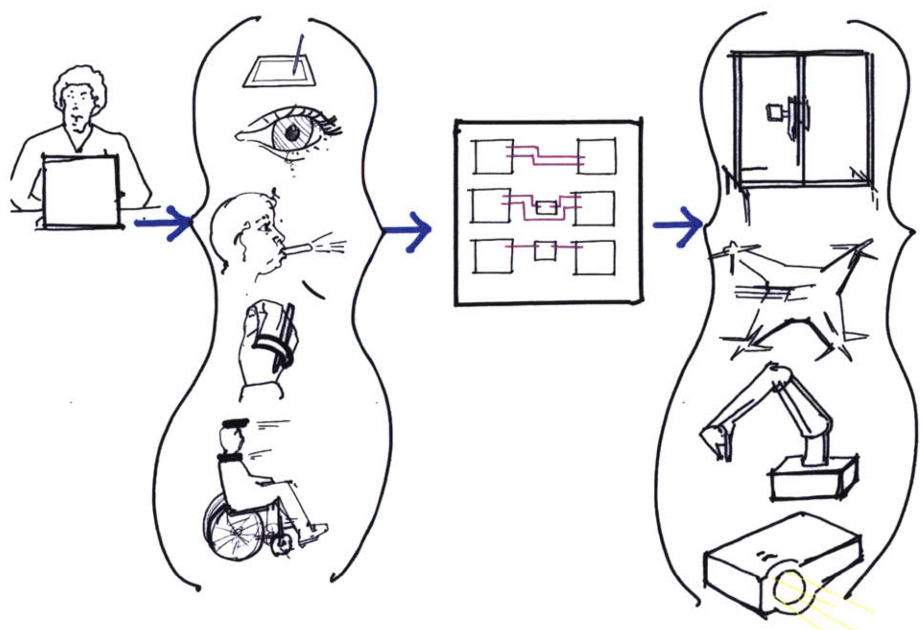

Figure 1 - User, Input Options, Processing System, Output Options (illustration: Benjamin David Tritt)

As demonstrated in figure 1, a user has a choice of one or more input methods, which get processed through a configurable flow system which supports filtering and routing of data streams, and finally output on one or more output systems. Input/output mechanisms shown are a examples of existing methods, and can be easily extended further as demonstrated later in this thesis.

The user's interaction environment is entirely flexible, and depends on the inputs/outputs used, and the user's preferences/needs. The setup used in our testing environment is shown in figure 2 below.

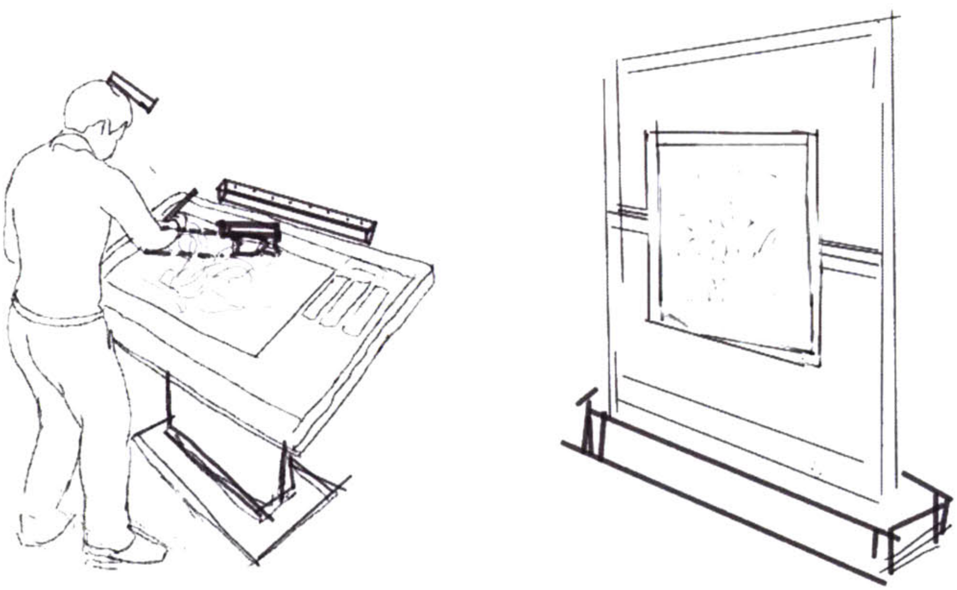

Figure 2 - Instrumented user with variety of interfaces, and gantry-based output mechanism (illustration: Benjamin David Tritt)

In the setup presented above the user is wearing a head-mounted laser, a hand mounted-IMU (in a phone), uses a Wacom pen, and employs eye-tracking. The various inputs can be combined, in virtually any way desirable to the user, and create a custom interaction environment. The console, for example, is entirely unnecessary in settings where the user wishes to use only input methods which do not require a screen; such as eye tracking, or IMU-based inputs.

1.3. Thesis Outline

This thesis begins with exploration of three issues: the therapeutic benefits of art and expression, the changing role of new technologies in expanding that expression, and changing trends in the perception of human disabilities. Painting, specifically, is explored as a focus, with an emphasis on the differences between the practice of painting in the digital vs. physical domains. The potential of technology to bridge these domains is outlined, with examples from recent projects at our lab.

We then review the design considerations we have developed in order to guide our work, and the collaborations supporting our process from the initial design and through the iteration towards the final prototype.

Related work is explored, covering existing input and output devices for expression. We then detail the design and development process, the selection of software and hardware components, and general architecture. A review of the evaluation is provided and discussed, including study protocols and result analysis and conclusions, including possible future work.

Chapter 2
Introduction and Context

"Drawing is like making an expressive gesture with the advantage of permanence." — Henri Matisse

2.1. Expression in Paint

Painting is both an expressive form of visual art and a form of therapy. It has been shown to have positive effects on well-being[6] in occupational therapy, physical therapy and art therapy.

One's ability to paint is defined not only by their physical capabilities, but also by the tools available to them. The paintbrush has been a main tool for painting, dating back, in various forms, tens of thousands of years. Brushes are generally used as handheld tools that require a level of dexterity which excludes large populations with neurological and muscular conditions such as ALS, Parkinson's, Cerebral Palsy, Paraplegia, Stroke, and others.

Assistive technologies exist for a wide and ever-growing range of activities in both commercial and academic research, whose main focus is enhanced productivity and self-sufficiency. Despite the many apparent benefits of expressive art activities, one rarely finds assistive technologies for creativity and enhanced self-expression.

Of the technologies that we were able to identify, the majority are either entirely digital forms of art such as eye-tracking based computer painting, or purely physical/mechanical tools such as rigs for mouth-painting[7]. The former benefits from the adaptability of digital modalities, and the latter benefits from tangibility, multi-sensuality and the many other benefits of physical art forms.

It is not surprising that this is the case, as the famous idiom goes "the squeaky wheel gets the grease", in the sense that the visible disabilities get the most attention. When observing a person with a disability, the explicit physical limitations are more apparent than those which are more implicit and relegated to the mind, psyche, and emotions.

Through the process outlined herein we designed and constructed a system combining digital and physical mechanisms in an attempt to achieve a best-of-both-worlds combination, with the primary goals being increased accessibility of painting as a creative, expressive, and therapeutic process.

2.2. Perspective and Current Trends

Google's ngram viewer enables analysis of the usage of terms over time[8]. The Google ngram plot in figure 3 below exposes interesting trends over the last few centuries with respect to the general attitude towards disability and the disabled. After a long period of relative stability in the frequency of use of both terms, the term 'disabled' starts to become less popular in the mid 19th century, perhaps due to displacement from the literature by references to disabilities themselves becoming more popular. The shift in popularity continued throughout the 20th century and even accelerated. Also notable is that the term 'disabled' reaches a plateau, while use of the term 'disability' continues to grow over the last 30 years.

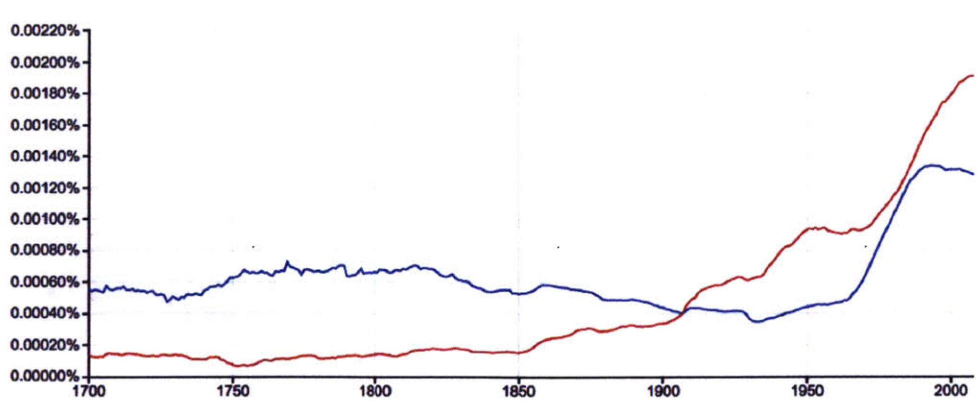

Figure 3 - Normalized appearance of unigrams 'disability' (in red) and 'disabled' (in blue) in the corpus of English books since 1700. Source: Google Ngram viewer

This distinction could be overlooked as an insignificant shift in fashionable phrasing or political correctness. Whether cause or correlation, the data does seem to suggest a genuine shift. These trends can be seen as a precursor to the rise of assistive technology and the transformation of the perception of disability throughout the western world.

At the time of the writing of this thesis, the term assistive technology is commonly used to describe software and devices that are designed to aid specific disabilities. These devices span many kind of technologies from no-cost DIY hardware hacks for holding tools[9] to mind-controlled robotic exoskeletons[10]. Ability Tools Weekly, part of California's Assistive Technology Act project, an organization mandated and funded by the U.S. Department of Education's 2004 Assistive Technology Act defines assistive technology as:

> *"Any device, gadget, hardware or software used by a person with a disability to do things for themselves that might otherwise be difficult or impossible to do because of their disability."*

This definition of assistive technology has been prevalent since the emergence of the term in the early 1990s. As can be seen from figure 4, the term gained its popularity in 1995 and has been stable in its representation in the corpus of English books since.

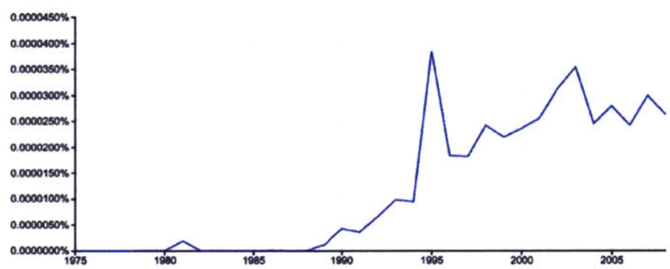

Figure 4 - appearance of bigram 'assistive technology' in the corpus of English book since 1975.
Source: Google Ngram viewer

Currently, attitudes towards disabled persons in particular and disability in general are in the process of shifting again, with the general trend being towards that of inclusion and integration[11], as opposed to treating disabled individuals as requiring separate treatment. This shift is apparent through popular media, academic publications, advocacy groups[12], as well as government policies.

Attitudes towards technology are shifting as well. In addition to the current trend towards perceiving all technology as assistive[13], there exists another, parallel, conceptual shift. The fabrication revolution[14] is rapidly altering notions of the both the speed and scope of innovation, iteration and development. In the intersection of these two revolutions, events such as hackathons specific to innovation in accessibility are becoming prevalent. Many such hackathons are held at MIT every year[15][16][17] and the topic of bridging the worlds of makers and NGOs is subject of ongoing research at MIT. One example is Tomer Weller's work of the Viral Communications group in his thesis under the working title 'This is How' (expected Sept. 2016.) connecting makers and communities to synergize for social impact. In anticipation of the fabrication revolution's impact on assistive technology development we modeled the framework to be open and friendly to hackers and makers.

2.3. Expectations and Ability

An important yet often overlooked aspect of limitations as associated with disability is the fact that a significant portion of the limitations which a disabled person experiences is derived from the expectations that are associated with the disability regardless of whether or not they actually truly derive from the disability itself[18]. One such example is that blind people are not expected to be able to navigate on their own - let alone ride bicycles - however, it is routinely demonstrated[19] that this is possible by efforts such as Daniel Kish's 'World Access for the Blind' organization.

Daniel is capable of basic navigation of spaces and detection of objects from plants to buildings through echolocation. His ability to echolocate apparently stems from a normal neural process[20] rather than an abnormal one. Combined with the observation that blind kids do have the tendency to use audio in their environment for navigation leads to the conclusion that the reason we don't see more kids achieve this ability to the same level as Daniel stems from society's expectation that the blind are unable to navigate. Daniel tells the story of a young blind boy going to his mother and telling her that he "heard a wall", and rather than celebrating this fact - the 'normal' response nowadays is to disregard the comment at best, or to actively tell the child to avoid saying that since it is perceived as strange.

Similarly to how Daniel discredits the notion that blind people cannot ride a bicycle, the story of blind artist Lisa Fittipaldi[21] refutes the notion that blind people cannot paint expressively. Technology can help amplify the efforts of pioneers like Daniel and Lisa.

In the context of ability being impacted by expectation, the role of technology is dual: both enabling an activity previously inaccessible to persons with certain disabilities, while at the same time positively impacting society's perception of the creative capabilities of the same population.

2.4. Technology and The Arts

There have been several distinct periods in art history that we witnessed shifts in the quality of creative output. The renaissance is noted for the invention of oil painting and printmaking. The baroque period brought new ways of reproducing effects of light and shadow in ways familiar to us now as photographic and cinematic. The nineteenth century brought photography as a new source material for capturing massive amount of visual information hitherto unavailable. All these changes brought about changes in three categories of improvement - quality, time and expense. Oil and prints made works cheaper, faster to create and reproduce, and of higher richness in quality. Lenses such as the camera lucida and later the camera obscura made accurate recording of light and proportions an almost mechanical process. Photography brought about numerous changes that not only changed painting but in many ways supplanted it with more captivating visual art forms. Each of these shifts made the visual arts, in some real measure, better, faster and cheaper.

2.5. Why Visual Art

There are many reasons that the visual arts in general, and painting in particular, are good candidates for the development of a universal access platform, including psychological factors (developmental, social, neurological) on the one hand and practicality of implementation on the other.

Social and Developmental Factors

Albert Einstein is known to have described his creative process as thinking of images first, and finding words later[22]. The process Einstein describes is probably familiar to us all, and clearly observable in children. Mark-making precedes language as a form of expression, and is often employed by psychologists to analyze a child's thoughts and emotional wellbeing. Both the expressive power of painting and the simplicity of the process make it an ideal candidate for this thesis work.

The perceptual-motor skill of drawing is often analyzed within a model of closed-loop movement control. In such models, the input a person perceives affects their kinesthetic choices in an ongoing manner involving perception of the world, one's body, and the relationship between the two. The result of the drawing itself creates a change in the observed physical world which in turn becomes additional input into this control loop. This form of connection to and expression within the world is highly intuitive. It is also a core principle in the design of human-machine interfaces and thus lends well to the utilization of existing digital interfaces towards a physical interaction.

Recording perception through interaction seems to be a basic human need, and one that develops in advance of explicit, or declarative memory. In the case of drawing, one is recording information as a means of self discovery as well as deliberate factual recounting. The representation is both a direct expression of an experience or memory and a method of recording one's unconscious feelings. It thus has the potential to impact one's perception of the world, oneself and the interaction of the two[23].

Practicality of Implementation

Controlling complexity and sustaining fast development cycles are key components to scaling software systems. Hardware systems, however, include an additional cost factor.

The low dimensionality of painting affords easy translation from relatively simple devices on both the input and output sides. On the input side, it allows the user to interact with the medium through virtually any existing input device that can be mapped to operate a computer mouse.

On the output side it allows for broad usage through simple planar mechanics and projections with simple affine transforms.

The plethora of available tools for interacting with paint in a digital form and the rich open-source communities around them provide rich ground for integration. The pervasiveness of the use of photo editing tools creates an ever growing set of hardware interfaces designed particularly for the purpose of painting. These range from simple stylus pens to Wacom-tablets, and most notably the recent release of apple's iPad Pro, the first modern apple tablet to work with a stylus.

Existing Use in Therapeutics

Painting is already in use as a medium for many kinds of therapeutic purposes, ranging from occupational, physical, and art therapies to psychoanalysis.

Painting is projecting personal experiences in the act of interpretation. It occurs at many levels simultaneously, including the sensory, cognitive, and affective levels; the results of which impacts on the complex sensory experience of the painter as well as audience of the art. It is not surprising that expression in art shows positive therapeutic effects, across the wide Expressive Therapies Continuum[24], many of which involve painting.

Gradual Learning Curve

Painting can be performed at varying degrees of complexity on many levels. Session length, for example, can range between minutes, hours and days. Simple paintings can be completed within minutes, allowing even those with little experience to see results and progress from the first attempt. Many other forms of expression, i.e. music and dance, require significant practice before any such results are to be expected.

Accessible Perception

Many describe the simple structure of canvas to be intuitive, including blind artist Lisa Fittipaldi, who describes the canvas as significantly easier to navigate than space[25].

Cultural Impact

History shows many examples of persons becoming artists by accident. One of the most prominent examples is the case of Henri Matisse, regarded one of the most important and influential painters of modern times[26], fundamentally altering the course of modern art[27].

Matisse studied law and was working as a court administrator. He first started to paint when his mother brought him art supplies during his long recovery period from appendicitis. He later describes the experience of painting as discovering 'a kind of paradise'. Later in his life Matisse suffered a debilitating illness. Diagnosed with abdominal cancer in 1941, he underwent surgery which left him bed/chair bound. Through this disability he shifted (with the help of his assistants) into new forms of expression.

Far from being the only case, it exemplifies the impact that enabling for even one person to practice visual arts could have on the field and on society.

2.6. The Digital-Physical Bridge

Advances in Augmented Reality and Virtual Reality in recent years prompt an investigation of the differences and similarities between digital and physical representations. Both interaction types have strengths, and they can be leveraged even further when combined. This work builds upon findings from previous projects in the Fluid Interfaces group which have shown the benefits of combining physical objects and an augmented digital environment[28][29]. These are further defined and explored in Yihui Saw's thesis on project Enlight[30]. We continue this tradition in our attempt to combine projection interfaces with physical objects, and expand upon it in that the projection appears to interact with the material, and cause permanent additive physical changes. As light is projected on a blank canvas, paint appears and the light disappears.

Physical Painting

What is painting?

The field of inquiry described as 'paint' or 'painting' needs definition as it is used to define a material, an action and an entire discipline. It's prosaic meaning, the substance of paint intended for dispersion over a substrate hides several other components which deserve to be expounded. Not uncoincidentally, painting's status as the sole holdout on adopting digital technology for any creative discipline is logical when one considers the complexity that defines this domain.

The medium of paint - pigments suspended in a liquid medium - is still used to define the discipline as it has been, up until this period, the only practical way of achieving the result we recognize as painting.

The Function of Painting

The said result, or the method in which paintings function is difficult to define, as it can only be captured in an individual's experience, not quantified in the same form as sculpture or architecture. The description of the desired result is as follows: the transformation of a uniform and undefined area into a visually complex 2.5D surface *and* an illusory window into an imaginary space.

The Painting as Object

The painting as object also affects the surrounding area, not unlike the way an actual window defines a building. Windows affect the experience of an individual wall, the character of the building as a whole and the relationship between inside and outside.

Painting as Object and Illusion

Painting thus, by virtue of its physicality *in addition* to its illusory nature, functions in two ways simultaneously in order to achieve the experience that allows us to define it as such. That is to say, it functions by combining two distinct domains that become mutually interdependent in the creation process. These two domains are the virtual and the real, or said differently, the illusory and physical. It functions simultaneously as both a window into an imaginary realm and a tangible creation projecting back into the physical space.

Until now, there has been no clear description or term for this interaction. We just call it "painting", but as any child experiences at their first moments of creating, the process seems magical. The experience of two places with no direct contact that seamlessly merge in the creation of this intermediary space, can only inspire wonder at both the need for a such a creation, as well as our natural ability to carry it out.

Physical Copies

Our experience tells us that seeing a painting on a computer screen is not a substitute for the actual painting, in that you cannot directly touch the image itself. That lack of tactility prevents the image from having any status within the domain of “painting.” A poster is closer, but it will still be in the realm of being "just a poster", not because it's a reproduction, but rather because it is flat - i.e. not containing the materiality of the painting itself.

Materiality in painting is composed of a few simple components that allow it to occupy the space of "painting". Most importantly, it is layered, it is tactile, and it exists in the context of space rather than information.

We do, unarguably, distinguish between an original and an image or print. Regardless of the reason why we distinguish, or what the difference is, it points out a vitality in the physicality of the experience. The experience of creating the image itself also differs, in the digital domain operations are predictable, repeatable, and undo-able, whereas mistakes in the physical world are hard to repeat, permanent, and unpredictable.

Crossing Domains

Many papers[31] have been written on the applicability of Walter Benjamin's seminal essay 'The Work of Art in the Age of Mechanical Reproducibility[32]' in the reality of digital copies which goes beyond what he could have imagined. In the digital domain every act is a copy[33][34], and interesting effects emerge when we explore the methods by which we use to cross between the digital and physical domains. Classically, we digitize the physical copy by scanning, and to go in the other direction we print.

Design historian Nitzan Waisberg (Née Brog) used to practice a technique where she would create a digital file and immediately print it in one copy, and at the same time delete the original file. In essence this technique creates a print which has a property of uniqueness similar to that of a painting. To get a similar effect in the other direction (digitization) we constructed a device which destroys the original physical copy as it digitizes it, essentially enabling a move operation (as opposed to copy) from physical to digital.

With the advances in screen technology, such as retina displays on devices ranging from hand-held phones to >100" displays, the borders between the digital and physical will continue to blur. At what point, if at all, will digital objects be able to hold the same intrinsic valence as physical ones is a topic presently under ongoing research.

2.7. Phygital Paint and TGUI

Recently coined in the context of marketing, the term phygital is expanding to also convey the transposition of virtual activities into the physical domain[35]. A core part of the interactivity for the user in our design is to allow the user to interact with the system in a natural and uninhibited form. (Velocity is a main limitation with mechanical systems, while not at all an issue for digital projection.)

By seamlessly mapping the user's drawing into projected light and constantly adjusting the projection such that the digital projection fades as the physical paint appears, a seamless experience is maintained in which the digital light seems to be 'drying' into physical paint. This phygital behavior expands the affordances of the digital paint to engage with the physical world in a similar albeit inverse way to the tangible interfaces described by Ishii et al[36][37]. At the same time, the fact that the output mechanism combines both a tangible (paint) and graphical (projection) element, with the ability to dynamically shift from entirely graphical (projection only) to entirely tangible (no projection) in a gradual fashion, enables different users to each find a comfortable spot for themselves on the tangible-graphical scale. By enabling a remote and seamless manipulation of the physical world, we allow for a further explorations towards the Ishii's radical atoms vision[38]. The most important contribution of the combination of digital and physical paint to the design, however, is that it allows digital control of physical paint while maintaining no discernible pause between cause and effect even at high rates of motion.

2.8. Vision

We hope that the technology developed through this thesis can assist in moving the world towards a future where any person, regardless of disability, is able to practice art.
Our platform for self-expression expands, in the domain of painting, the abilities of artists and would-be artists, empowering persons with disabilities to practice the art of painting.
Designing towards a universal framework, we hope to enable others to extend the system and improve its performance, expanding the accessibility to the tools and abilities of artists of all kinds throughout the population.

Chapter 3 Designing for Creative Interaction

"A computer is like a violin. You can imagine a novice trying first a phonograph and then a violin. The latter, he says, sounds terrible. That is the argument we have heard from our humanists and most of our computer scientists. Computer programs are good, they say, for particular purposes, but they aren't flexible. Neither is a violin, or a typewriter, until you learn how to use it." — Marvin Minsky

People express themselves creatively in many ways, with and without the use of technology. When creating technology in the specific context of enabling creativity the design of the machine interface needs to balance, in addition to the usual considerations, the effect the design has on the user's choices. I examine these in the context of paint below.

3.1. General Principles

3.1.1. Support Flow

Creating a state of creative flow[39] is a difficult task while inhibiting flow can be done with relative ease, for example, by introducing a delay into the control loop. When faced with even very brief delay, on the order of 1 second, users report annoyance and discomfort which leads to abandonment of the tool. For this reason, attempting to provide all the conditions required for flow is not only difficult but also not necessarily sufficient, such as in the presence of an inhibitor of flow.

To design for support of creative flow I borrow from the principles Schaffer suggests[40], enabling the user to experience high levels of challenge and skill, while being able to determine what to do, how to do it, and assess their own performance in an environment with minimal distractions.

All self expression is inevitably tied to a chosen means of expression, in other words, a discipline and set of tools. In the visual arts in particular, the intrinsic motivation to pursue any specific medium emerges from the perceived allowances for continued challenge and a broad range of possibilities.

The interface itself therefore should enable sufficiently complex outputs in order that the user can set goals which they perceive as challenging, while also enabling novice users to whom simple functions could be perceived as challenging. The range of possible outputs should thus be large, such that novice users are able to experience flow, and that this flow can continue as they improve.

3.1.2. Embodiment

The principles for flow are required for a creative task, but are not sufficient. The user needs to also be able to perceive the work being done as their own. From the phenomenological perspective the user's experience should be such that they perceive the operations as performed by them rather than the machine.

When interviewing painters about the important components they feel should be included in a drawing technology the top three were: the feeling you are in the process of creating, that it is you creating, and that it is an extension of your body. To support the embodied experience two perspectives should be considered - input and output. From the input perspective, devices that integrate with the body as hand-held or wearable can be of assistance. From the output perspective the visual feedback that is primarily guiding the user's motions needs to respond in a way in which the connection between the input and output is clear and intuitive from the point of view of the operator.

3.1.3. Expressiveness

No technology can be considered to enhance self expression if the user does not perceive the result as conveying their intent. This requires the user having control of the output, combined with the ability to output an intended result. In painting, the space of intended results is constrained by the size of the canvas, paint types and delivery technique.

3.2. The Machine in the Loop

3.2.1. Affordances

To support the general principles outlined above, we need to take into consideration the perception of the machine by the user. The affordances perceived by the user drive the user's actions[41][42]. A user might perceive a tool as purely functional, used to enhance or simplify a specific task. At the other end of this affordance continuum, the user perceives the objects without intuiting any immediate applications. A single object could, of course, be on both sides of the spectrum, depending on the observer. A hammer, for example, when considered by an adult carpenter is strongly tied to a specific use, to drive or extract nails - whereas the same person as a child might have used a hammer to drum, or even paint. Therefore, when designing an intermediary tool to assist in channeling creativity, I try to consider the affordances which the system communicates to the user.

In the early stages of this work, I observed my daughter Shira painting on an old Compaq iPAQ PDA - an early form of handheld computer and one of the first to have a full-screen natural stylus interaction in color. Shira is of the first generation of children growing up with technology virtually invisible in their understanding of interaction with nature. Her interaction with the virtual palette prompted her to mix the color with the stylus as if with a natural brush and genuine paint. The distinction of computer interface as distinct from the actual palette, colors and canvas were seamless enough to engender a mixing of behaviors. The important conceptual distinction to be made here is the slow blurring of instinctual behavior between those that constitute a natural outgrowth of our own biology and as those that affect mechanistic processes extending the use of our biology.

This observation served as a reminder that sophisticated technology is not required in order to provide an affordance for natural interaction. Rather, sometimes an interface which lacks a pre-associated digital affordance can trigger a more naive, albeit natural response. Such responses assist in reducing the number of perceived layers between the creator and the creation and serve for a more immediate interaction.

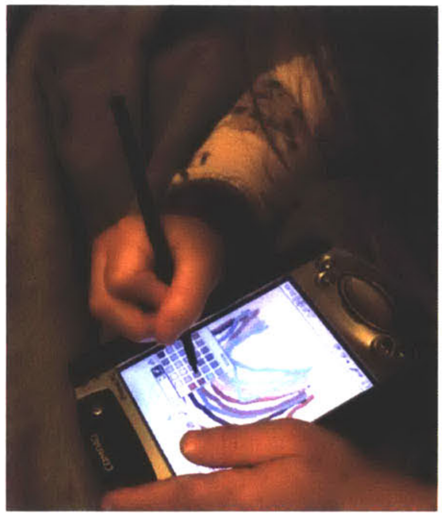

Figure 5 - Picture of Shira using a stylus on an iPAQ

3.2.2. Invisibility

Invisibility has long been a goal in assistive technologies. We can see this in the use of contact-lenses instead of glasses, and in ever-shrinking hearing aids, where invisibility sometimes trumps comfort and function. An invisible system can easily be made visible, while the inverse is usually hard. A prominently discernible interface, would hinder the expressive interaction in a number of ways: distraction, confusion, implicit affordance, and a bounding of performance parameters. Even more so if the interface requires interaction that disrupts the user's control of the output.

Distraction and confusion are caused by drawing attention away from the natural interaction of painting. That is not to say that there are not situations in which control of parameters in a visible interface would not enhance an expressive experience, but rather that these are options that should be reserved for a user who wishes to adjust such parameters. Hiding the configuration interface by default allows a teacher or caregiver to decide when and how to expose the student user to further complexities of the system. Gradual adaptation of a user to a system is a common practice in interface design[43], allowing the user to progress from novice to expert at their own pace. In extreme yet not uncommon cases the confusion emerging from facing an unfamiliar interface can cause deterrence from use - an undesired effect in a tool aspiring to be universally accessible.

Even if distraction and confusion can be minimized or avoided, a user's exposure to configuration parameters or simulation stages drives an understanding which can foster the building of mental boundaries on the range of intended behaviors by the user, as well as guide use of the system to fit into the simulation rather than in an intrinsic exploratory fashion. We have observed such effects in deployment of an augmented reality pendulum tracking system as described in the sub-section dedicated to project Enlight.

The system design already includes all the necessary components to support an interactive experience, as the computer is connected both as an input and output device. While the design principles lead towards the digital mediating layer having a minimal presence, as described above, invisibility is not a requirement for the system to function but rather a guideline in support of an uninterrupted affordance of natural interaction from input to physical output.

3.2.3. Human-Machine Collaboration

In some situations, such as for an advanced user, or a user actively seeking to utilize the digital tools, the hidden digital features can be exposed and provide the user with a range of collaborative experiences. The collaborative human-machine expression ranges from merely directed paint, such as tracing projected images to a range of activities with varying degrees of computer interjection. The experience of working in tandem with the computer in the physical realm is many times more provocative than in the digital. The experience is heightened with the resultant feedback loop causing significantly more change in the user and resultant work, enhanced by the fact that the physical medium does not support backup and undo operations.

The Extended Intelligence[44] framework proposed recently at the Media Lab envisions a world where machine intelligence and human intelligence work together in creative ways. The involvement of artificial intelligence in the translation process can assist the user 'in-line' with their movement, in a seamless way. It can act as an intelligent extension of the user rather than a counterpart to it. This stems from a design perspective of creating a symbiotic-like, seamless integration between the user and the machine, rather than a division of responsibility. While our current implementation lacks active collaboration abilities, the design allows for an easy interface which can be used for human-human collaboration as well as human-machine collaboration.

3.3. Adaptive Interaction

Methods have been developed to adapt inputs and outputs for diverse needs. The adaptation of content for screens of all types is extremely common and desirable, responsive and accessible web page design adapts to anything from large screens to phones, watches and braille displays.

Dynamic adaptation of user interfaces to inputs has also been implemented[45], allowing for increased flexibility through redesign of the input and presentation layers to adapt to existing diverse inputs rather than developing additional inputs or different interfaces. Foley et al. open their influential essay 'The Human Factors of Computer Graphics Interaction Techniques' with the following statement[46]:

> *"For the system designer the choices are bewildering: How does one put together, from a multitude of techniques and devices, the combination best suited to meet the needs of a human being who must perform real work? "*

For the design challenge we faced, the interaction tasks cover a small area of the spectrum of interaction tasks as described by Foley, making the choice simpler. Additionally, the graphical interface is a minimalistic and natural one - an open 2D canvas. Within that context, the design choice we made for broad adaptivity was, as previously described, to allow for easy and rapid deployment of new input methods, as well as a simple and immediate way to route and condition input signals to output effectors. Through this design we attempt to advance towards the Dynabook[47] ideal described in Kay and Goldberg's 'Personal dynamic media':

> *"Some mass items, such as cars and television sets, attempt to anticipate and provide for a variety of applications in a fairly inflexible way; those who wish to do something different will have to put in considerable effort. Other items, such as paper and clay, offer many dimensions of possibility and high resolution; these can be used in an unanticipated way by many, though tools need to be made or obtained to stir some of the medium's possibilities while constraining others. We would like the Dynabook to have the flexibility and generality of this second kind of item, combined with tools which have the power of the first kind"*

3.4. Collaborations

3.4.1. Deborah Dawson (NYC District 75)

In September of 2015 Rosalind Picard shared with the lab an email she received from Deborah Dawson, a teacher in NY, regarding her project involving painting with kids with neuromuscular disabilities. Deborah has been working with students from New York City's Department of Education's District 75[48] and has adapted lasers to create a new method of collaborative painting. Her process, enables students who would otherwise be incapacitated, to create complex paintings through directing Deborah's motions.

After Deborah reached out to the Media Lab we invited her to visit the lab for an ideation session and to further teach us about her process of Laser Painting, its origins, and challenges.

Deborah described to the team how she started working with kids with disabilities and the evolution of her Laser Painting project. At the time she was looking to replace the heavy and bulky gun-mount lasers which she was using. In collaboration with Daniel Goodman we designed a prototype for a lightweight head mounted laser described in further details later on.

About a month later I took a small team to visit Deborah at her NYC Public School 138 workshop, where we observed her work with 3 disabled individuals of varying degrees of motor disability and verbal ability, and we explored the robotic airbrush and air-flow control device prototypes which we brought with us from the lab.

Deborah's experiences with the kids provided us with an invaluable baseline for the prototyping process. Understanding the differences in ability that different kids have even when they suffer from the same condition inspired the core design principles for the project.

Deborah's students who often suffer from multiple disabilities, many of them non-verbal, are able to create rich paintings while clearly enjoying the process - as expressed by the students as well as their caregivers.

Figure 6 - Works and process of Debora Dawson's Laser Painting

In our interviews with professionals from New York City's District 75 school system, as well as with disabled artists, we have identified the need in the educational system for assistive devices of self expression, and several teachers who have been exploring technologies to assist with this effort. They generally describe the results of their attempts as positive and promising.

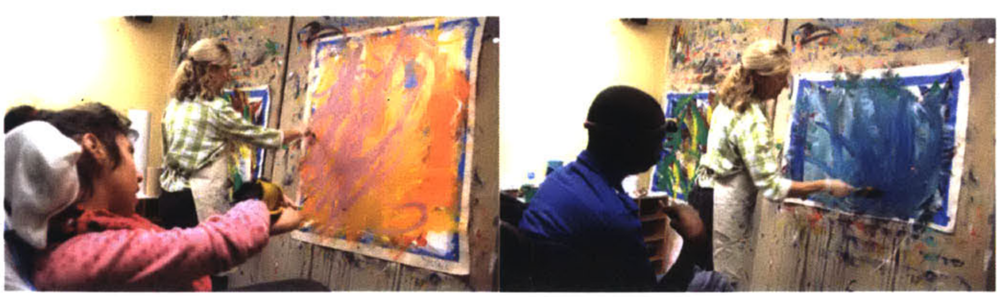

Figure 7 - Laser-painting at District 75, NYC, NY. A head mounted laser (left), and a hand mounted laser (right).

The interviewees describe current technologies which focus on purely digital solutions (such as eye tracking control of a graphical tool) as missing important aspects. They focus on the end-result rather than the process and experience. The convenience of eye-tracking should not trump the benefit of using the body in order to better enable an embodied experience.

The work presented in this thesis is inspired by Deborah's work, the challenges she faced, and the wonderful results she achieves day by day.

3.4.2. Cristina Powell

Cristina was diagnosed with Cerebral Palsy as an infant. Her mother was told by her doctors that Cristina will never walk or talk. She defied the diagnosis and is not only able to walk, and speak but she is also an accomplished full-time artist.

Cristina runs a nonprofit dedicated to helping people cope with medical conditions they or their loved ones suffer from, by running workshops where she teaches medical students and cancer patients how to paint, as well as by donating artwork to pain centers at hospitals.

Her experiences and interests mean she is uniquely positioned to provide invaluable feedback on our design both from the perspective of an artist as well as a person with Cerebral Palsy.

Cristina went through an extensive exploration process mostly motivated by her mother and often against the recommendations/beliefs of the medical and educational institutions. This exploration included many varied activities such as tap dancing, which, although unsustainable as a means of self-expression, proved extremely meaningful to her. This exploration process culminated in discovering her artistic abilities at the age of twelve.

Cristina is lucky, the form and severity of her cerebral palsy allows her to hold a watercolor brush with enough dexterity and for long enough periods to enable her to paint without requiring any additional technology. Her ability was not immediately apparent, far from it, it required years of dedication and an exhaustive search to find it. In addition, her ability at its current level is likely linked to the many hours of dedicated practice and high motivation.

Today, Cristina's art is hanging at pain clinics and rehab institutions around the Boston area. People often comment that their most calming part of their day is seeing her art on the walls of the clinics (primarily pain clinics). It makes Cristina feel good when she paints, but even more than that is that her art has impact on others as well.

Cristina describes the experience of other people approaching her with with prejudice. The assumptions from others that she is not fully aware of what is happening around her, or projecting from the fact that it is hard for her to talk, must mean she can only understand if spoken to in the same way, have been obstacles she has been forced to deal with in her personal and artistic development. Her success is enabling others with the same challenges, and helping outsiders see possibility where previously they only saw limitations.

3.4.3. Daniel Kish

No design will be truly universal if it excludes visually impaired and blind individuals. Exclusion of the visually impaired from the creation of visual arts by claiming their disability makes it impossible for them to participate in the process, might be considered a compelling excuse, but is an excuse nonetheless. We explored this domain through a collaboration with Daniel Kish, an expert on perception and human echolocation, who is also himself blind.

While it is entirely out of scope for this project to implement the complex mechanisms which are required to achieve this task, we inform through Daniel's feedback the current design consideration as well as intended future work, with hopes to enable opportunities for making the system inclusive of visually impaired and even blind persons. This relies on recent developments and discoveries about human perception, i.e. the fact that human echolocation is processed by the visual cortex[49].

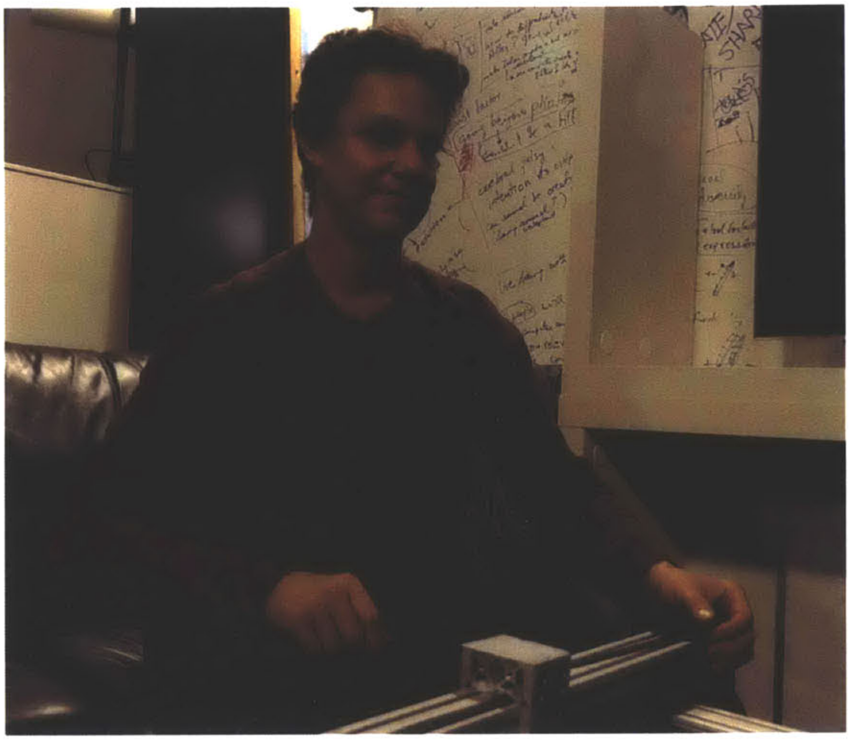

Figure 8 - Daniel Kish evaluating a proposed prototype input device for blind painters.

Chapter 4

Related Work

"That was the first time I've drawn anything for 7 years. I feel like I had been held underwater, and someone finally reached down and pulled my head up so I could take a breath." — Tony Quan on EyeWriter

4.1. Accessible Input Devices

4.1.1. EyeWriter

EyeWriter[50] is an eye tracking technology created by hackers to provide an open source alternative to high-cost medical-grade devices, inspired by graffiti artist Tempt1 who was paralyzed by ALS. One of the co-creators of the technology referred to it on stage at TED as "an amazing device, but it is the equivalent of an etch-a-sketch, and someone who has that kind of artistic potential deserves so much more, so we're in the process of trying to figure out how to make it better, faster, stronger."

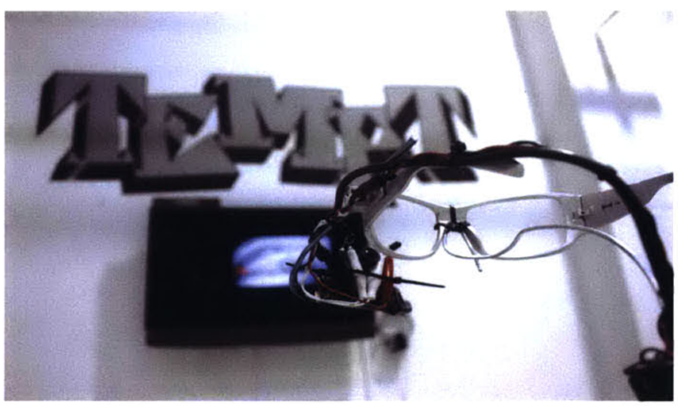

Figure 9 - EyeWriter, with an example of a logo created on it and then printed.
(Photo credit: urban_data@Flickr, CC BY-SA)

As can be seen in Figure 9 the technology consists of hardware and software. The hardware is constructed of a cheap camera and infrared LEDs mounted in the form factor of glasses. The software takes the input from the camera and processes it to track the pupil and produce 2D paths.

4.1.2. Expressive Assistive Device for Hyperscore

A key inspiration for this project, as previously described, is Adam Boulanger's Expressive Assistive Device for Hyperscore in which he worked with Dan Ellsey (pictured below) to enable Dan to express himself in music.

Figure 10 - Adam Boulanger, Dan Ellsey, and Tod Machover

4.2. Physical Output Devices

4.2.1. Digital Airbrush

The digital airbrush[51] developed at the Media Lab is a mechanized airbrush such that the control computer is aware of the position of the brush with high accuracy in 7 continuous dimensions: 3 spatial dimensions, 3 rotational dimensions, and the airbrush trigger position. Through integration of this data, and knowledge of the color of paint in the brush, the computer has a simulated image of the canvas.

A paint governor is mounted on the brush and controlled by the computer, allowing the computer to collaboratively participate in the drawing process, while the user has full control over the position of the brush and partial control over the trigger. While the computer has primarily only the ability to restrict painting, it can prompt the user through auditory and visual signals.

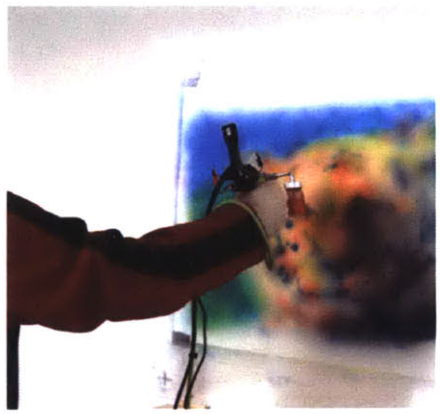

Figure 11 - Physical rendering with a digital airbrush

4.2.2. dePENd

dePENd[52] is a computer guided method for directing a user in illustration or tracing. Through an invisible magnetic control for a ball-point pen, the user is guided on where to paint, and to some extent - how, i.e. line style / speed. The user has the freedom to shift locally or disengage at will, as well as full control over the pressure and tilt.

The dePENd system benefits from an invisible interface which is mostly intuitive, but it does not provide the user true spatial freedom, and lends well (in its current form) only to continuous lines. While the system can detect the pen's location, it requires a special pen to do so. dePENd's invisible interface provides a magical experience with potential in many fields.

4.2.3. Photochromatic Canvas

Photochromatic canvas[53] is paper that reacts to an electronic "paint brush" emitting light to create patterns. This process provides a portable medium, and a high degree of freedom in both shape and size. This medium benefits from the engaging interactions that exist in the digital form of drawing, not normally possible in the physical form - creation of marks without physical interaction with the surface.

4.2.4. LiveWriter

In the original version of EyeWriter (as described above), the feedback output was only on-screen, and was also projected on walls/buildings. As part of their improvements to the system a robotic arm output was also developed. The robotic arm, while allowing for physical tagging of surfaces was fixed to particular fonts rather than freeform.

4.2.5. e-David

The e-David[54] (Drawing Apparatus for Vivid Interactive Display) project constructed a robotic system that is able to paint with physical color on canvas, combining a visual feedback mechanism and brush simulator software to predict the best outcome with the given parameters.

The machine consists of a camera, robotic arm, and processing computer, and works in a closed control loop. With this strategy a gradual approach towards a target image is maintained.

While the project in its current form focuses on specific target images, and in that sense acts like a printer, the availability of this technology to a user affects the way the user would think about working with digital paint in the same way that shifting from a black-and-white printer to a color printer changes the way a user would utilize a word-processor. A physical painting machine means that now the user can think about new and different ways to prepare digital works with the intent of outputting them on canvas in a layered fashion later on. At the same time, it is important to acknowledge that it also imposes limitations on freedoms that exist when strictly working in digital media, such as choices of color, and an availability of virtually infinite numbers of layers.

4.3. Virtual Experiences

4.3.1. HTC Vive + Google's TiltBrush

Recently released, the HTC Vive[55] system is a virtual reality system with fast and accurate tracking of head position. One of the applications released with the system is a painting program developed by Google dubbed 'Tilt Brush[56]'. The Vive system, with Tilt Brush as one of it's main preview components, has been receiving extremely positive reviews by both artists and engineers.

Figure 12 - Benjamin Tritt painting in Tilt Brush

As can be seen by the body posture of the painter in figure 12 above, the experience of painting in VR with the accurate tracking is engaging.

It should be noted that the system is far from being the first, but is receiving positive reviews in relation to comparable previous attempts (based on our observation across the media lab, recent conferences, artist trials and published reviews[57]). It begs the question - what makes the difference, what is the critical component which carries the perceived performance of the Vive system beyond the uncanny valley[58]?

Chapter 5

Design & Development

"The power of the web is in its universality. Access by everyone regardless of disability is an essential aspect." — Tim Berners-Lee

5.1.1. Design for Universal Access

The various populations to whom painting is inaccessible are vastly different. If one chooses to design a solution for one group, it is unlikely to be a good fit for another because of the wide spectrum of conditions and the complexities associated with each. Therefore we choose to employ universal design[59] methodologies in an attempt to create a tool accessible to people of all backgrounds and abilities. The seven principles[60] inform the design decisions as follows.

Equitable Use

Equitable use is a main consideration in the design and is the main reason behind the selection of input and output technologies as well as the modularization of the processing components. We aim to make the system as widely accessible as possible, but we also recognize that it will not be accessible by *absolutely* everyone. Therefore, we design the framework with this in mind to consist of open, simple to use, and extensible interfaces at every intersection.

The best examples for this are the input drivers and standard outputs. The input drivers enable simple integration with virtually any sensor, and the outputs are in standard representations which have widely available implementations already - such as G-code and gml. Hopefully future work can build upon our design and reach populations which we will not be able to.

Flexibility in Use

We take the flexibility principle into account by allowing fast and personalized calibration of the inputs - this supports not only different use types (such as moving an IMU from being hand mounted to head mounted) across users but also across different use times for the same user, as the user's needs and abilities might change from time to time. Different use requirements have been observed to be caused not only by changes in physical ability, but also changes in medication, for example.

Simple and Intuitive Use

Simplicity is difficult to achieve in complex systems, especially ones that need to be adaptable to a wide range of uses. As the system grows and capabilities are added, care needs to be taken to ensure that complexity is tamed. Compartmentalization of configuration parameters into their specific module, for example, will prevent a situation where global configuration becomes overcrowded and difficult to maintain. On the other hand, dependencies across configuration parameters would make such a compartmentalized system impossible to maintain. Designing for compartmentalization, without the ability to introduce horizontal interactions is key.

Perceptible Information

Through immediate feedback, we provide the user an ability to understand the control loop. This is most apparent while painting, as movement gets translated to the movement of the brush on the canvas and paint appears. Some other aspects such as color selection might be delayed in response - such as when selecting a color while not actively putting paint on the canvas. For such situations immediate feedback will be provided upon the setting change.

Tolerance for Error

We minimize hazards by maintaining a distance between the user and any moving parts. We allow the user control of errors by providing a projected preview, if so desired. The delay is configurable, and the effects of the delay on usability is one of the main things to be investigated through this thesis. It should be noted that the definition of 'error' in an artistic context is very subjective, and some users might desire to allow for errors. They can do so by disabling any preview, and/or configuring the filter components.

Low Physical Effort

By integrating with a wide variety of sensors, many of which are already used in assistive technologies, we strive to provide the users with as comfortable and familiar an interface as possible. For example, sip-and-puff straws which are used to control wheelchair movement can be used to control the brush.

Size and Shape for Approach and Use

We designed the system to be easily transportable and fit within existing spaces such as clinics, and even a transport bus for the disabled - allowing users to comfortably use the system regardless of their own mobility.

One aspect which is not currently addressed is height and angle - some users would require the canvas significantly higher or lower than others, and some would even require a tilt. Since this would greatly increase the cost and complexity of the project, and since this is a problem that is easy to solve with existing mechanisms that are ubiquitous in the environments where they are required, this feature is deemed out of scope.

5.1.2. Prototyping

The desired system allows for users with varying levels of ability to paint on a canvas. We constructed a few prototypes of user input methods with existing technology for computer accessibility. Our method for painting on a physical canvas is a custom designed 2D linear stage system that moves a digitally controlled airbrush. The following information provides the details of the prototype implementations.

5.1.2.1. Head Mounted Laser

To explore the basic interaction a head-mounted laser affords, as well as some of the complexities of tracing laser art, the team experimented in pairs with our early prototype for a computer-controlled head mounted laser.

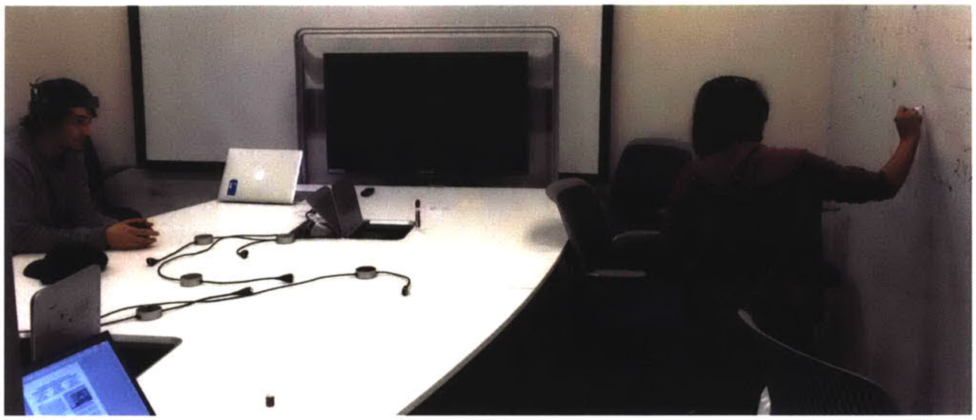

Figure 13 - Head-mounted Laser Experiments.
Left to Right: Jan (laser) and Missy (tracer)

The most prominent reaction was a complaint about the lack of ability to turn the laser off, a fact that meant the laser-painter cannot communicate the difference between an intent to paint and an intent to move to a new drawing position (pen-up / pen-down actions).

Interestingly, in our setup we did not experience issues with the laser shining into the tracer's eyes, in contrast to what we've seen in the field observations. This could be explained by the relatively short experiments and the small team size, as well as by the technical level of the laser operator. Regardless of the reasons, it demonstrates well the value of field observation as well as experiencing the technology from the perspective of the users.

5.1.2.2. AOIP - AirOverIP

Airflow and wind have been shown to be favorable for the enhancement of virtual environments. Various wind displays have been developed for virtual environments showing increased sense of presence[61].

In preparation of integrating with an airflow sensor we constructed an early prototype with basic binary control over remote airflow. We connected a container of compressed air to the system to make it mobile, and linked the solenoid controlling the flow out of the tank with the output of the flow sensor. This prototype was used during the Media Lab's 30th anniversary celebration to blow out the candles on the lab's birthday cake (cake courtesy of Joscha Bach).

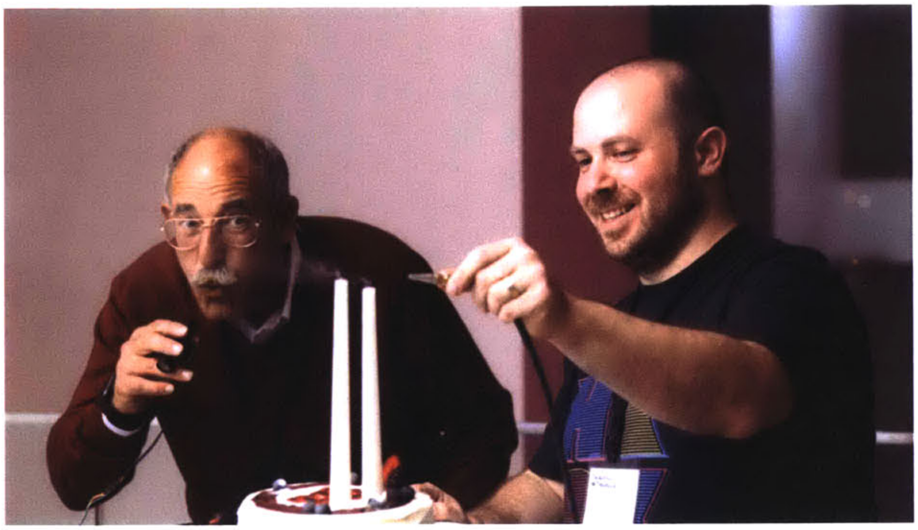

Figure 14 - Andy Lippman blowing out the candles over IP

5.1.2.3. Behind-the-Canvas Airbrush Trials

To test the feasibility of using the airbrush behind the paper/canvas in order to allow the interaction to be less distracting, we conducted simulations to model and understand the user-experience. A member of the team would hide behind the canvas while the test subject would aim a laser pointer at the canvas to direct the painting. This 'Wizard of Oz' style testing allowed us to validate the experience as well as gain a better understanding of what the user expectations are from such a system in terms of speed, responsiveness, etc.

In figure 15 below a progression of one of the tests can be seen through four frames, taken seconds apart. The laser pointer can be seen with the paint trailing about 1" behind.

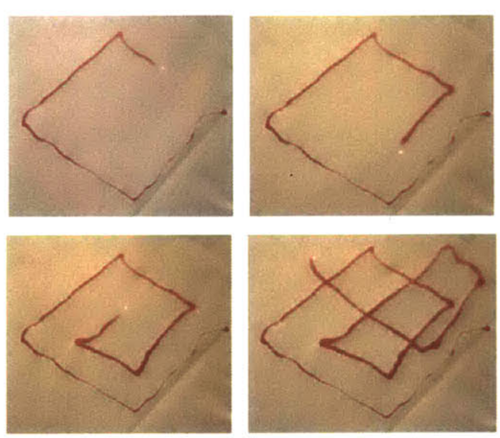

Figure 15- Trials painting behind-the-canvas, progression

Figure 16- Team members (Daniel Guberek, Tal Achituv, Missy Lopez)
with one of the resulting test images.

5.1.2.4. Prototype Milestones

Throughout the design process I tested several prototypes. Most tests were with the help of lab mates. The prototypes were continuously tested and improved, in an agile fashion. Keeping a working system throughout the development process was important in enabling speedy progress, and parallel work. Three major milestones were spaced about 3 months apart.

Milestone #1 consisted of basic mechanisms for control of airflow and an off-the-shelf airbrush. Users were able to have rudimentary on-off control over the brush with the use of airflow. Positioning was entirely manual.

Figure 17 - initial prototype hardware

This milestone coincided with the Media Lab's Fall 2015 Member Event (and 30th birthday), and its evaluation performed in the form of an observational study during a period of a few days in which it was available for play outside our lab.

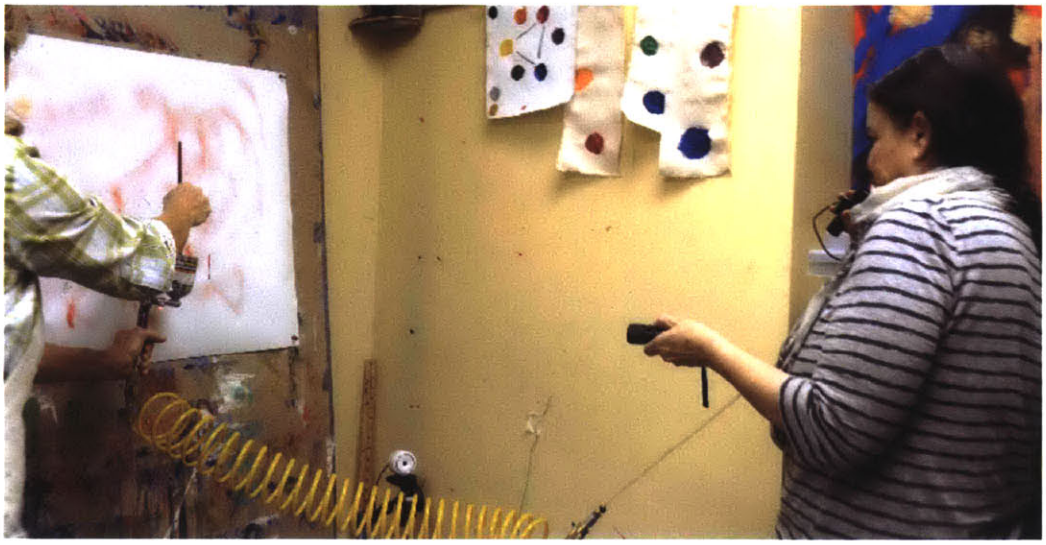

Figure 18 - Testing in NY of milestone #1 prototype

Milestone #2 was developed during IAP[62], and included a motor-controlled airbrush, with color-changing abilities, on a basic single linear stage (x-axis). We deployed this prototype over a period of several days in which students from many parts of MIT as well as invited artists were painting basic lines through remote control with the stylus, airflow, and mouse inputs.

Figure 19 below shows artist Benjamin Tritt testing the milestone #2 prototype in one of the rare occasions that the system was tested on different paper and paint types, and in-front of the canvas.

Figure 19 - Benjamin Tritt painting Marvin Minsky on the milestone #2 prototype through a primitive stylus interface

Milestone #3 was completed in time to be tested at the Media Lab's Spring 2016 Member Event, this prototype is very close to the final prototype in almost all aspects, and its deployment during the member event served as a pilot for the user studies described in the evaluation chapter.

Figure 20 - 2016 Spring Member Event (Prototype milestone #3),
Patrick Shin using the Stylus input (left), and an artist painting a portrait (right).

5.1.2.5. Final Prototype

In the decision between building or buying a gantry for the output stage, we had to take into account several aspects including cost, performance, and availability. The final design is created from a balance of off-the-shelf components and in-house design which achieves both an affordable solution (two orders of magnitude cheaper than other alternatives) as well as performance high enough to satisfy the the specifications obtained in the initial experimentation stages.

These experiments informed the design decision to work with a gantry and airbrush. The mechanical gantry's maximum speed will impose a limit on the user's motion, distancing the user from their creation. Even though the projected portion of the system will be able to cover the difference, it is desirable that the user be able to choose not to have a projection whilst still able to move at the desired speed. We determined the speed required for the reliable reproduction of the experience in the test cases is ~4 ft/sec.

Using an airbrush reduces significantly the complexity involved with maneuvering a brush on a canvas as well as loading the brush with paint. To support our design considerations, the brush would have to be quiet, responsive, support multiple colors, allow for fine control, and be inexpensive.

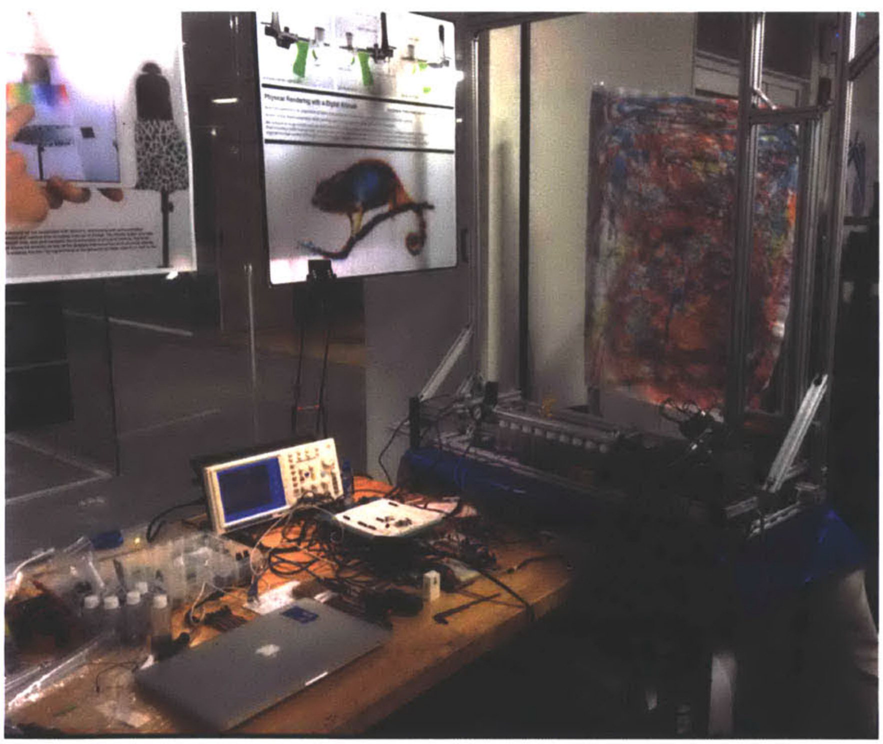

Figure 21- Experimental setup in the lab of the robotic paintbrush and gantry

Existing Technology

The only existing systems that achieve these requirements which we could find are industrial grade printers, used for printing on large objects. These systems start at the $30-50k range, and are unsuitable for other reasons as well, such as the fact that they are only capable of printing line-by-line. Even with modifications to the driving mechanisms, to allow non-raster use of the X-Y positioning system, the printing head would still only be capable of creating locally-square raster-like prints, rather than brush-like lines at arbitrary angles.

Building the system from off the shelf parts was also examined and found prohibitive. Color mixers alone cost $10k+, and linear stages at reasonable sizes cost upwards of $4k each, and run at significantly slower speeds than the specifications above.

The selection of parts for our own design, as described below, takes into consideration cost-effectiveness, and attempts to create a system that would be reliable and robust enough for testing, in a way that could inform a cheaper design for the next version of the system which would be geared towards DIY production. A relatively inexpensive final design to enable schools and rehabilitation centers to build their own versions is a secondary, yet important, goal.

Choice of Motors and Motion Control

To achieve the response speed goal, a combination of fast motor and fast-travel linear system needed to be constructed. In such systems with fast brief motions a precise motion control mechanism must be employed. Fast linear travel at reasonable motor speeds (~1400 rpm) was achieved with a high speed acme lead screw with 2" travel per rotation (12 starts). The driving motor was a CPM-SDSK-2311S-RLN[63] (CPM) operated at 75 volts. The intent of the linear screw design was to reduce the number of moving parts in the assembly and simplify the overall design.

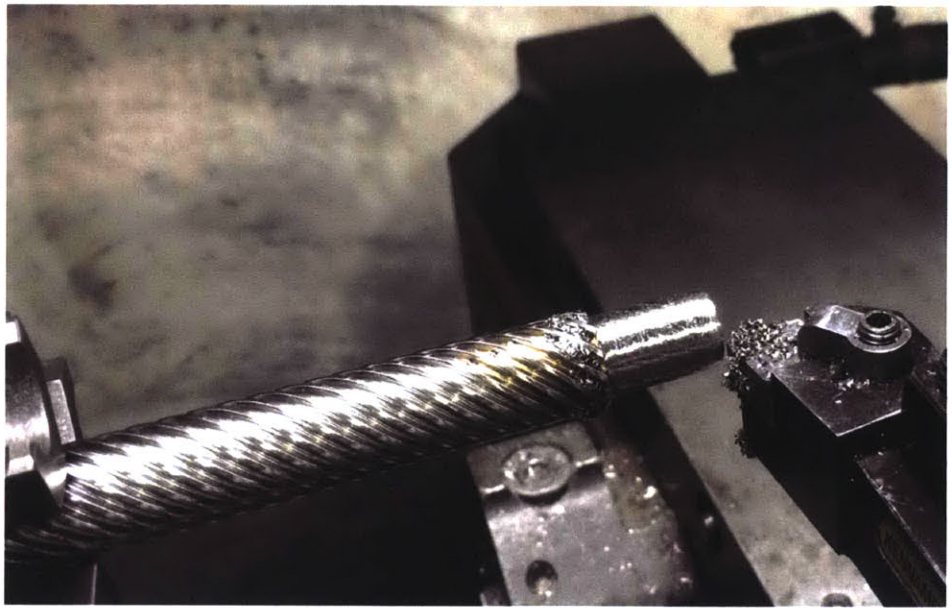

Figure 22 - Lead screw edge being machined to fit into bearings.

The CPM can output a continuous torque of 58 oz-in at speeds up to 2500 RPM. To achieve 4ft/sec travel using a high speed linear screw with 2-inch travel per rotation, the CPM needed to spin at 1450 RPM. The linear screw can be treated as a large inclined plane[64] and it was determined that the motor could move a load of 6.5 lbs. at 58 oz-in and a max load of 13 lbs. at peak torque of 100 oz-in at 1450 RPM. Before the design was completed the overall weight of the airbrush assembly was determined to be trivial, and the traveling carriage/cassette would be the main source of weight. Additionally, the combination of the CPM and the linear screw allow for high resolution control as the motor step resolution is 0.45 degrees. This translates to a potential minimum step size of 0.017 inches.

Gantry

The gantry was assembled using 80-20 because of its flexibility during prototyping which allowed for multiple redesigns. Future versions of the gantry could be improved with custom-designed fixed parts that reduce the cost, increase stability, and improve the ease of assembly.

Figure 23 - The 8020 frame with X and Y stages in an inverted T setting

The gantry was designed around the lead screws forming an inverted T, as seen in figure 23 above. The horizontal lead screw was mounted to the base of the frame, with the vertical lead screw and its driving motor were mounted on the bottom slider. The vertical screw is connected to a passive slider on the top of the frame. This design is beneficial when only using two linear stages, it minimizes moving parts, and keeps the center of gravity at the base of the robot. Additionally, the design reduces the load on the motors. Initially there were challenges with the vertical screw behaving as a pendulum, the lead screw would no longer be perpendicular and the whole system would jam. This effect is minimized through software control that limits acceleration in conjunction with high quality linear bearing sliders. However, the gantry would greatly benefit from using three driven lead screws, with a stationary lead screw mounted at both the base and the top of the frame. As a cost saving measure this was not implemented. The adaptor between the lead screw and slider carriages, as seen in figure 24, is a 3D printed bracket that connects to the flanges of two lead screw nuts. Although the nut is a long sleeve, the flange acts as a single point of contact on the screw and unintended external forces on the screw are not dispersed. External forces caused by minute misalignments with the frame or unwanted rotation of the vertical lead screw can cause the system to jam. The use of two nuts increases the number of points of contact which greatly increases stability.

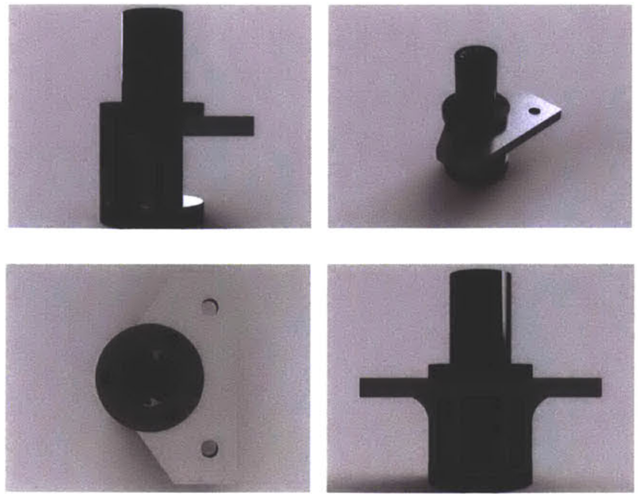

Figure 24 - 3D-printed Acme-nut to frame (8020) adapter

Motor Selection

Stepper motors are very common in designs that require precise repeatable motion. Steppers are cheap and reliable, but are an order of magnitude weaker for their size, and do not have intrinsic knowledge of their state - meaning there is no closed-loop control. To achieve positional accuracy while at the same time allowing for fast and jerky motions, we chose to use closed-loop stepper-servo motors which have recently dropped significantly in price through integration.

We found ClearPath motors to be very well fitting for our use case. They are cost-effective ($300) when considering their power and integrated components, chiefly the encoder, drive electronics, controller, and debugging mechanisms. The ClearPath motors are available in two main configurations, the MC series and the SD series. In the MC (Motion Control) series the motor has several control modes which greatly simplify control. Essentially the driver needs only tell the motor the destination, and the motor gets there smoothly. In the SD series (Step & Direction) the only available interface is that of a classic stepper controller (step input and direction input), at a slightly cheaper price point.

For initial tests of the mechanics of the system we used MC series motors. By having an integrated, state of the art, motion control system we were able to test the linear stage design in a variety of load, speed, acceleration, and torque specifications, while monitoring torque, position, and velocity with high fidelity.

Power Supply Unit

36V balances cost, safety, and availability with motor torque performance. As can be seen in figure 25 below, a 36V supply is sufficient to sustain ~0.25 Nm at ~1500 rpm which is safely above the maximum performance required both in terms of speed and force. A 24V supply could work as well, but system performance will need to be capped at a lower maximum speed.

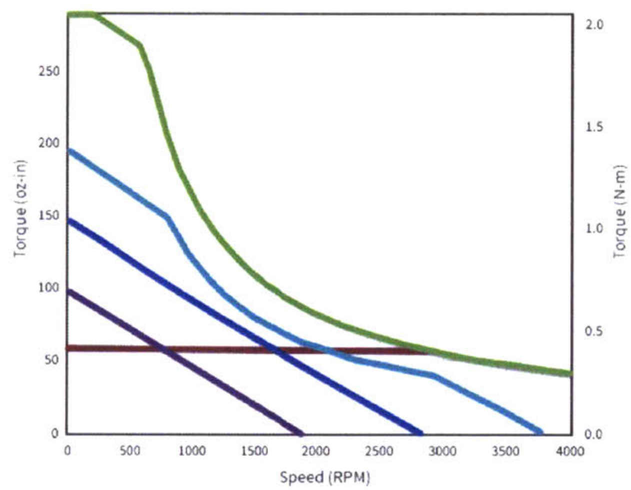

Figure 25 - Motor peak torque at 24V (purple, lowest), 36V (blue), 48V (teal), and 72V (green, highest), with maximum constant torque (red) at ~0.4Nm.

It should be noted that during our development the power supply we chose did not have sufficient back-EMF protection and would shut down during fast breaking situations. Requiring a properly protected supply means increased cost. This could likely be avoided by properly bounding the motor performance envelope, or adding protection ahead of the supply.

Linear Stage Design

Lead screw, belt drive and rack-and-pinion were all considered as designs for the linear stage system. When the lead screw is rotated a nut will travel linearly along the screw if the nut is constrained from rotation. A major advantage of the lead screw is that the motor never has to lift its own weight, or the weight of another motor. The screw also does not require any moving parts in addition to the sliders that carry the load of the carriage. However, there were some initial concerns with the achievable linear velocities with the lead screw as most common implementations of lead screws operate at much lower speeds pushing heavy loads.

A belt drive was closely considered, primarily due to their common use in 3D printers as well as Laser cutters which operate at high speeds. It is also possible to configure a belt drive for a 2D linear stage so that all motors are stationary, however the belt drive assembly is rather complex with numerous pulleys and multiple belts where belt tension becomes a major concern given the size of the gantry. For these reasons the belt drive was not pursued further.

A rack and pinion (RP) assembly was briefly considered. However, the RP system requires all motors to be mobile, and for the motors to lift its own weight. This poses a challenge for the wiring of the system and limits the potential speed and weight of the airbrush assembly.

Motion Control

Several motion control schemes were explored, including Arduino libraries for stepper control and commercial motion controllers. The 'Stepper' and 'AccelStepper' libraries for the Arduino are, unfortunately, not mature enough at this time to support our needs. Specifically, they lack in ability to synchronize the different stages.

Commercial motion controllers are prohibitively expensive, and the integrated controllers in the Teknic ClearPath motors, while very cost effective, come on the account of having direct control over position and velocity at the same time.

The main motion control library we used, therefore, is Grbl - an open source CNC controller, with slight modifications, such as enabling line-number feedback and buffer-depth reporting. This feedback data is required in order to synchronize the projected interface with the physical paint.

Parameter	**Our Prototype**	**CNC** ('standard defaults' from grbl)
Steps/mm	15.748	250
mm/min	72,000	500
mm/sec^2	100-1200	10

Table 1 - Final machine control parameters as compared to a CNC's 'safe' defaults.

5.1.2.6. Robotic Airbrush

We selected to work with an airbrush which has already been adapted for multiple colors - the Silentaire Spectrum 2012.

Figure 26 - Exploded view of the airbrush (image courtesy of Max Lieber)

To robotically control the airbrush the following three separate processes need actuation: paint on/off, flow rate, and color. In manual operation the paint on/off is operated by depressing a trigger, and the flow rate is controlled by the horizontal position of that trigger. A servo mounted above the trigger is used to depress the trigger, and physical limiter prevents horizontal motion from accidentally changing the flow rate. The flow rate can be controlled by horizontally actuating the rod, via servo, at the back of the airbrush. The rod's full range of motion is 2mm, a lever is used to convert 180-degree rotation to a 2mm a sliding motion. This allows for high resolution control of the flow, via a simple mechanism, but at the cost of increased wear as the lever slides against the rod's stopper.

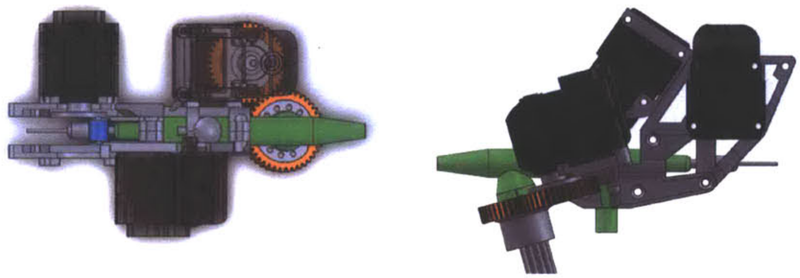

Figure 27 - Top and side views of the airbrush with the motors mounted.

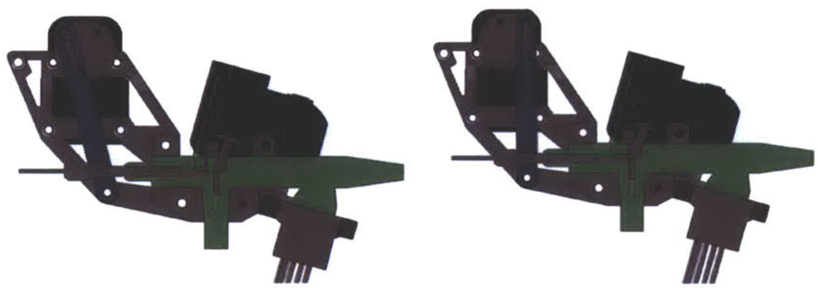

Figure 28 - Cross-cut side view of the brush (in green)
with the paint-flow lever (in blue) in the 100% flow (left) and 0% flow (right) positions.

For color control the airbrush uses a dial with nine incoming paint tubes, adjacent colors can be mixed for a total of 17 (9+8) distinct positions. Since we use at least one color container for airbrush cleaner, the effective number of colors we can utilize is 8 'pure' colors and 7 potential mixtures for a maximum total of 15. The color dial was machined to have a flat edge for keying a 3d-printed gear. The printed gear is press-fit onto the dial, and a servo with a matching mounted gear is used to rotate the dial to predefined positions.

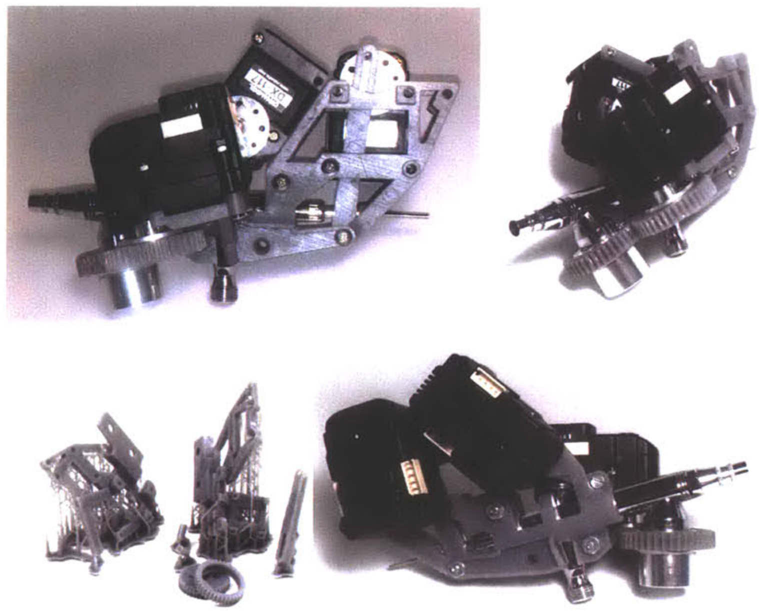

Figure 29- 3D printed airbrush motor mounts

5.1.3. Components

The system consists of input, processing, and output stages, as can be seen in the figure Figure 30 below. Hardware components are colored green (input) and red (output) and software components are blue (processing), yellow (output normalization), and purple (output control). Arrow colors indicate protocol, where blue represents WebSockets, red represents RS232, purple represents HDMI (or other display technology), orange is TTL step & direction control, and black is RS232 over RS485.

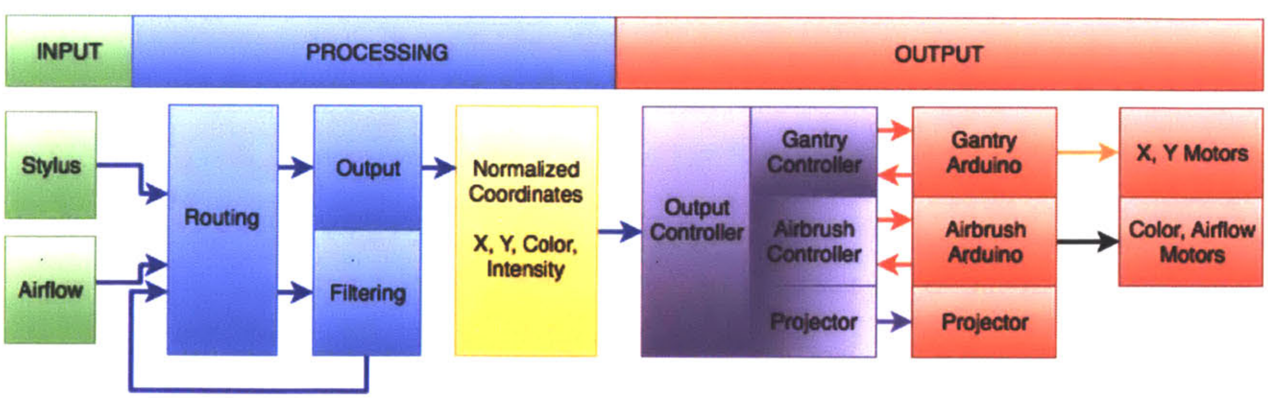

Figure 30 - System structure and data flow

5.1.3.1. Software

Our software stack relies primarily on JavaScript technologies which are interoperable through WebSockets with virtually any other network-accessible technology. Node.JS is used to run the WebSockets server as well as serve the static web pages that serve as input channels.

Joint.js, and P5.js are used extensively to provide the user-interface components, with Joint primarily used for configuration and P5 for user interface components.

Paper.js is used for simple 2D path processing, mostly in the backend, due to its simple design which is powerful enough to serve all of our needs.

5.1.3.2. Hardware

Two Arduinos are used, one to control the gantry, and the other to control the airbrush. Arduinos are cheap microcontrollers that are capable of connecting to input/output devices such as motors and sensors. The Arduinos communicate with a PC through a USB serial. The ClearPath Motors mounted to the gantry can achieve high speed and high precision motion control. Coupled with their relative low cost and ease of use, these motors were best suited for our needs.

Dynamixel Motors that control the airbrush are digitally controlled servo motors. These motors are high power, and high precision and provide force feedback. They are slightly overpowered, and over priced for our need, however they helped improve performance during the prototyping stage.

5.2. Input(s)

For our prototype we implemented support for the following input methods; some are trivially available (i.e. computer mouse) and used as-is, others were developed nearly from scratch (i.e. airflow controller).

5.2.1. Mouse

Through the HTML interface, using any modern (HTML5) browser, a box is presented to the user which represents the gantry. Mouse movement inside the box is sent to the processing server. This is the most trivial method of control for a computer interface, and extends naturally to touch-screens through HTML compatibility between touch and mouse events. Color controls were separately provided in the form of HTML sliders.

5.2.2. Stylus

Building upon the mouse interface, stylus control can be trivially added for position data. Additional work needs to be done to integrate stylus pressure, tilt, and auxiliary data such as on-stylus buttons.

For this prototype two types of stylus input were created, a relative one and an absolute one.

In relative mode the stylus is used on a Wacom-style tablet, off-screen. If the user lifts the pen and places it down at a different spot, the gantry does not move. Only motion on the pad is translated to gantry motion.

In absolute mode the stylus is used inside a square (on screen or on a tablet) which corresponds to the paintable area on the canvas. If the user lifts the pen and places it down at a different position the gantry moves to that new position.

Figure 31 – Painter Don Eddy using the stylus input on a Wacom screen

5.2.3. Foot Pedal

A simple foot pedal was integrated with the system to allow for simple triggering action. This input modality could be expanded to support pressure (rather than position) data.

5.2.4. Laser

Laser pointers can be used as input devices by means of a computer vision algorithm that tracks the laser and sends the coordinates to the system for processing.

Instead of computer-vision, human-vision can be used to track the laser's position, through tracking a user observing a laser signal. This method, while redundant and relying on a rudimentary form of human-computation[65], as well as an additional person, is incredibly robust to noise and environmental conditions. While this task can be hard for a human to do for long stretches of time, it requires no skill or training.

Two laser-pointer systems were developed for this purpose, with a design goal of fitting both our system as well as the one deployed in Deborah Dawson's Laser Painting setup.

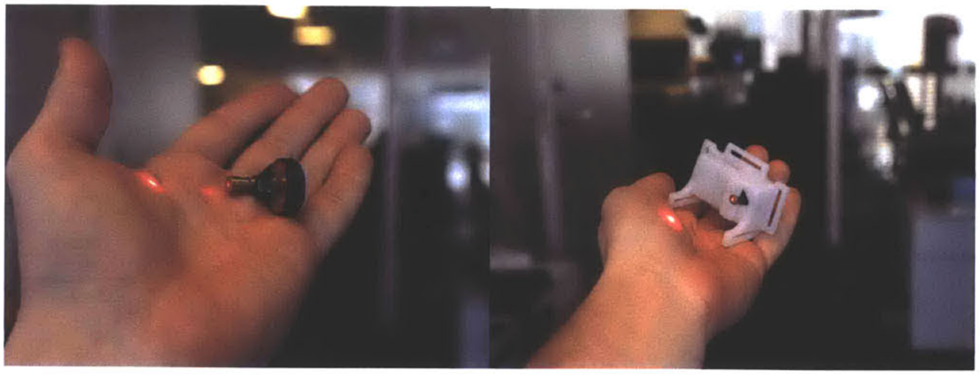

Figure 32 - LaserLight (left), SmartLaser (right)

5.2.4.1. LaserLight

The LaserLight model is engineered to reduce cost, and weight. Constructed entirely of salvaged components, the cost of the prototype is zero, while to construct this new from parts would cost less than $5.

LaserLight has no unneeded parts, consisting of only a coin cell battery holder and a laser diode. The diode is mounted on the battery holder in such a way that it points forward when the holder is mounted such that its largest surface is vertical.

A universal Velcro-style mounting dot is attached to the back of the battery holder.

5.2.4.2. SmartLaser

The SmartLaser is designed with functionality in mind, rather than cost. It consists of a LightBlue Bean (by Punch Through Design) an Arduino-compatible Bluetooth development platform. On the Bean we mounted a laser diode, control transistor, and Infra-Red demodulation module.

As seen in figure 32, the complete module is encased in a 3D printed box designed to enable flexible and easy mounting at three different orientations - to fit head-band and arm-band style mounting.

The SmartLaser supports remote control operation to allow a human tracer, if present, to turn the laser off when they turn their heads towards the laser operator. There are a total of four modes of operation, the main 3 modes are for use with a remote control at low, medium, or high brightness while fourth mode is only available in high brightness and is a robust mode in which the remote control function is disabled. This mode was added to support operation in environments where infra-red noise might cause sporadic on/off behavior.

5.2.5. Eye Tracking

We adapted the Tobii EyeX system for use on a screen as well as on the canvas. The EyeX system is a new, low cost solution released as a beta product under a developer license by Tobii. It has state of the art performance at a very low price point roughly 1-2 orders of magnitude cheaper than a few years ago. This is driven by a simplification of the hardware, at the cost of requiring a strong CPU and USB-3 connectivity.

When used on the screen the eye tracker works in the out-of-the-box configuration, simply replacing the mouse. Since our on-screen interface is web-based, it works seamlessly with the eye tracker.

For use on the canvas, we installed the eye tracker in mid-air, about arms-length away from the user, as per the original intent of the eye tracker. No modifications are made to the eye tracker nor its software. The eye tracker produces coordinates of gaze in the 2d space immediately above it, as if a screen were there. The transformation from this 'phantom screen' coordinate space to the canvas coordinate space is achieved using an affine transform calibrated by prompting the user to look at each of the four corners of the canvas.

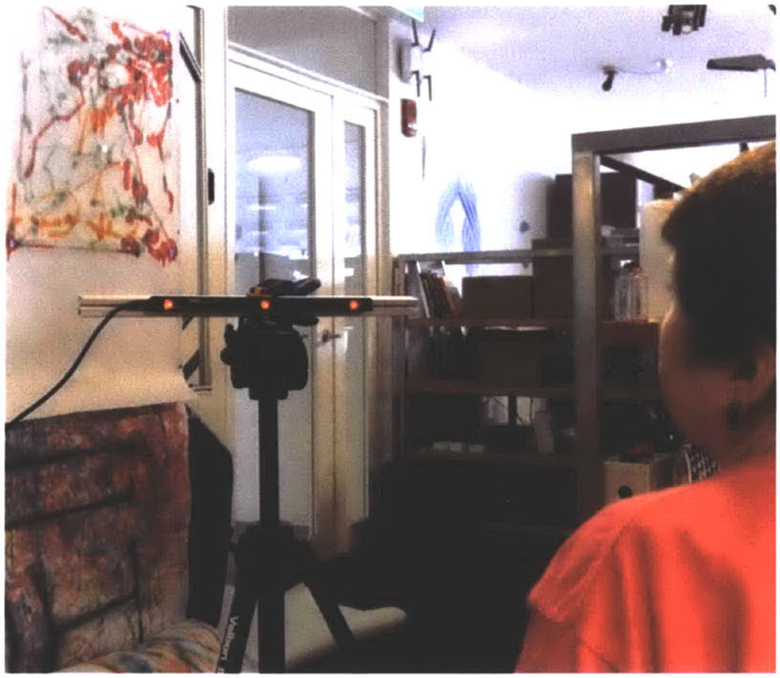

Figure 33- Drawing by looking, eye tracker mounted between user and canvas.

Figure 33 above shows the setup of on-canvas eye tracking. The eye tracker is mounted on a tripod to enable easy lifting and tilting which was required for compensating for subject's eye level when seated. On the left the canvas is visible with a drawing entirely performed through eye tracking within a period of 1-2 minutes.

In our tests (n=30) accuracy of the mid-air mounting, in most cases, did not seem to suffer as compared to the on-screen case. While accuracy is lower, it was below the noticeable difference for >85% of the users. Users for which the accuracy degradation was noticeable were ones that had worse performance than average even with the traditional on-screen mounting. In our small test group this seemed to align with wearing glasses or other corrective vision devices.

In both the on-screen and on-canvas cases users reported similar issues, primarily about the difficulty of using the eyes as an output device. This was resolved, for most, by adding one of two kinds of feedback: external laser light and/or on screen projection. In both cases most users reported a significant improvement in ease of use, which in many cases also turned the experience from a negative one to a positive one.

5.2.6. Airflow

We integrated an airflow sensor with the system. The SFM-3000 series sensor provides high frequency, highly accurate, medical grade, data on the rate of flow of air through the sensor's body.

The sensor dimensions are similar to industry standard flow sensors and inhalers, a comfortable size for holding in the palm or by the fingertips.

Figure 34 - Sensirion SFM 3000 Series
Low Pressure Drop Airflow sensor

To control the sensor, we developed an Arduino driver interface which takes the raw airflow data and provides it to the computer in a format compatible with our processing system. The data from our driver is used in two modes, one uses continuous sampling and the other samples only when triggered. In continuous mode the sensor directly controls the airbrush's paint flow. In sample & hold mode the driver samples the sensor continuously, but reports to the computer as if the samples are constantly at the level as measured during the trigger.

Continuous mode allows for a very natural and intuitive interface, but is difficult to sustain over time. This type of interface is used in commercial and DIY drawing games for kids, where a straw is used in conjunction with wet paint on a page, or attached to the wet tip of a marker.

Sample & hold mode allows the user to control the flow using their breath with the same accuracy as in continuous mode, while enabling sustained use on account of a reduced time-domain resolution.

Figure 35 - User holding flow sensor (fingertip held)

5.2.7. 3D Haptic Device (Geomagic Touch)

A Geomagic Touch device is a pen-shaped input device with 6 degrees of freedom input as well as force-feedback outputs. We programmed such a device to constrict the motion of the user to a square with the same perspective as the canvas (code contributed by Ronen Zilberman), the overall integration time for the project was <2hrs.

The development of this input was performed after we had already begun testing and hence was not formally included in the usability study (see evaluation section), however it was tested with several users and received generally good reviews. The control was comfortable, but there was some difficulty for users to map the movement space of the device to the canvas space.

Figure 36 - Cristina Powell using the 3D haptic input device

The depth axis (in / out of the canvas) has no intuitive meaning, and some users reported discomfort regarding the fact that the 3d pen allowed motion in that axis. This can be easily resolved by constricting the motion on that axis in the motion feedback code, however this would essentially mean the only benefit of the device over a Wacom tablet is the flexibility to position the X-Y plane arbitrarily in space. For many kinds of users with motion disability this could be an important feature.

5.2.8. IMU (phone)

Inertial Measurement Units enable measurement of force/motion, and are commonplace in electronic devices such as mobile phones. Through an android app (developed by Remy Mock) which transmits the data to the server over WebSockets.

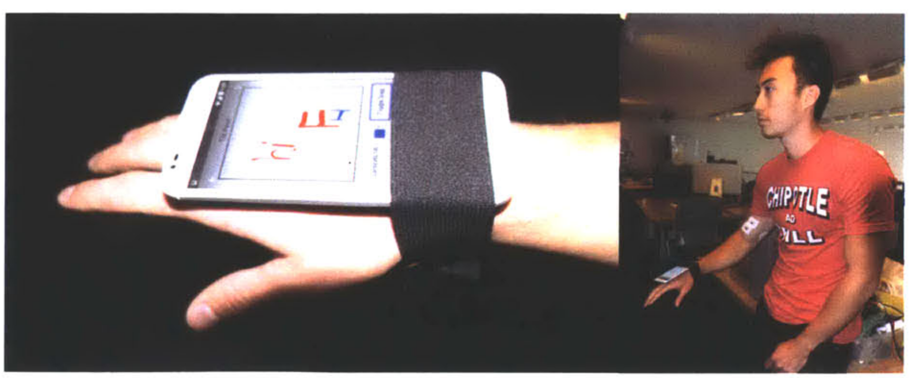

Figure 37 - Phone-based IMU input app GUI (left), worn by Remy Mock (right)

The phone is calibrated in a given position by pressing a 'zero/center' button. The IMU data can be converted into X/Y coordinates in two ways - relative and absolute.

In the relative mode any tilt, relative to this 'zero' position in the two axes of the phone's screen plane then causes an increase in the position coordinate sent to the server. This is similar to holding a marble on a glass plane - tilting the glass at a fixed angle causes continuous motion of the marble. Whereas in absolute mode the relative tilt is converted to a fixed position.

5.3. Output(s)

To output the user's intent, the input streams are processed as described separately below. There are virtually limitless devices which could be controlled as an output. The output developed for this thesis consists of four main components: projection, gantry, brush, and canvas. These components work in tandem to provide a phygital user experience combining digital and physical paint, as previously discussed.

5.3.1. Projection

A projector is used to display, in real time, the processed user input streams. The digital canvas sent to the projector can be easily transformed to correct for any (reasonable) projection angle on any flat surface through an affine transform. The projected paint matches the airbrush's color, opacity and dot-dimension. Figure 38 shows an example of a projection, in purple paint.

Figure 38 - Projected path.

The projector can be used with or without a complementary paint delivery system, as a user might choose to paint in the digital domain alone.

Additionally, projection can be used to augment other systems or processes that complete the physicalized painting process. In the case of Deborah Dawson, she could employ the projector as a persistent guide to work collaboratively with the user. A projector system has the advantage of persistence over the laser-pointer based system which Deborah uses today.

5.3.2. Gantry

To convert the digital path to physical paint, we synchronize the gantry and airbrush according to the processed input streams. The gantry control can be output, currently, in several formats which enable extending the same software to a variety of commercially available, as well as DIY setups. Supported protocols include: raw (x, y, color, pressure) output, PID control (configurable) in 2 axes, and generic G-code output.

5.3.3. Airbrush

The airbrush is controlled by a custom protocol which converts the color & pressure to the proper servo positions to achieve the intended output.

The airbrush controls need to synchronize to the gantry's position, since each is controlled by a separate driving mechanism. To achieve synchronicity, the gantry controller has been modified to output the id of the command it is currently processing, and the airbrush controller changes modes based on the currently processed command.

5.3.4. Canvas

The combined projection, gantry and airbrush require a canvas to operate on. In the setup where the projector is in the front, and the airbrush in the back, the selection of paper and paint needs to be chosen in such a way that the paint is able to penetrate the canvas.

For the majority of the developments, and for all of the formal assessments, we used white craft paper which was readily available at the lab, and always in the paint-from-behind setup.

On several occasions the system was tested with other kinds of paper as well as with fabrics, drywall, and glass.

Additional kinds of paper could be used but have not been tested. Interesting results might emerge from use of thin clear plastic sheet in combination with acrylic paint, as suggested by several of the artists who participated in the studies. This would allow for a very interesting interaction where the painting looks different from the front and the back, where color-mixing is partially invisible to the painter who will only be able to observe the first layers to hit the sheet in each location.

Matching of the ink and reducer to the type of paper used was more complicated than expected. At least seven factors were found to affect the behavior of paint/paper interaction:

- Pigment type
- Ink translucency
- Reducer composition
- Mixing ratio (pigment : reducer)
- Paint pressure
- Air pressure
- Paper type

Most of these were expected to affect the result, but it was the extent to which results differed which was surprising. The component with the largest contribution to the visibility and soaking time of the paint (in the kraft paper case at least) was the reducer composition.

5.4. Processing

The processing stage is the heart of the system. The ease of configuration and expansion of the processing capabilities is key to the modular architecture from which nearly all of the benefits of the system arise.

5.4.1. User Interface for Configuration Management

One of the main benefits of the design stems from the simplicity and speed of adapting the system to a particular user. To achieve this, careful consideration needs to be given to key aspects of the user interface.

5.4.1.1. Main Considerations

The configuration for the processing stage has two main design goals, it needs to be simple to use and easy to understand. The configuration of the system consists of routing input signal sources into output action sinks.

A complete understanding of the system's configuration needs to be glanceable. All the information required should be available in one flat view rather than hidden with buttons or menus.

Changes to the configuration are immediately reflected in the interaction, i.e. if a user removes the connection to the X axis, it stops moving immediately.

In addition, sensible defaults should be provided such that the system works 'out of the box' without requiring any setup - unless an adaptation is required.

5.4.1.2. Inspiration

I draw inspiration from two prominent interfaces for flow configuration: MaxMSP[66] and GNU Radio Companion[67][68].

MaxMSP is a visual language for programing complex interactive systems which requires no knowledge of traditional programming languages. It is predominantly used for audio and graphical applications. An example of a relatively simple program is shown in Figure 39.

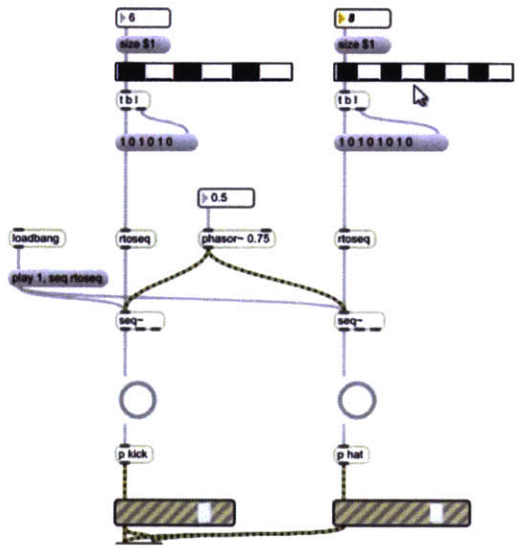

Figure 39 - MaxMSP Interface

GNU Radio Companion (GRC) is a graphical user interface for configuration and execution of GNU Radio scripts. These scripts are essentially directed flow-graphs from sources to sinks, with a library of nodes available in a searchable hierarchical format. A flowgraph presents the entire configuration information at once while allowing for rapid editing. In figure 40 a complete 5-stage flowgraph is presented.

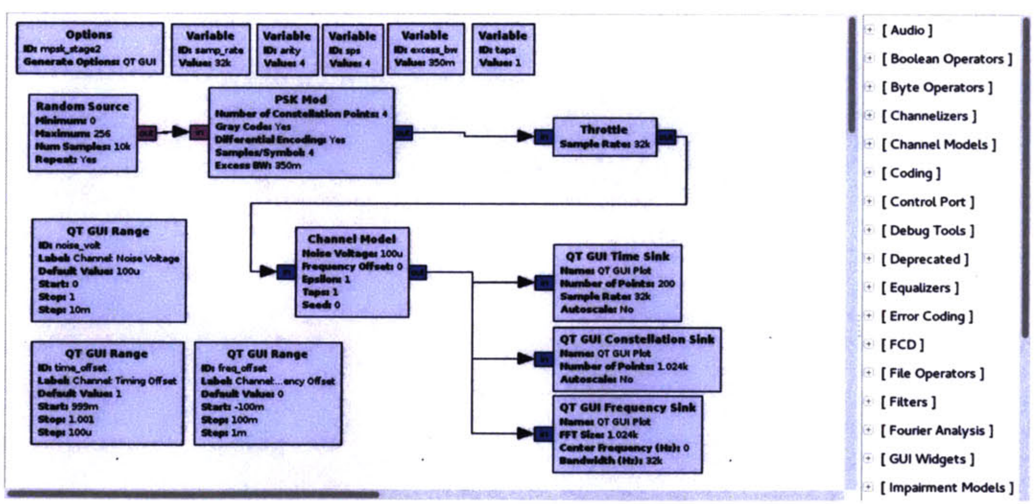

Figure 40 - GNU Radio Companion Flowgraph

5.4.1.3. Design

5.4.1.3.1. Configuration Management

Our system's configuration interface draws upon the strengths of MaxMSP and GRC, and has a look-and-feel which has similarities to both interfaces.

The configuration page consists of input (source), filter, and output (sink) blocks, as can be seen in figure 41. Data flows from left to right. Input blocks generate data, and have ports only on the right, output blocks consume data, and have ports only on the left, and filter blocks have data-in ports on the left and data-out ports on the right.

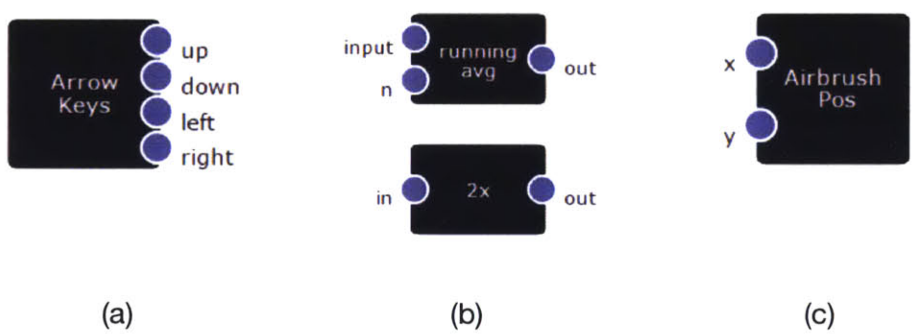

Figure 41 - (a) An input block, (b) Filter blocks, (c) An output block

To create a desired user experience, input blocks need to be connected to output blocks. Connection is achieved by dragging and outgoing port of an input block onto an incoming port on either a filter or an output block. Such an operation creates a link (arrow) between the two desired blocks. The direction of the link's arrow indicates the direction of the data flow. To remove connections, the user clicks a 'delete' icon (red circle with white X), which appears while the pointer (mouse/stylus/finger) is in a hover state over the link, or when the link is clicked on. Figure 42 shows a configuration where the keyboard's number keys change the paint color.

Figure 42 - flow arrow, with delete icon (appears on hover)

Data can flow from one input into more than one output, as demonstrated in figure 43 where the mouse X position data is used to control both the airbrush's X position as well as the color. Notice that the Y coordinate does not change. (take into account the perspective transform, where in the canvas-space the lines connecting the four corners are orthogonal.

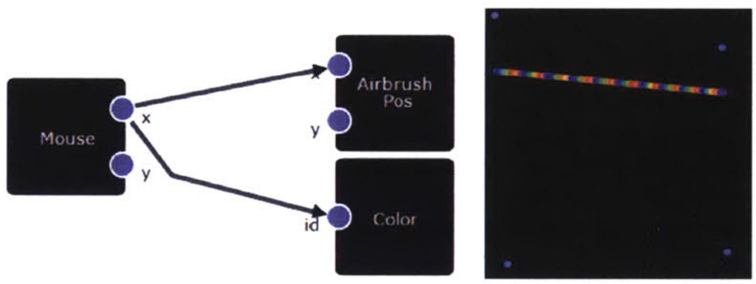

Figure 43 - a configuration with X controlling both position and color (left).
The output of increasing mouse's X and Y (right)

In figure 44 chaining of filters is shown, in this case the mouse X coordinate is doubled and then timed by 10, for a total of x20 increase.

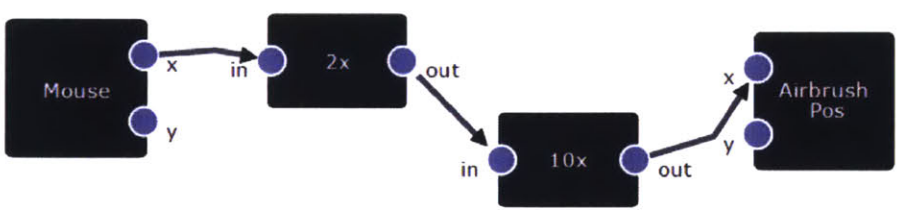

Figure 44 - Chaining of two filters (x2 -> x10) for a total increase of x20 in step size

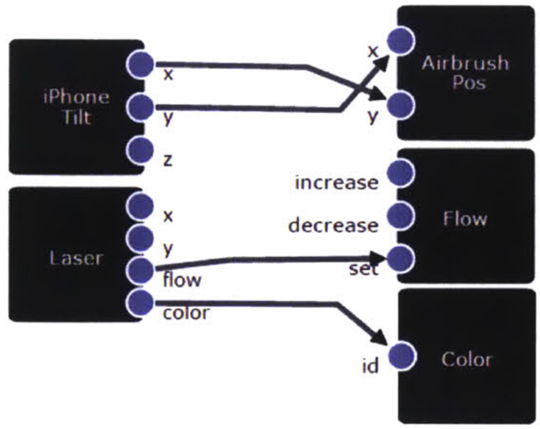

Figure 45 - Configuration switching of x & y mapping

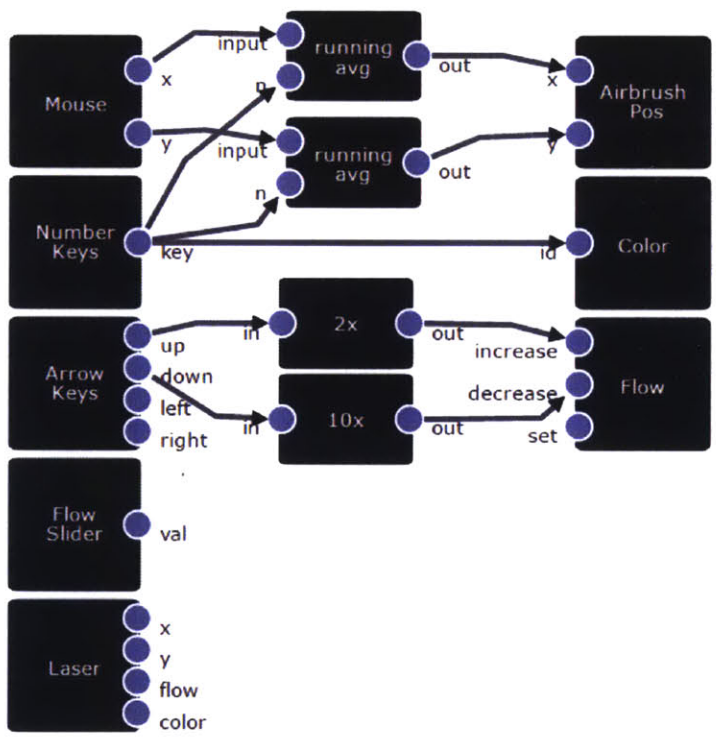

Figure 46 - Sample configuration with filtering

In figure 46 the configuration performs low-pass filtering (by means of a running average) on both X & Y. Additionally, the up arrow increases flow by steps of size 2, while the down arrow reduces it by steps of size 10. This configuration could fit, for example, for a person interested in filtering out jerky motion, fast increase in flow per up-arrow click, and an even faster decrease per down arrow click (with a ratio of 1:5, and 50 clicks for full flow).

Access to the configuration page is not necessary for operation of the system, as the configuration is persistent. A user would load the configuration page either for initial configuration or when changes need to be made. This provides for a transparent experience, where none of the processing components are visible during routine use. For advanced users, frequent configuration changes could be an integral part of the experience, such as in cases where the user wants to frequently change the operating parameters to achieve certain output results not otherwise possible, or to switch between input/output devices.

5.4.2. Filtering

The design and implementation of filtering is a key component in making the system adaptive. While some filtering can be implicit and some explicit.

Implicit filtering can be performed at the input or output driver level, to condition the generated data or to sanitize input data. Implicit low-pass filtering might be performed, for example to reduce noise from an input device, or to dampen signals to match a performance envelope of an output device.

Explicit filters can be created and applied to streams with relative ease. The two main ways of implementing a filter are by adding it in JavaScript to the configuration page, or by registering an external WebSockets based filter. Such filters can be written in any language, including C and Matlab.

5.5. Sample outputs

Examples of outputs are provided below. These are from different periods over the last phase of the project (~4 months), and not always created with the intent to create art, but rather some are outputs of technical trials.

Figure 47 - Tal, Cristina, and her mother with Cristina's first drawing on the final system (left), and one of Cristina's drawings from her portfolio (right). Showing the similarities in style on both systems.

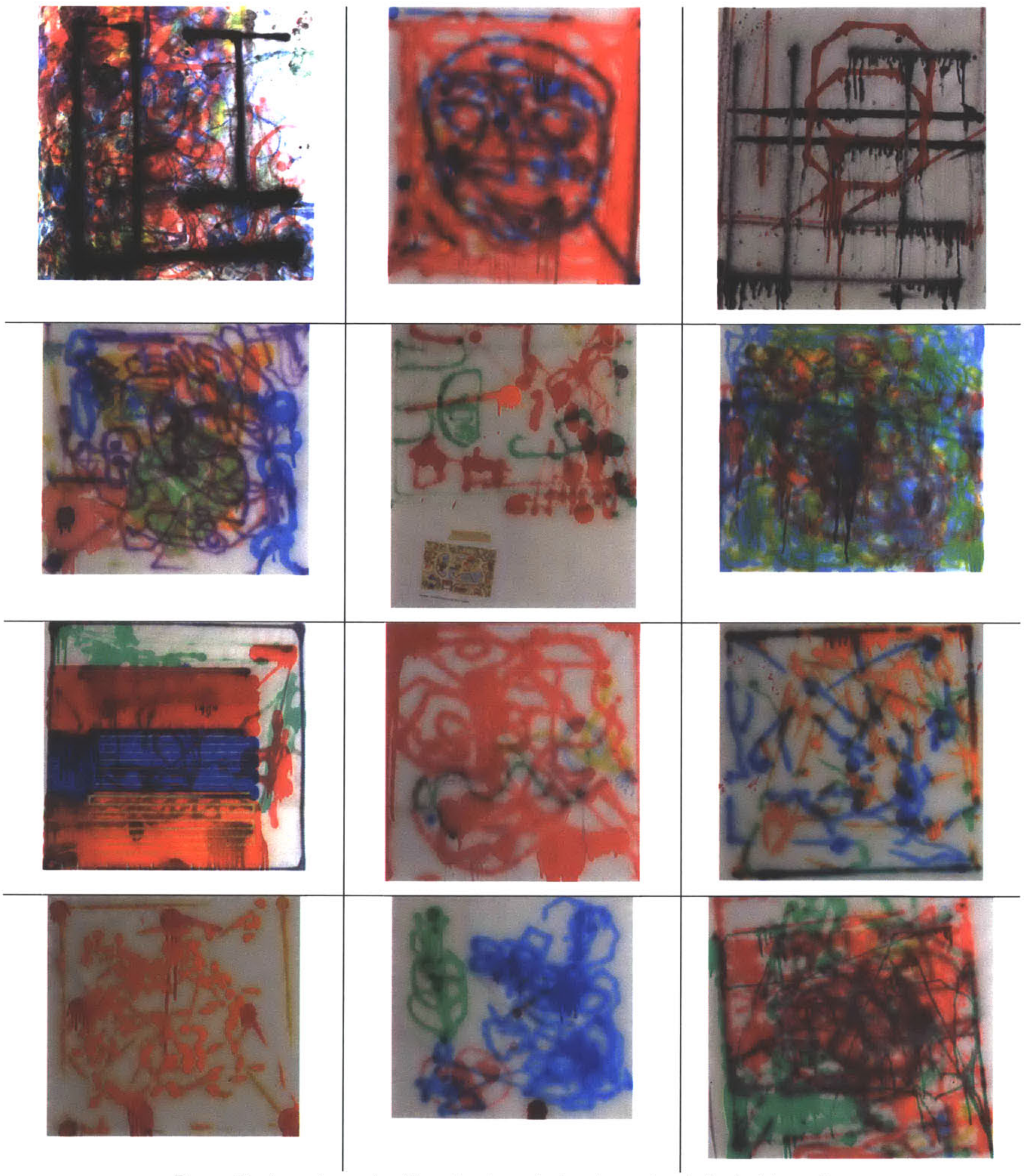

Figure 48 - A small sample of the artwork created on the system in the last 4 months.

Chapter 6

Experiments and Validation

"... technology alone is not enough—it's technology married with liberal arts, married with the humanities, that yields us the results that make our heart sing." – Steve Jobs

6.1. Usability Tests

To evaluate the usability of the system user studies were conducted. Participants were brought to our lab where they were introduced to the system and asked to use the various input methods.

6.1.1. Research Population

The studies were performed over several weeks. Participants self-selected from a population of invited persons. The invitations were sent to artists, engineers, medical professionals, and patients of rehabilitation centers in the Boston metropolitan area. Some of the participants were Media Lab students. Of those - only the ones who did not have prior experience with the machine were included in the dataset for the study. The total number of valid participants in the usability tests was 19 (n=19).

6.1.2. Limitations

The setup was constructed such that the technology was least-visible, within the limits of performing tests within a lab environment where technology is everywhere. The lab setting can have an effect on the user's association of the device with technology both ways, on the one hand it is clear that there is technology involved, while on the other hand technology is everywhere at the lab. With 6 laptops within the immediate vicinity of the device and a dozen others in clear sight, the association of the technology with the painting device in particular could be blurred. Similar concerns could arise when deployed in real-world conditions, they could even be expected to lean in different directions in each condition - we must therefore accept this is a serious limitation on the study. With these in mind, a study protocol was developed.

6.1.3. Protocol

The participants were presented with the device, and the various input methods for interacting with it. Some methods were already familiar to some participants, such as the Wacom tablet, while others were entirely new for most participants, such as eye tracking.

To reduce novelty effects, the participants were made familiar with the input technologies prior to using them for the study. For example, the eye-tracker's calibration and demoing platform was introduced to those not familiar with it and they were allowed to play around, uninterrupted, for a significant amount of time (5 minutes, unless they exit it themselves first, and longer if requested).

Participants were told there were no wrong answers, and it was explained that no specific outcome was desirable, rather that understanding their true personal experiences was the goal of the study. They were asked to think aloud and prompted by the researchers with the following questions:

- How does it feel?
- What do you like/dislike about the experience?
- To what degree are you able to achieve the result you planned for?

Each participant was asked to evaluate the system by answering the following questions (on a symmetric 1-7 scale, unless otherwise noted):

1. For each input - what is your level of comfort using this input?
2. For eye tracking and stylus inputs:
    a. To what degree are you able to achieve your intent? (Intent rank 7=100%)
    b. Who is drawing? (Ownership rank 7="me")

6.1.4. Analysis

A linear regression of score against disabled-status and question-asked was performed on the questions relating to comfort, ownership, and intent, and the results are presented below.

6.1.4.1. Comfort

In the statistical analysis there appears to be no significant difference between disabled and non-disabled people, but this masks variation between different conditions as can be seen in the graphs in figure 49 below. The size and sampling of the study population was chosen to include people with diverse conditions, which unfortunately meant that there aren't enough representatives of any particular condition to draw conclusions beyond this on a per-disability basis. The data can be used however to perhaps pick particular areas to explore, such as usability of eye tracking across populations.

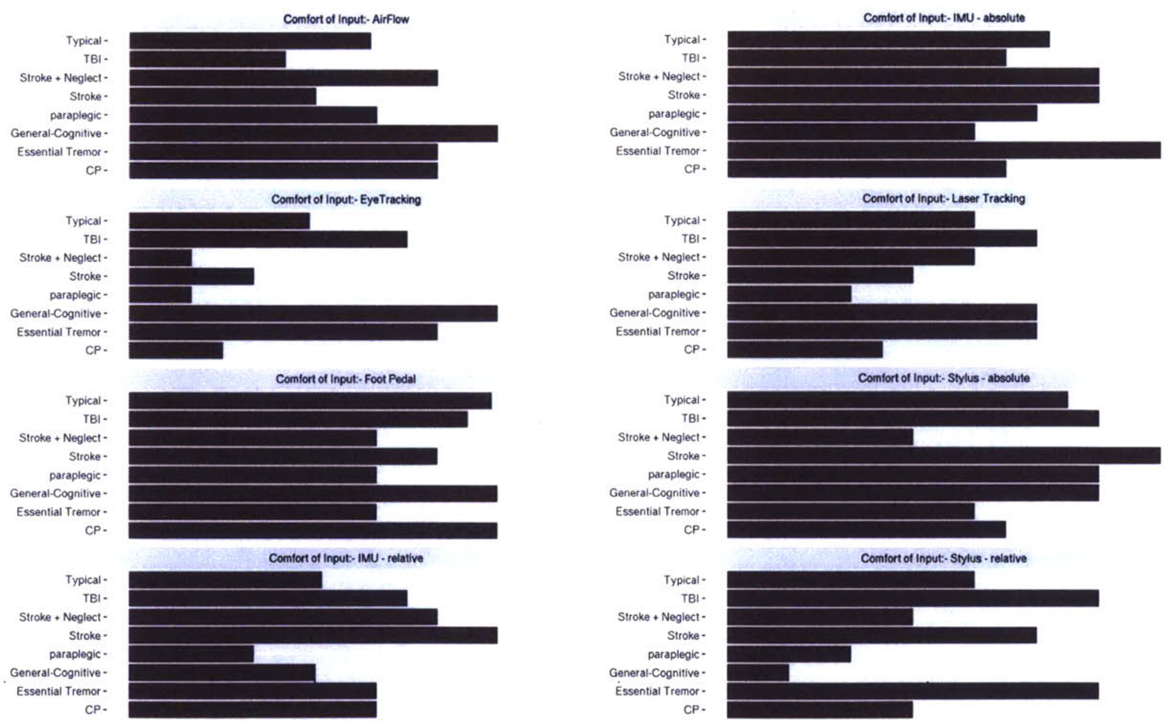

Figure 49 - comfort ranks, top-down left-right:
airflow, eye tracking, foot pedal, IMU relative, IMU absolute, laser tracking, stylus absolute, stylus relative

There were however significant differences amongst the comfort levels across different devices between the populations: Stylus (Absolute) ($p<0.01$), IMU (Absolute) ($p<0.05$), and Eye Tracking ($p<0.05$) were all significantly favored by the disabled subjects over the average score of the subjects without disability, while the foot-pedal was liked less by the disabled population ($p<0.01$).

The limited power of these tests should be stressed - the size and diversity of the population, as well as selection method all mean that the results are to be considered tentative, even when significant. We hope to use these results to inform further development and research, both on this project and others.

6.1.4.2. Ownership and Intent

Both intent and ownership all show very positive results, which are even more positive than we expected to see. Every respondent had a positive response for both intent ("I am able to achieve my intended result") and ownership ("I am creating the drawing") with the exception of eye-tracking which had some neutral responses with respect to intent as well as an entirely negative response. The entirely negative response was in the case of an individual post-stroke who was unable to recognize that his gaze was in any way related to the output.

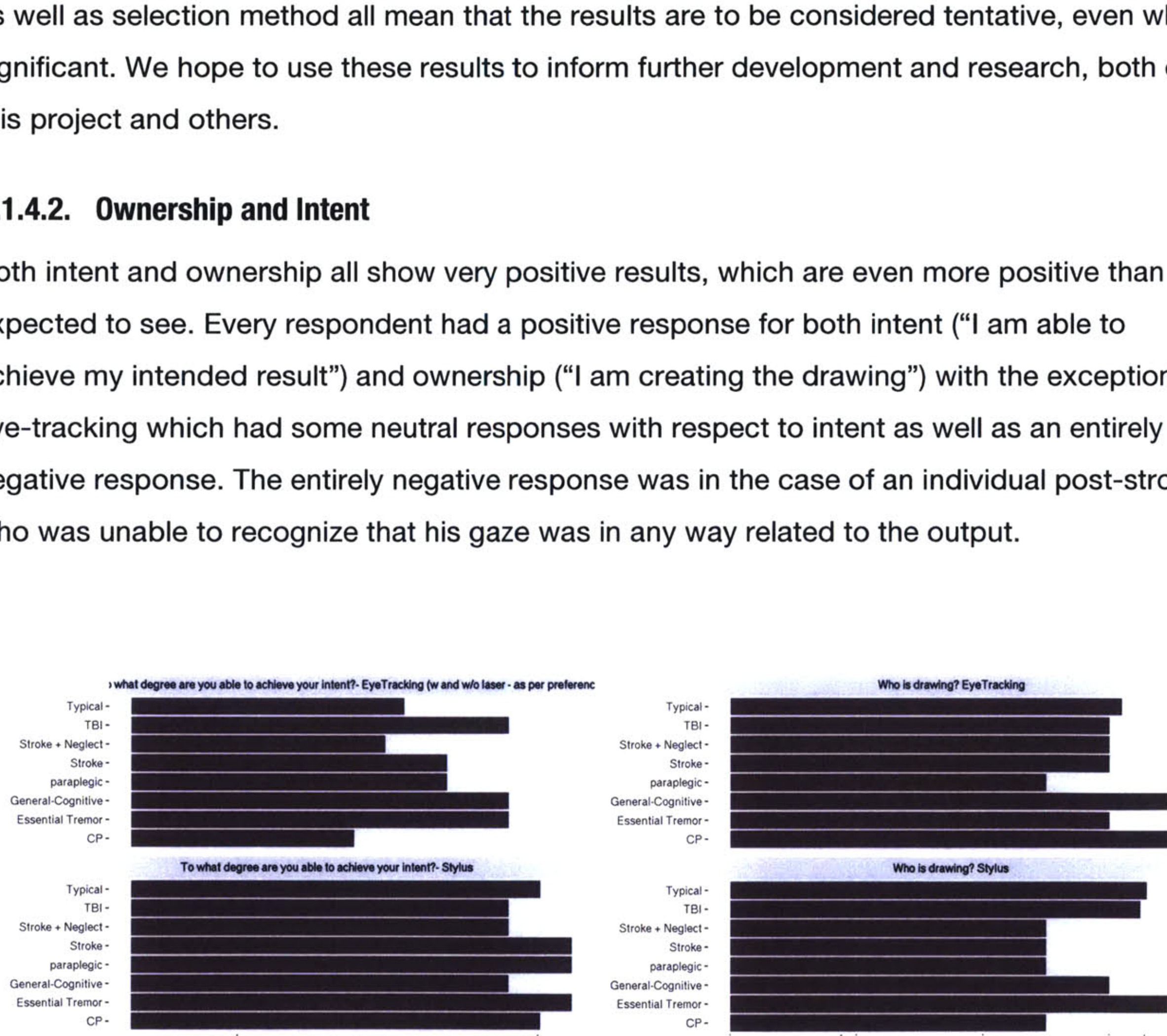

Figure 50 - left: intent rank, right: ownership rank

6.2. Developer Trials

The ease of use of WebSockets, especially when provided with sample code, means that any developer could integrate with the system. Even though none of the developers we consulted disagreed with this statement - we decided to put it to the test in order to validate that we are not missing any details in the implementation guidelines which would cause confusion to someone who is not familiar with the system. In other words - to validate the ease of integration as well as to double check that we weren't missing anything due to being too close to/familiar with the system.

Seven developers from varied backgrounds and levels of experience were given our sample code and asked to integrate an input mechanism of any kind (such as a mouse). All seven developers were able to complete the task. No other statistics were collected due to logistical reasons, and since it would be difficult to justify any meaning (even if significant) due to the small sample size, differences between participants, and the non-controlled environment, since each developer was doing something slightly different, and with different levels of engagement.

6.3. Impact on perception of disability

In two separate sessions students (n=30) were asked to rank the ability of people with or without certain conditions on a symmetric scale of 1 through 7. The participants were then exposed to the gantry with robotic airbrush, and observed a (non disabled) student use the system for one minute using a variety of input methods. An hour later they were asked to fill the same form again - without seeing their previous responses. They did not know why they were filling out the form, nor did they know to expect to fill it out again later. A non-disabled user was selected since we feel that a result outside the context of disability is, arguably, stronger than with a disabled person.

Of all responses, only two participants did not show an increase in ranking of ability, and only one participant filled in '7' for all categories (in both the pre and post conditions).

Further examination of the data (presented in figure 51 below) was performed through a linear regression of score against disability, session, timing (before/after exposure), as well as interaction terms between timing, and the disability and session, respectively.

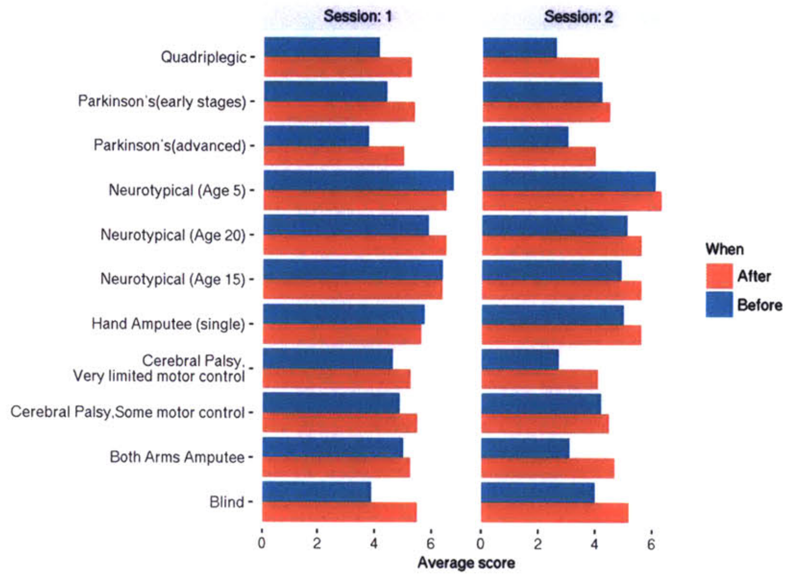

Figure 51 - Answer distribution on perceived ability

The change in score was on average significantly higher after the exposure than before (p=0.01) suggesting that exposure to the system does cause an improvement in the perception of disability.

Scores were significantly different between sessions but the change in score was not significantly different between the two sessions (due to the confidence interval of the interaction of change in scores with session covers 0: [-0.79..0.33].)

'Neurotypical (age 5)' category shows significantly less improvement in rank than average (P=0.04)

6.4. Therapeutics and Diagnostics

The system was presented to several professionals including doctors, physical, occupational, and art therapists. Nearly all of the professionals consulted reported that they can see clear uses for the system in their line of work. As previously described, many areas have been identified with applicable uses for the system.

While therapeutics and diagnostics applicability are out of scope for our evaluation, several encouraging observations were made. One that stood out in particular is the difference in painting area, across input methods, by a person with hemispatial neglect, as seen in figure 52 below.

Figure 52 - Binary map of areas painted (black) by person with post-stroke hemispatial neglect.

Chapter 7

Future Work

"Technology is anything that wasn't around when you were born" – Alan Kay

We envision several directions for future work. Expansion for additional inputs and outputs is a clear path. Improvements for reduced cost, better resolution, mobility, and connectivity.

Platform

Future deployments should include an open platform specification which enables extension not only of this platform, but also allows for the platform itself to be subject to iteration and evolution.

Scale

Smaller (mobile) and larger (fixed) versions could be constructed, to complement the current transportable design. Smaller versions could be significantly cheaper and used for amateur artists, or as a game for kids. A larger version can be used for industry, research, and large-scale art projects.

Further Accessibility

Through our collaboration with Daniel Kish he visited our lab for several days and provided unique feedback regarding the fit of input and output mechanisms for blind individuals. While an interface for the blind is out of scope for this thesis, the development of such an interface was taken into account as part of the scope that the design should support through extension. Auditory and haptic outputs for blind individuals, as explored in the brainstorming sessions with Kish, can be constructed using existing technologies, and have the potential to expand access greatly.

Additional Outputs

Connecting the system to additional outputs can greatly extend its abilities and make it more interesting for a larger variety of artists and would-be artists. One project which we have already explored integration with, in addition to the gantry, is the Flying Pantograph[69], seen in figure 53 below, developed in our group by Sang-won Leigh and Harshit Agrawal.

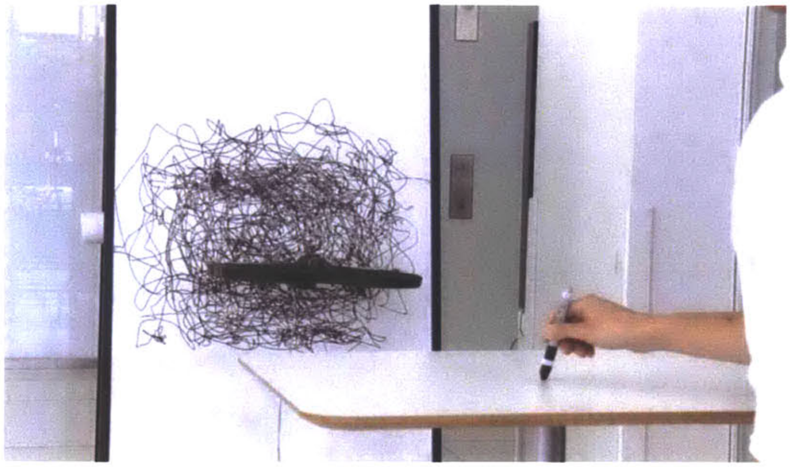

Figure 53 - A Flying Pantograph
(photo credit: Sang-won Leigh)

Extended Intelligence

Expansion of the abilities of the system to interact with artificial intelligence and extended intelligence systems is particularly interesting, but contingent upon the further development of such systems. One such example is Tandem[70], which as previously discussed, when combined with a physical output device can extend its collaborative abilities to the physical domain.

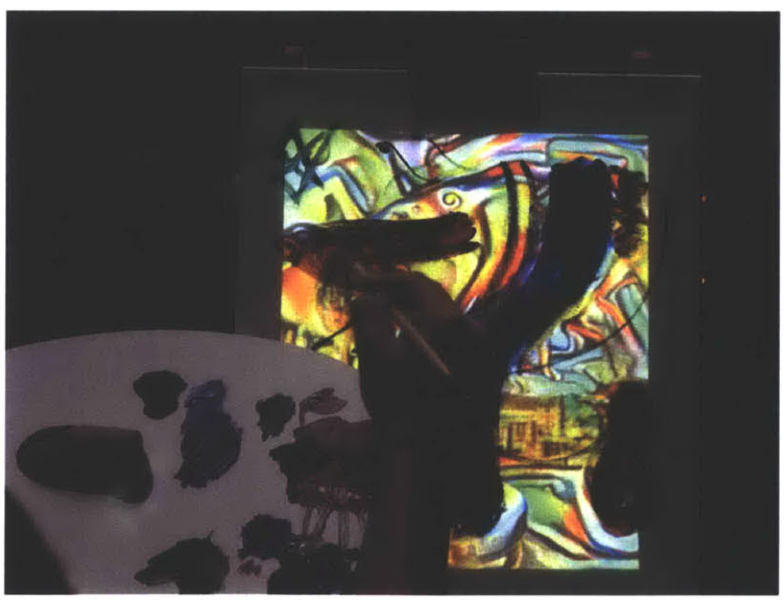

Figure 54 - Tandem by Harshit Agrawal,
A Deep Learning Conversational Art Medium
(photo credit: Harshit Agrawal)

Blurring the Digital/Physical barrier in arts

The future of the technology is the disappearance of the technology itself. To reiterate, the power of the medium and discipline of painting lies in the interdependence of the image (virtual field) and physical composition of the painting. As digital images have increased geometrically in complexity, they have challenged the aesthetic demands of traditional painting. Where painting can now re-enter the "discussion" is transforming digital images into physical form in ways that increasingly blurs the exact boundary between digital and virtual. This *blurring* is an act that accelerates and improves through the juxtaposition of creative and technical talent in environments that foster such engagement.

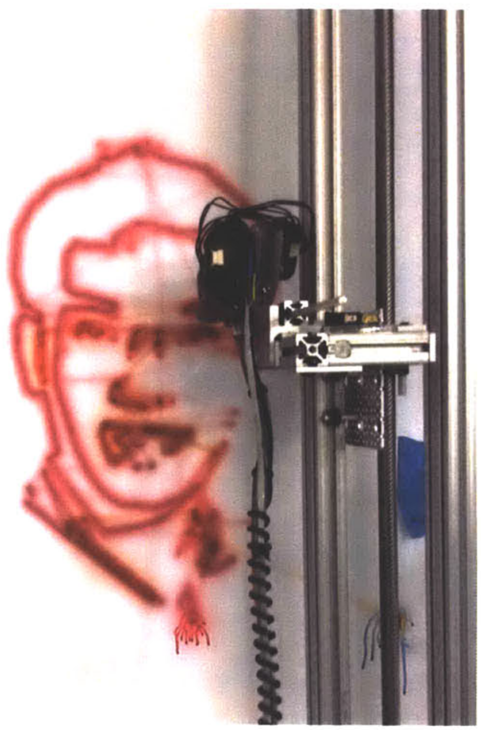

Figure 55 - Mechanical Reproduction of a Digital Image

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