

Kinesthetic Feedback on interactive display surfaces

Using Stick-Slip to provide directional forces and
kinesthetic feedback on interactive display surfaces

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Abstract

Modern interactive surfaces and displays provide powerful and highly efficient visual and auditory human-computer interfaces. However, the usage of haptics is still in its infancy. Often limited to primitive vibrotactile warning or notification signals, the possibilities of haptics to communicate complex images and information have not yet been realized. Based on research done in previous years, new methods have been developed to deliver more specific tactile information about objects and their surfaces. Nevertheless, the kinesthetic sense, which enables to detect different object properties such as weight, inertia and impedance, is rarely discussed as a part of a haptic system. Relying on kinesthetic information has been proven to be beneficial in order to detect, recognize and interpret haptic images in the virtual world. This has been achieved by using linkage-based multi-dimensional manipulators, exoskeletons or robotic arms. Based on the increased usage of mobile devices, new challenges are arising, especially considering linkage-free technologies. To approach this challenge, this thesis describes a system which is able to apply directional forces, linkage-free to a stylus tip, in order to control user behavior. The stick-slip phenomenon has been used as the basic technique to deliver directional forces in the absence of kinematic chains and mechanical linkages. Based on the theoretical approach, the prototype requirements were specified and the configuration of the system (mechanical components, actuators and control parameters) were discussed. By using the resulting system specification, three mockups were developed which led to a final system implementation. During the course of this research, it was demonstrated that it is possible to generate directional forces on an interactive display in order to move a stylus linkage-free over the touchscreen in a fully controlled and efficient manner. The technology described in this thesis opens new possibilities for interacting with displays. The developed system can be used to provide continuously-supervised learning or feed forward systems which predict the user behavior and modify kinesthetic signals.

Keywords: kinesthetic signals, stick-slip phenomenon, electromagnetic actuators, piezoelectric actuators, multithreading, C#, virtual COM port programming, FTDI programming

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1 Introduction

Modern life is highly connected to technology. During a normal day, an average person interacts with various kinds of intelligent surfaces and displays. This includes mobile phones and tablet PCs as well as general information terminals and interactive kiosks found in public spaces. To interact with these devices, direct manipulation interfaces are mainly used rather than the traditional desktop input devices such as keyboard, mouse, trackball or touchpad. This shift towards touch interfaces provides a lot of advantages. The most important one is that touch interfaces are very natural, as it is much easier to directly interact with the objects on the touchscreen rather than using a mouse, trackball or touchpad which requires a high level of hand-eye coordination. The development of interactive displays was a millstone in human-computer interaction because direct pointing and selection is an extremely intuitive input technique. Nevertheless, moving objects on the screen by direct manipulation describes only the input side of the human-computer interaction. Additional information which is retrieved while grabbing an object and feeling its properties such as weight and inertia also needs to be taken into consideration. By only relying on the visual or auditory representation, it can be difficult to really understand the environment because things are not always what they seem. Often, the sense of touch is needed in addition to visual cues to clarify the specific features of virtual objects. By using touch, complex information can be easily perceived. It is possible to assess and understand the material structure (soft, hard, sticky). Also the texture can be recognized. It can feel pleasant, dangerous or even cheap or expensive [1]. A simple touch can communicate complex feelings and this is a phenomenon which is rarely used in modern human-computer interaction.

1.1 Motivation

In 2014, the usage of mobile devices for accessing Internet content exceeded for the first time the usage of traditional desktop PCs and laptops. One major reason for this development is that mobile devices can be used at home, in public places, at work or during leisure time. Basically, they are accessible everywhere and at any time. This change from using computers only in clearly defined environments, such as a working place or at home, towards using them anywhere, introduces completely new challenges. The user is confronted with noisy environments or changing lighting conditions. Therefore, the mobile device needs to be usable while walking and it needs to provide a maximum amount of information with minimum mental effort and attention. Finding a solution for all those requirements is very challenging, especially when considering that the user needs to understand the information provided by the device in every situation. One possible approach to solving this problem is to involve multiple senses at the same time. Based on the human sensory system, five major senses can be identified: sight, hearing, taste, smell and touch. The two senses, primarily used by most of people, are sight and hearing which resulted in the development of powerful visual user interfaces for interactive

surfaces [2]. The sense of touch is used as well, but often only in a very primitive manner. It is mostly limited to vibrational cues which only communicate warning or notification signals to the user. When considering the various places where mobile devices are used, it can be seen that most of the time at least one of the two major feedback techniques can not be utilized [2]. For instance, it can be too noisy or vice versa, either way it may not be appropriate to use audio to communicate information to the user. In addition, it might be too sunny and the content shown on a display is hard to perceive and recognize. There are various situations where the sense of vision or hearing can not be used. Therefore, it is important to involve the sense of touch more into modern interactive devices. As explained in the introduction, it is possible to communicate complex feelings by using touch. There are plenty of opportunities to create a much more intuitive interface and including the sense of touch is one important step towards it.

1.2 Scope and Goals

The goal of this master thesis is to investigate into a new interaction technology which allows to control linkage-free kinesthetic components of the haptic space in a more integrated and meaningful manner rather than the tactile sense alone. It should provide a discussion about how the new technology can improve human-computer interaction and demonstrate the development of a fully functional system for demonstration purpose. The thesis focus on kinesthetic information which proved to be the missing link in using the haptic sense effectively [2]. It discusses the stick-slip phenomenon and how it can be used to deliver linkage-free kinesthetic information to the user on rigid, interactive surfaces and displays. To reduce the complexity of the task and system, the input technique is limited to the stylus-based interaction. The clearly defined contact area and material limit the amount of additional parameters which interfere within the system. Direct manipulation via fingertip will be out of scope of the present study and therefore not be discussed. As a result of this research, the theoretical background should be defined and a system should be produced to demonstrate the main functionalities and concept of the new interaction technique. It should show that it is possible to generate controlled directional forces on an interactive display surface in the absence of stiff kinematic chains and mechanical linkages.

1.3 Research Context

Various research techniques have been explored which try to integrate haptics into mobile devices. Since Motorola patented the first primitive vibratory alert device in 1995 [3], many attempts towards a more sophisticated haptic sensation were made by integrating complex vibration patterns. In this way, it was possible to assign a certain sensation to a specific event [4]. These so-called tactons were used to present non-visual information to the user where visual or auditive feedback were not practical or possible. The main limitation of those tactile icons

was that humans have to learn which pattern stands for which event. This none intuitive pattern to event mapping limited its practical usage, at least for people without visual impairment [5]. Another approach was to move away from global, towards more local screen vibrations [6]. By using multiple actuators instead of a single one, researchers tried to deliver a richer set of tactile information. The goal was to provide vibrational signals to specific parts of the display. Besides the usage of tactile signals to communicate haptic information to the user, kinesthetic signals were also considered. One relevant research which presented a method for creating kinesthetic signals on a flat rigid surface was published by Winfield et al. [7]. The authors described a method to create virtual forces by modulating the friction coefficient between the user's finger and the screen. In that way, they were able to make objects and textures perceptible on a plane rigid surface. The same principle was adopted by other devices such as the "Large Area Tactile Pattern Display" [8]. Another approach of how kinesthetic signals can be created on an interactive display surface was introduced by Kaye [9]. He discussed the possibilities of using a sawtooth-shaped vibrational pattern to create a virtual force sensation which could be applied to the fingertip of the user. This allowed to generate a feeling of a 3D surface which provided a much richer set of touch interaction. One example Kaye described in his paper is shown in Fig. 1. The image shows one scene from two different perspectives. The first one (a) shows the visual representation and how the user would see the scene. The second one (b) shows the force representation and how the user would feel the scene.

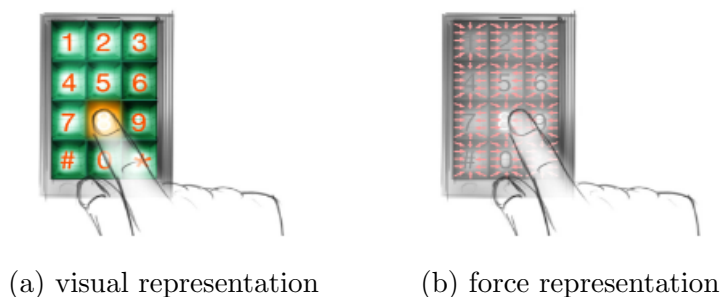


Figure 1: Force feedback example application, adapted from [9]

The concept discussed by Kaye has been elaborated one step further within this thesis. Instead of providing only a sense of virtual forces, it has been a great challenge to deliver physical force-moments and kinesthetic sensations on an interactive display surface. By applying physical forces to the user, a new communication channel between human and computer can be created. The device would physically interact with the user instead of only providing a virtual sense of imaginary forces. The haptic space would no longer be limited to only reacting to the user's input. Instead, it could actively support or modify the user input which is still impossible to realize without cumbersome haptic tools such as pantographs and cable-driven systems [10, 11].

1.4 Thesis Structure

This master thesis consists of three main parts. The first chapter provides an introduction to haptic based interaction. It defines the term haptics and shows that kinesthetic signals are the most crucial components in the integration of the haptic sense. Chapter three and four specify the technical approach of how the kinesthetic sense can seamlessly be integrated into interactive displays. Consequently, the stick-slip phenomenon is introduced and the system requirements are defined. Chapter five, six and seven discuss the development, prototyping and implementation of the demonstration system. These sections provide an analysis of related technologies and mockups. As a result, the final system is described, including the main software and hardware components and their functionality. The last part of this thesis discusses the limitations of the current demonstration prototype and further areas of research.

2 Introduction to haptic-based interaction

In order to successfully interact with the environment, human beings developed five major senses: sight, hearing, taste, smell and touch. For the majority of people, the two most dominant ones are sight and hearing [2]. Based on that fact, most interactive surfaces provide a user interface which is optimized for those two senses. One of the senses which is frequently neglected as a natural communication channel is the sense of touch. Often reduced to simple and primitive tactile cues, most of the consumer electronics on the market only integrate it as vibrotactile feedback [6]. The sense of touch is more than just a primitive sense, as it can be easily shown by comparing it to the sense of sight. By looking at an object, it is easy to perceive many properties such as size, shape or color. In fact, a lot of properties still stay hidden until the object is touched and physically manipulated. By using the sense of touch, it is possible to perceive much more characteristics such as weight, inertia, impedance, material, temperature and many more [10, 12]. In order to show the possibilities which the sense of touch provides, this chapter begins with an introduction to haptic-based interaction. It defines the term "haptic interaction" and demonstrates that the sense of touch can be used for more than just primitive tactile-feedback cues. Subsequently, the kinesthetic sense is discussed including the most promising approaches to connect the real and the virtual world by using advanced haptics. To conclude, the last part of this chapter presents an approach of how the kinesthetic signals could be integrated into interactive display surfaces.

2.1 Perceptual haptics

The word haptics has its origin in the Greek language and translates to sensing or manipulating the environment by using the sense of touch. In its traditional meaning, it only described the interaction of humans with real objects. In the late 1980s, the term was extended to cover all human-computer touch interaction including the physical and virtual space [2]. When manipulating an object through touch, receptors located in the human skin are able to selectively detect and recognize different signals. These signals can be divided into four categories: discriminative touch (touch, pressure, and vibration perception), pain and temperature, proprioception (pose and position of the body and limbs) and the kinesthetic sense (perception of body and limbs movement) [12]. Each object property can be detected using at least one of the four signal categories. Distinct characteristics such as material, texture or temperature can be detected exclusively relying on discriminative touch, pain and temperature signals. The receptors used for sensing these signals are located close to the surface of the skin and distributed over the whole body. Coarse properties such as shape, weight, inertia or impedance have to be integrated over the region and cannot be identified in the absence of proprioception and the kinesthetic sense. The receptors for those signals are mainly found in muscles, tendons, and joints [10].

2.2 Haptics: more than just a primitive sense of touch

When talking about the sense of touch, it is common to diminish it to simple tactile feedback. This can be observed in the way most of the commercial products on the market make use of it. The majority of them, only include vibrotactile feedback which is mainly used to provide non verbal information about events that happened, such as pressing a button or receiving a message [6]. It is relatively easy to generate vibrotactile feedback by using simple actuators, which provide vibration to specific areas or the whole device. The major drawback is that tactile signals alone are only able to deliver very vague information and often it can only be interpreted in combination with visual (pictorial) or auditory cues. A good example of this behavior is virtual objects displayed on an interactive surface. When considering a pillow and a stone, it is commonly known that these objects have totally different physical properties. One is soft and lightweight, the other one is rough, solid and often very heavy. In the real world, humans would interact with both object in a different manner. In the virtual world on the other hand, both objects have the same or different virtual properties and there is no perceivable difference between them from the interaction point of view. Some devices allow to generate different vibrotactile patterns for both objects but there is no difference in the amount of force required to move the virtual objects around. This mismatch between tactile perception and required force indicates that especially the kinesthetic sense is not coordinated with the touch/tactile sense, or is even totally neglected. As already mentioned in the previous subsection, the kinesthetic sense is used to identify the coarse object properties including weight, inertia or impedance. It can be said that the kinesthetic sense is crucial to develop a mental model of the object. When closing their eyes, a person is still able to explore objects with their hands and imagine (mentally reconstructing) their shapes. That demonstrates that no visual or auditory signals need to be involved to imagine the object and its particular features. This effect of forming the haptic image has been demonstrated by Thyriou and Roll [13]. For their experiments, the authors used a set of vibrators to stimulate the mechanoreceptors of the participants arm muscles which are usually involved while performing a drawing or handwriting task. By providing a specific signal pattern, it was possible to stimulate haptic imagery by creating induced 2D and 3D mental images related to muscles and tendons involved (previously) in handwriting and drawing movements. In that way the participants of the experiment were able to draw numbers, letters and simple shapes in the absence of visual and auditory information. This demonstrates that the specific stimulation of the kinesthetic and proprioceptive sense can be used to induce motor illusions and may provide a valuable tool for motor rehabilitation and learning purposes. But it is important to not consider the kinesthetic sense in isolation. Only a combination of both, tactile and kinesthetic sense can provide a full haptic image to the user [12]. Information conveyed through the haptic communication channel is very natural and intuitive because it is based on feelings and the somatosensory (muscle) memory. Including the kinesthetic sense allows to create new ways of interacting with computer systems and visualizing data and that is everything else than primitive combinations of vibrations.

2.3 Kinesthetics allows to feel haptic space

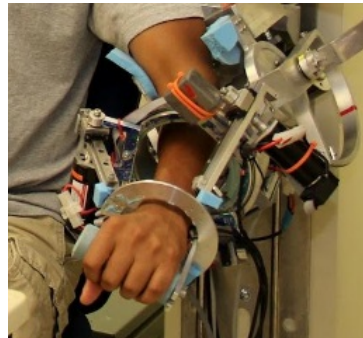
The kinesthetic sense can be used to feel the shape of a virtual object. By providing force and torque feedback to the user, the virtual world becomes perceptible. Different transducers can be used to generate these forces. The most common ones are pneumatic, hydraulic, electro-magnetic, electrostatic, piezoelectric, thermoelectric, and polymeric [12]. Based on these transducers a large amount of devices have been developed which use the kinesthetic sense to convey information to the user. In general, two categories of kinesthetic devices can be identified: impedance and admittance, which are both explained below:

Impedance devices are the most common type. Based on the virtual object model and collision detection, impedance devices provide a force vector to the user according to the location. The main idea is: displacement in - force out [14]. The most popular examples of this category are phantom devices, as shown in Fig. 2a. The utilization of a probe with six degrees of freedom enables the user to explore the virtual world in a three-dimensional space. If a collision is detected between the probe and a virtual object, the phantom device generates a force feedback according to the object model [10].

Admittance devices on the other hand, are significantly less common. Instead of providing force feedback based on the location, admittance devices calculate the expected displacement based on the applied force. In general, the main principle is: force in - displacement out [14]. One good representative of admittance devices are exoskeletons (Fig. 2b) which are used for teleoperation, surgery and rehabilitation [11].



(a) Impedance Device



(b) Admittance Device

Figure 2: Linkage-based force feedback devices

2.4 Linkage-free kinesthetic stimulation on interactive display surfaces

When creating a device to deliver meaningful haptic information based on directional forces and micro-displacements, the main intention is to design it as transparent as possible (in the absence of kinematic chains and mechanical linkages). The user should not feel or notice the layout of actuators. The primary focus should lay on the information presented by the kinesthetic

sensations, in order to make the interaction as smooth and natural as possible. Nevertheless, most of the kinesthetic devices available are linkage-based desktop systems and mechanisms which applies to phantom devices as well as to exoskeletons. In a world where mobile devices are getting more and more important, it is essential to provide a solution which is portable and can also be integrated with mobile phones or tablet devices.

To overcome those problems, a technique to generate linkage-free directional forces on interactive display surfaces must be developed. By generating force feedback directly over the display surface, no additional kinematic chains and mechanical linkages are required. In that way force feedback can be directly applied to the input device in order to influence the user's interaction behavior. By creating kinesthetic signals on an interactive display surface, the haptic interface would become a totally invisible bi-directional communication channel. Through the continuous contact between input device and interactive display, the haptic channel is able to deliver much more information in an intuitive manner. Furthermore, the tactile sense could be easily integrated. By combining the vibrotactile feedback, which is already embedded in many interactive surfaces, and force feedback which stimulates the kinesthetic sense, a full haptic image could be perceived directly on the plane display surface. The haptic image in combination with the visual and auditory sense can provide a completely new multimodal approach for visualizing the virtual world. The new technology would be able to simulate various physical properties for different virtual and augmented objects. Such technique presents a notably more natural and efficient interaction because it activates and relies on inherent and adaptive mechanisms of sensorimotor learning and skill acquisition. Moreover, the prior experience acquired in the physical world can easily be mapped to the virtual world. That would prevent confusion and simplify knowledge acquisition, interpretation and retention by involving the muscle memory [15].

3 Stick-Slip phenomenon in the haptic space

In the previous chapter it was shown that kinesthetic signals can improve the user interaction with digital systems. By applying directional forces to an input device, the computer system is able to optimize the user interaction behavior for specific tasks. This chapter examines a technical approach for applying controllable kinesthetic signals to deliver complex information through the haptic space. It also provides an overview about related work and demonstrates that none of the current approaches provides forces which are strong enough to supervise the user behavior. Instead, only haptic information such as warnings or notifications can be applied through the generated virtual forces. In addition, the relation between friction and inertia is defined and it is shown how both can be used to generate directional forces on a plane interactive surface. The feasibility of the suggested approach is examined by discussing an already existing real life example for the usage of the stick-slip phenomenon.

3.1 Generating virtual forces on interactive surfaces

Currently, the only way of creating virtual sense of directional forces on an interactive surface is by modulating the friction coefficient [16]. In order to simulate tangential forces, the friction between the input device, such as the finger or stylus, and the surface of interaction is modulated. If the friction is artificially raised, moving an input device over the interactive surface requires a greater force than before. On the other hand, if the friction coefficient is artificially lowered, moving the input device over the interactive surface becomes much easier. By switching between both states, a perception of virtual edges and surface structure (virtual textures) can be generated. Friction modulation can be achieved in multiple ways. The first approach was described by Müller et al. [16]. The researchers developed a stylus containing a steel ball tip and an electromagnetic coil. When moving the stylus over the display surface, the steel ball tip rotates, which produces only a very small amount of friction. By using the electromagnetic coil, the steel ball can be attracted, which increases the friction force. Thus, the force required to move the stylus over the display surface can be modulated.

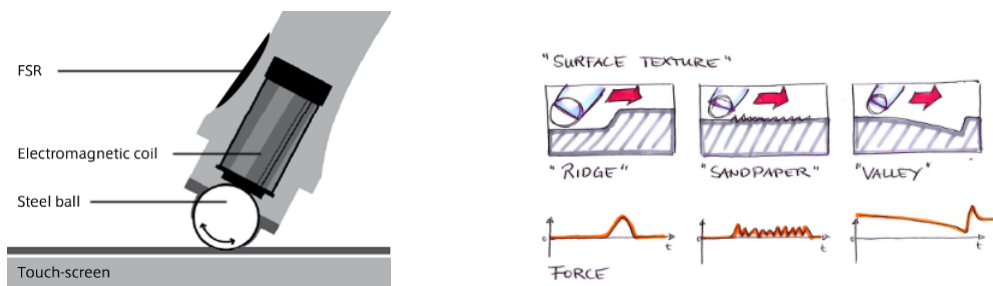


Figure 3: Stylus based friction modulation, adapted from [16]

The second approach was presented by Levesque et al. [8]. Using 26 kHz vibrations, produced by a piezoelectric actuator, the authors were able to create a squeezed air film which reduces the friction on an interactive display surface. By using this technique, the just noticeable difference

in friction has been recorded to be approximately between 30% and 40%. Nevertheless, the presented approach allowed to simulate multiple friction levels that could be used for the tactile presentation of different object structures and well-distinguishable levels of the virtual surface. The third approach is to create lateral forces in order to simulate virtual edges and surface structures. This concept is based on research done by Robles-De-La-Torre [17], who described the importance of lateral forces to perceive and recognize planar shapes. Based on their research, the T-Pad (Tactile Pattern Display through Variable Friction Reduction) was developed by Winfield et al. and presented at EuroHaptics, 2007 [7]. The authors utilized piezoelectric actuators to alter the friction coefficient and to simulate lateral forces.

In conclusion, it can be said that none of the approaches discussed above produces forces strong enough to change the direction of stylus or fingertip movements. The difference in friction force that the user encounters, can only be perceived when they have initiated the actual movement. Therefore, it is not possible to feel the difference in friction coefficients by keeping the input device in the same position which means that the user has to actively move it. For that reason the current solutions can be described as passive because they are only reacting to the user action instead of supervising and influencing the user's behavior.

3.2 Friction and inertia for generating directional forces

The technical solutions discussed in the previous subsection describe how virtual forces can be generated by modulating the friction between an interaction device (either fingertip or stylus tip) and an interactive surface. Directional forces can be obtained by balancing between two independent variables – friction and inertia. This concept can be described based on the interaction of two objects (Fig. 4), A and B [18], where object A can be considered to be at rest regarding B . Both objects, A and B are in contact with each other which means that a friction force exists between them. When an external force (F_e) is applied to object B , Newton's first law of motion comes into the picture which states that: "When viewed in an inertial reference frame, an object either remains at rest or continues to move at a constant velocity, unless acted upon by an external force" [19]. Thus, when object B is accelerated, A tries to remain in its current state (at rest). The only force which makes the object A to follow the movement of B is the friction force. It can be said that the friction force (F_{fric}) works contrary to the force of inertia ($F_{inertia}$). The friction force can be calculated by using the normal force which works upon object A multiplied by a constant factor which describes the friction between both materials. This factor is called "Coefficient of Friction" (COF) and is typically denoted as μ . If the force of inertia is greater than the friction force, the object on top remains in its current state. As a result, object A slips over B . If the force of inertia is less or equal to the friction force, the object changes its static state into a dynamic state. In other words, A starts to follow the movement of B .

$$\vec{F}_{inertia} > \vec{F}_{fric} \Rightarrow \text{Object A slips over B}$$

$$\vec{F}_{inertia} \leq \vec{F}_{fric} \Rightarrow \text{Object A sticks to B}$$

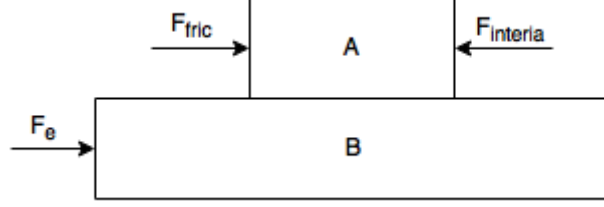


Figure 4: Relationship between inertia and friction force

To use the friction-inertia principle for generating directional forces, an application needs to alternate between the sticking and slipping phases. This alternating motion is also called stick-slip effect and it has been already used in technical applications such as building friction–inertia actuators [18], performing part manipulation tasks [20] and designing novel types position control linear actuators [21]. To examine this effect in more depth, the different stick-slip phases need to be analyzed. As can be seen in Fig. 5a phase one (I), the force of inertia that works against the acceleration is smaller than the friction force, which causes object *A* to stick to *B*. In phase two (II) on the other hand, the force applied to *B* results in a force of inertia which is larger than the friction force. Thus, object *A* slips over *B*. In phase three (III), object *A* and *B* return back to their initial position. It can be seen that object *A* has moved in relation to *B*. The constant repetition of these three steps allows it to continuously generate directional forces using the friction-inertia principle.

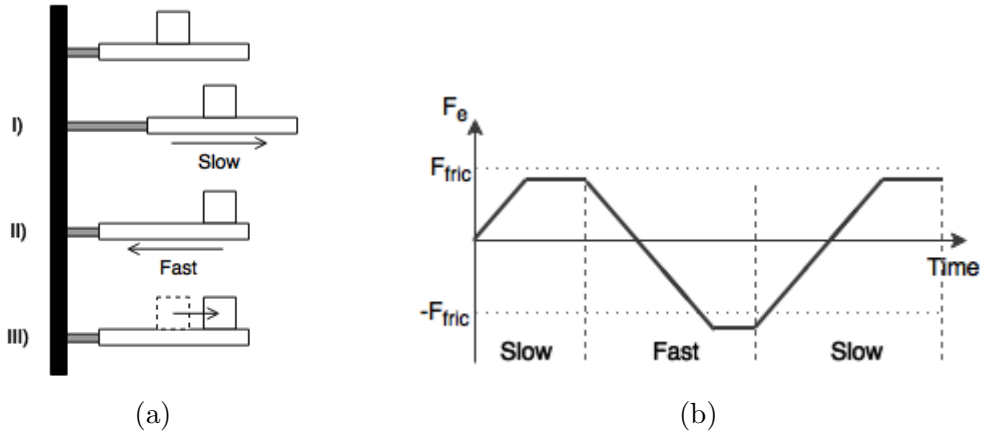


Figure 5: Generating directional forces using friction and inertia

3.3 Linkage-free object manipulation

The idea of using the stick-slip effect for manipulating objects on a plane surface has been described by Reznik and Canny [20] in the year 1998. At that time, their goal was to manipulate

different physical objects, such as instruments and small pieces, on a plane rigid surface. The authors tried to optimize object sorting by replacing the "sequential" pointing and selection method with a much simpler one. As a result of their work, they demonstrated that it is possible to manipulate objects on a plane surface by providing directional forces with respect to the central point P (Fig. 7a). By doing so, tangential forces can be applied to all objects located on the plate. How those objects respond only depends on their inherent physical properties (inertia and friction). To understand the concept, the forces acting on a circle can be considered. As can be seen in Fig. 6, two forces work against each other: the centripetal and the centrifugal force. The centripetal force is directed towards the central point and ensures that the object follows the circular trajectory. The centrifugal force, on the other hand, is directed away from the central point causing the object to leave the circular path. Given that $F_{centripetal} \geq F_{centrifugal}$, the object follows the rotational movement. If $F_{centripetal} < F_{centrifugal}$, the object leaves the rotational motion and moves away from the central point. It is important to highlight that the object's distance to the central position of the circular path is directly proportional to its velocity.

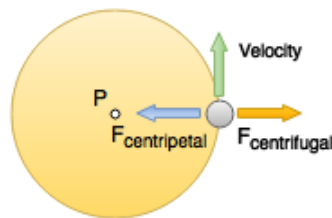


Figure 6: Forces on a rigid plate applied to any object located over, when twisting force (torque) was applied to the plate.

Reznik and Canny used this phenomenon to move and sort objects on a plane rigid plate in a predefined direction. Herewith, the centripetal force was determined by the friction between the object and the plate. This friction coefficient is static and its value does not change. The centrifugal force, on the other hand, can be controlled by the acceleration of the rotational movement and by changing the virtual central point. In other words, it is possible to move a specific object on a plate by choosing the acceleration and the central point in a specific way. An example of this behavior is given in Fig. 7. The field of controllable, directional and twisting forces shows a rotation with respect to the central point P . This motion causes the object O to change its position to O_s . The resultant vector of forces, which are applied during the rotation, can be seen in Fig. 7b.

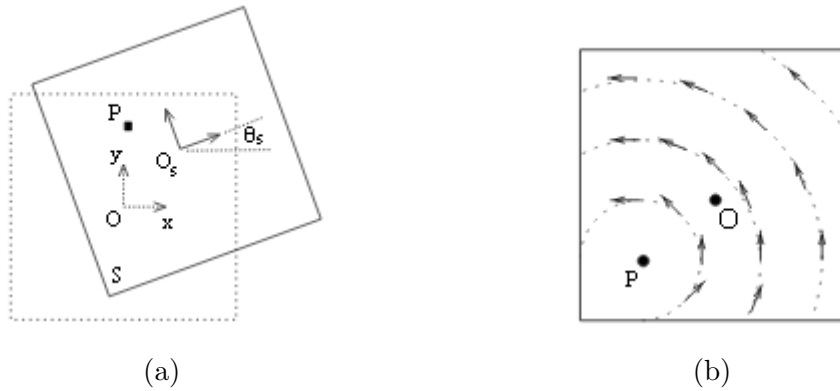


Figure 7: Rotation around the point P (a) and the resultant forces with respect to the point P (b), adapted from [20]

3.4 Using the stick-slip phenomenon for interactive surfaces

Modern interactive surfaces and displays are mainly relying on direct input through touch interfaces. Those interfaces are nothing more than rigid plane surfaces, as studied by Reznik and Canny [20]. Thus, the idea of using the stick-slip effect to deliver directional forces to an object in contact with a the screen is not new. However, until now a technical solution, which would be appropriate for mobile computing, does not exist. By directly actuating the display or an overlay, forces can be generated which cause the object on the screen to oscillate between sticking to the surface and sliding over it. Unlike Reznik, the actuation is not done by using sine waves. Instead, sawtooth pulses are generated as described by Zhang et al. [18]. The directional forces applied, can be used to manipulate objects being in contact with the screen surface, still in the absence of any stiff linkages or joints. As can be seen in Fig. 5, a sawtooth actuation pattern shows a non-symmetrical shape of the signal envelope. In phase one (I), it is assigned to perform a slow movement of the overlay surface towards one direction, by relying on the friction force. In phase two (II), contrary, the signal applied to the actuator produces a fast movement of the overlay surface into the other direction which creates a relative motion, based on the objects inertia. Thus, the object (fingertip or stylus tip) can be displaced on a plane rigid interactive surface of the touchscreen overlay. The position and pressure of the object can be continuously monitored by using the input capabilities of the touch screen. Based on this information, an algorithm can compute the actuation pattern of the signal envelopes. To move an object into the desired direction, the resulting signal only needs to be applied to the assembly of actuators.

4 System and requirements analysis

Generating forces on a plane surface can be achieved by using the stick-slip effect. As it has been discussed by Kaye [9], the technology presented by Reznik and Canny [20] can be applicable to rigid interactive displays. This chapter gathers the major system requirements, required to prepare the implementation of a linkage-free stick-slip-based haptic interface. As a part of the requirements elicitation process, two different user scenarios are analyzed. Their main purpose is to demonstrate how tangential forces on an interactive surface can be used to optimize human input behavior by improving the kinesthetic experience. The last part of the chapter presents the research approach including the iterative mockup development.

4.1 User scenarios

User scenarios are an easy and common technical approach to high-level requirements specification in agile projects. The principal reason for their popularity is that they are easy to understand and to communicate. Based on the end user's point of view, they describe a functionality which the system must provide for them. In the next subsections, the main two user scenarios are defined. Each of them describes a basic system feature which utilizes the kinesthetic signals to improve the user's interaction behavior and performance [22].

4.1.1 Kinesthetic learning and handwriting skills

Humans are individuals and therefore each of them has their own way of learning new things. Barbe and Milone Jr. [23] believed that the general learning styles can be divided into four different groups: visual, auditory, kinesthetic and learners with mixed styles. According to their research, 30% of the population are learners relying on the visual sense, 30% on a mixed approach, 25% prefer auditory information and 15% learn mainly through movements (kines-thesia). However, as described by Saddik et al. [2], the two major senses used with interactive displays are sight and hearing. Thus, it can be concluded that a system which is intended for teaching can only provide an optimal learning environment for approximately 85% of the population (if the mixed approach does not include kinesthetic learners). Using a combination of interactive stylus, force feedback and accompanying kinesthetic signals, this problem could be overcome and therefore improve the teaching process of drawing, handwriting and even reading skills. The system would be able to intentionally move a pen while the user holds it, the guided movements would be sensible. In that way, the kinesthetic modality could facilitate the integration of already existing outputs: visual and auditory components of the learning environment.

4.1.2 Kinesthetic support of gestural interaction by limiting possible extra movements

The design of modern interactive displays compared to those devices commonly used a couple of years ago, has changed tremendously. Physical buttons have been replaced by on-screen buttons. The system keyboard console, mouse, video-as-input and CRT display have merged and turned into a universal multimodal computer interface – the touchscreen. The whole device has become one large screen which development has encouraged the integration of new interaction styles. The most common one which can be found in nearly all interactive displays are touchscreen gestures. However, Norman and Nielsen [24] believe that gesture interaction means taking two steps back. They discussed that the current implementation of gestural interfaces violates important design guidelines. The major violations are: visibility, feedback, consistency and standards, discoverability and reliability. In their research, two of those violations are considered the most problematic ones: visibility and feedback. Gestural interfaces are not easy to use because they operate on a hidden layer of interaction. A user needs to learn which gestures can be used within the given context. Whether a gesture can be used or not is often only visible by visual result or no result. This leads directly to the next problem: feedback presentation. It is very problematic when the only feedback signal given are visual cues. While performing a gesture, the user often does not get any feedback signal about the success or failure of their actions. Hence, the user does not know if the right gesture was completed and where the gesture starts and ends. The use of tangential forces, applied to the fingertip or stylus tip, allows it to support or even to amplify kinesthetic feedback on rigid interactive displays which would solve the two most problematic violations. As shown in Fig. 8, the haptic interface would be able to properly support gestural communication with a computer. For instance, a user could explore which gestures are possible by simply swiping over the screen. By feeling such kinesthetic support or opposed forces, the user would not only see the results of their actions but also feel them. Directional force feedback could either actively support or oppose the finger or stylus movement. In such way, the haptic space could signal to the user where a gesture starts and where it ends, adding the possibility to communicate the exact direction and length of a gesture.

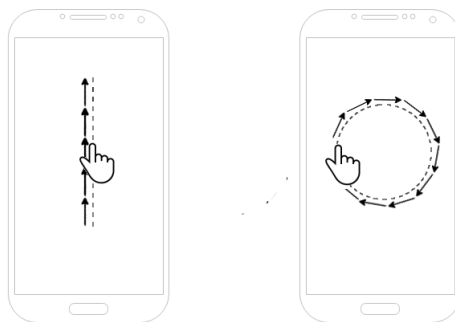


Figure 8: Gestural interaction, visual and force representation

4.2 Requirement analysis and elicitation

Requirements are agreements upon which services the system must provide in order to reach the expectations of the client. As defined by Sommerville and Sawyer: "Requirements are a specification of what should be implemented. They are descriptions of how the system should behave" [25]. Due to the fact that the system behavior and timing constraints are not known at this point, the requirements analysis will mainly focus on functional requirements. In general, it is important to define the requirements before the implementation phase of any project. Usually many stakeholders are included in the project design and everybody has its own view upon the system functionality. The common goal is established by specifying the properties, parameters and other features, and by agreeing to them. After the requirements have been collected, it is necessary to prioritize them in order to implement the most important ones first. For this thesis a simple three group prioritization has been chosen. Based on Wiegers [22], the following priorities have been used:

- High priority
- Medium priority
- Low priority

As already mentioned by Wiegers, a three-level prioritization approach is imprecise and subjective. Nonetheless, considering the relatively small amount of requirements and the uncertainty level of this research, a prioritization scale as suggested by Wiegers is suitable. To determine the priority group, all requirements are assessed, according to their urgency and importance. In the context of this thesis, urgent requirements describe a functionality which needs to be implemented as soon as possible in order to determine whether a certain technology can be used for the final system implementation or not. The importance of a requirement on the other hand, is assessed by how important the feature is for the core functionality of the final system. As a result, Table 1 presents a two by two (2x2) matrix which shows the priority assignment based on the previously defined urgency and importance level.

	Important	Not Important
Urgent	High Priority (H)	Do not implement these (X)
Not Urgent	Medium Priority (M)	Low Priority (L)

Table 1: Requirements Prioritization, adapted from [22, p.251]

4.2.1 Project vision statement

For users of mobile phones, tablets or tabletop devices who need to use them in noisy and distracting environments, kinesthetic feedback on interactive display surfaces can provide a much more exhaustive and informative mechanism to supervise the user’s behavior than primitive tactile feedback. It can significantly improve the multimodal interaction of the haptic space and increase the usability of computer systems in distracting environments or under constrained conditions. Unlike the currently used vibrotactile cueing [26], kinesthetic information can actively interact with the user. By optimizing the interaction style, strategy and cognitive resources needed to solve a personal task, the impact on the user behavior is much larger than standard technologies commonly used in modern devices.

4.2.2 Software requirements

ID	Description	Priority
S1	Detect and recognize an object on the screen including its exact position	H
S2	Recognize the surface inclination angle	H
S3	Provide USB communication with the hardware layer to change parameters of the object position and speed of movements	H
S4	Recognize the object movement parameters: displacement, direction and speed	M
S5	Get the pressure provided by the object on the screen	M
S6	Create a graphical user interface to allow the user to interact with the system	M
S7	Variate the stick-slip motion in order to compensate force variations generated by an input device	L
S8	Detect the input device and adapt the stick-slip motion accordingly	L

Table 2: Software Requirements

4.2.3 Hardware requirements

ID	Description	Priority
H1	The linear actuators have to be capable of generating a fast and sufficiently strong (3-10N) stroke in one direction and a slow movement into the opposite direction	H
H2	The hardware control unit needs to be capable of translating instructions from a USB port into a certain actuation pattern	H
H3	The linkage-free interface needs to be invisible for the user to avoid distraction and physical constraints	H
H4	The hardware control unit needs to be small enough to be used with mobile devices	M
H5	The power supply used by the system needs to be portable and capable of using batteries	X

Table 3: Hardware Requirements

4.3 Research approach

The research was conducted in an iterative manner. For that reason the "Prototyping" methodology was chosen as a research approach. The implementation of a linkage-free force-feedback kinesthetic device by using the stick-slip effect has been discussed but not yet performed. Therefore, it was unclear which non-functional properties, such as actuation frequency and minimum displacements, needed to be applied to the fingertip or stylus. By using the prototyping approach as described by Hughes and Cotterell [27], it allowed to speed up the development process and to cope with an informal requirements specification. After each prototype or iteration cycle, the requirements have been refined and updated which led towards a fair and completely specified system.

5 Applying the Stick-Slip effect to interactive displays

After the basic functionality of the system was specified, the possible technological solutions were approved and the system requirements were defined, this chapter discusses the crucial mechanics and physics of the system design. In particular, different technologies for generating stick-slip movements and specific material properties that influence the friction are discussed. To control a tangible object (user's finger or stylus) through the stick-slip phenomenon, a certain actuation pattern has to be applied to a specific configuration of actuators. Therefore, three suitable linear actuators are presented including their benefits and drawbacks. Given that, actuating the entire touchscreen is exceedingly power-consuming and impractical, a display overlay (similar to a protective screen film) is presented and its surface properties are defined. The last part of this chapter discusses the interaction device properties and its influence on the stick-slip motion.

5.1 Limiting factors of the direct input: the stylus-based interaction

As of now, there has only been a discussion about how the stick-slip effect can be used to deliver linkage-free directional forces and kinesthetic information. To prove this hypothesis, it is necessary that the results are unambiguously reproducible. The most common input technology used by modern devices is direct touch via the fingertip. The problem is that mechanical, physical and physiological properties of the human skin such as elasticity, viscosity, mechanical impedance (stiffness), friction, temperature, moisture and sensitivity vary from person to person. Besides common factors such as age, gender and vocation, the skin is also subjected to external conditions which may affect its properties [28, 29]. In order to create a stable development environment and limit the amount of influence factors, this thesis only focuses on stylus-based interaction. Stylus-based interaction comes very close to common touch input because it allows direct screen interaction. Furthermore, this technology provides the following three advantages: First of all, stylus-based interaction provides very precise information about position, pressure, direction of motion, slope (virtual gradient of friction and texture) and other features of the interactive surface. The second major feature of stylus-based interaction is that the stylus tip can have various configurations (Fig. 9) of different materials, providing a highly stable mechanical contact area regarding, friction, elasticity and surrounding conditions. Lastly, stylus-based interaction is more ergonomic in comparison with any other input technique since it provides a natural and intuitive hand and wrist position. Thus, stylus based interaction can prevent injuries of the hand or wrist such as the carpal tunnel syndrome.

In conclusion, it can be said that the stick-slip phenomenon significantly depends on the friction between the surface of interaction and the object of manipulation. Touch input appends a large amount of additional variables to the system under development. Stylus-based interaction, on the other hand, is temperature-independent and provides fully controllable and reproducible input parameters.



Figure 9: Stylus tip configurations, adapted from [30]

5.2 Linear actuators and their specifications

To generate a stick-slip motion, a quick linear actuation is required which needs to move the surface of interaction (touchscreen overlay) fast in one direction and slow into the opposite one. The decision regarding what type of actuator should be used during this thesis was based on the following requirements:

Size and weight: The actuator in combination with its control unit need to be small and light enough to be integrated into a mobile device such as a smart phone or tablet PC. The weight of the additional setup should not exceed the weight of the mobile device itself. The entire setup needs to be small enough to be easily portable.

Load force: The load force needs to be sufficiently high to be able to move the touchscreen overlay with the desired speed. The minimum force can be accessed by the average force which is used by a person while performing a pointing task on a touchscreen surface. Based on Akamatsu and MacKenzie [31], this force can be estimated to be slightly higher than 3N.

Stroke length: The stroke needs to be long enough to generate a displacement which is noticeable. At the same time it needs to be small enough to provide a smooth displacement, to avoid vibrations that could distract the user. The minimum and maximum values for the stroke length are very difficult to estimate because they depend on the maximum acceleration, which can be produced without generating the slipping movement. Therefore a maximum stroke length of 5-10 mm was defined as suitable. However, no estimation was made for the minimum stroke length.

Power consumption: The power consumption of the system should be minimum. Given the fact that the system under development is mainly developed for demonstration purposes, the power consumption can be neglected as long as it can be covered by a standard laptop 60W power supply (19V, 3.5A).

Response time and stiffness: The response time of the system is crucial because the stick-slip movement has strict timing constraints (sawtooth shape). Therefore, the system reaction time to input signals needs to be minimal. At the same time the actuator stiffness needs to be

high. Additional vibrations, created while changing the direction of movement, can limit the stick-slip effect.

Based on the requirements specified previously, three suitable types of actuators were identified during this study. The next subsections provide a basic characterization of these actuators which were found and explain the reasoning behind their selection.

5.2.1 Piezoelectric actuator

The piezoelectric effect describes the ability of certain materials to generate an electrical charge while they are compressed (mechanical stress). This effect also works inversely. By applying a certain voltage, piezoelectric materials extend in the direction of the electrical field. An average extension rate is about 0.1%, which is considerably low. To overcome this limitation, piezoelectric elements are stacked in multilayer blocks and series of blocks which provide a higher overall length, force and extension (Fig. 10).

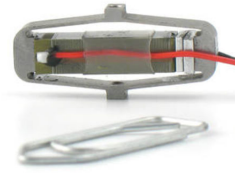


Figure 10: Piezo actuator composed of two blocks, adapted from [32]

The main benefit of piezoelectric actuators is their construction. No additional movable parts are required which makes them highly robust. In addition to that, piezoelectric actuators support high frequencies up to multiple kHz and they are significantly small, powerful, precise and lightweight. The principal drawback of piezoelectric actuators is that their extension is directly proportional to the applied voltage. The voltage ranges are varying between 100V for standard linear actuators up to 1000V for high force piezoelectric actuators. Moreover, the actuation provided is rather small (Table 4).

Type	Size (L x W x H in mm)	Weight (in g)	Stroke Size (in μm)	Load Force (in N)	Frequency (in kHz)
APA50XS	12.80 x 9 x 4.7	2	70	18	12.4
APA 120S	28.70 x 9 x 13	7.2	130	44.4	7.463
APA 600M	48.50 x 12 x 14.6	14.2	618	26.3	1.436

Table 4: CEDRAT Technology, piezoelectric actuator properties

5.2.2 Electromagnetic actuator

Electromagnetic actuators such as the solenoid type consist of a current driven (electrical) coil which is wound around a ferromagnetic core, the so called plunger. By providing electrical energy, the generated magnetic field either attracts or repels a plunger which leads to the actuation.



Figure 11: Electromagnetic actuators

The major benefits of electromagnetic actuators are their large translation movements and force which is proportional to the current (in amperes) and to the number of turns of the coil. In addition to that, many linear electromagnetic actuators are cheap and commonly available. One of the best examples are solenoids which are widely used in commercial applications such as electronic door locks. Other suitable electromagnetic actuator types are voice coil linear motors or linear servo motors. The main disadvantages of electromagnetic actuators are their high power consumption and large size. Especially high power electromagnetic actuators are extremely large and heavy.

Type	Size (L x W x H in mm)	Weight (in g)	Stroke Size (in mm)	Load Force (in N)
Solenoid Pull-Type	20 x 17 x 14	23	10	10
Voice Coil Linear Motor	41.9 x 20.6 x 20.6	86	15.2	3.8
Linear Servo Motor	205 x 30 x 30	400	100	8.8

Table 5: Representative electromagnetic actuator properties

5.2.3 Magnetostrictive actuator

Just as electromagnetic actuators, magnetostrictive ones use a current-driven coil which is wound around a rod. The rod is made out of a specific magnetostrictive material which expands when an external magnetic field is applied. The main difference to electromagnetic actuators is that the rod does not move itself. It only expands under the influence of a strong magnetic field [33]. One benefit of magnetostrictive actuators over piezoelectric actuators is that their extension is slightly better. Under standard conditions, the magnetostrictive material expands

from 0.1 up to 0.6% of their own length. Magnetostrictive actuators have a high resolution and their maximum operating frequency lays around 30kHz. Additionally, the force which can be generated is rather high. When using specific magnetostrictive materials such as Galfenol, an even higher expansion can be achieved (up to 6% under 2.5 Tesla). The limitation of this specific material is that it is not able to hold the required force. The main drawback of magnetostrictive actuators is that the rod needs to be produced from rare-earth materials such as Terbium (Terfenol-D) or Gallium (Galfenol) to generate a reasonable extension (stroke). Hence, the result is that magnetostrictive actuators are rather expensive (about 800 Euro per actuator). Other ferromagnetic materials also display such properties, however their actuation is not nearly as noticeable. Moreover, they require a complex control circuitry to regulate the strong magnetic field (tens of Tesla) and a specific configuration of the magnetic flux to achieve the required extension.

5.3 Surface properties / features

To generate a stick-slip motion it is not only required to provide a suitable actuation pattern. Also the specific properties of the movable overlay, which slides over the display surface, need to be taken into consideration. Therefore, the following three different properties are discussed: the overlay weight, the stiffness and the structure of the contact surface.

Overlay weight: The overlay weight has a large effect on the inertia of the system. It increases the overall forces which need to be generated by the actuators. When the friction is ignored, the force required to accelerate a certain mass is given by the equation $F = m * a$. That means that the overlay weight is directly proportional to the force required to generate a motion or to work against it. Thus, the screen overlay needs to be as lightweight as possible.

Overlay stiffness: When generating the stick-slip movement, the overlay is actuated in a specific way. This actuation can be seen as a periodic horizontal movement. If there are inaccuracies while building the mechanical parts, vertical vibrations may be introduced into the system. These additional vertical movements cause problems because they deform the overlay and reduce the friction between the objects interacting with it [34]. When actuating the overlay horizontally, different friction coefficients can be measured among the surface which makes it nearly impossible to generate a controllable directional movement. To overcome this problem the overlay material should be as stiff as possible to resist more to external deformation [35].

Surface structure: The surface structure affects the system regarding the coefficient of friction. The force which is required to overcome the friction force depends on the friction coefficient between the overlay surface and object surface. To simplify the model, an object with a mass m should be moved over a surface. The force which is required to move the object can be

calculated by $F = g * m * \mu$, where μ is the coefficient of friction. It can be seen that μ is directly proportional to the force required to make an object stick or slip, with respect to the contact surface. This is important to take into consideration when calculating the stick-slip frequencies. The maximum force which can be applied during the sticking phase also depends on the coefficient of friction. If the surface is very smooth and the frequency is too high, the object will start slipping in both directions and no directional tangential force is generated. On the other hand, if the coefficient of friction is too high, the tangential force which is applied might not be strong enough to overcome the friction. In that case, the object on top would stick to the surface in both phases of the applied signal.

5.4 Interaction device properties

When applying the stick-slip effect to interactive displays, the input device also needs to be designed in an appropriate manner. There are two major concerns which need to be taken into account. First of all, the interaction device tip (pen or fingertip) which is in contact with the overlay surface needs to have a certain coefficient of friction. A material which is too slippery would cause the interaction device to slip on the screen overlay during the stick and the slip phase of the signal. On the other hand, a coefficient of friction which is too high would cause the interaction device to always stick to the overlay surface. The second problem is that the user does not always apply a constant force while interacting with the screen. As it has been shown by Akamatsu and MacKenzie [31], the force applied to the overlay surface varies while performing a manipulation task. How the variation of applied force affects the stick-slip effect is shown by using the friction force. By replacing the gravity force F_g which would be applied by a static object to the overlay screen with the pressure applied by the user, it can be seen that the pressure is directly proportional to the force.

$$F_{fric} = m * g * \mu = F_g * \mu$$

$$p = \frac{F}{A} \Rightarrow F_{pressure} = p * A$$

$$F_{fric} = p * A * \mu$$

As the equations above show, the system needs to take the user's pressure into account when generating the stick-slip movement. Depending on the pressure changes, the system has to adapt accordingly by increasing or decreasing the stick-slip frequency.

6 Project cycles and evaluation of their deliverables

As a result of the technical analysis, the following chapter describes the construction of three different prototypes. It discusses the main actuator technologies and mechanical parts required to generate the stick-slip movement. The chapter is divided into three major parts, each of them describes a project iteration. It provides an overview about the prototype evolution and the changes in technology which leads to the definition of the final system implementation.

6.1 Amplified piezoelectric actuator: mockup 1

Considering the analysis done in the previous chapter, it was concluded that piezoelectric actuators fulfill the specified requirements the best. They are lightweight, small, powerful and their power consumption can be covered by a standard 60W laptop power supply (19V, 3.5A). The only disadvantage of piezo actuators is their rather small stroke length. Based on the fact that no reference values were available during this stage of the project, the stroke length was considered to be sufficient.

6.1.1 Mechanical coupling and energy transmission

As can be seen in Fig. 12, the base of the prototype was constructed from a plexiglas sheet. As an actuator, the APA120S developed by CEDRAT technologies was used [32]. The piezoelectric actuator was affixed with a screw glued into one side of the base. On the other side, the actuator was connected to the screen overlay by a very stiff, L-shaped piece of aluminum. In that way, the actuation should be transmitted to the screen overlay and it should be actuated in relation to the base. The required actuation pattern was generated by a computer program which created a sawtooth-shaped signal at the line-out port. The output magnitude was amplified with a peak-to-peak value of 40V. In order to identify the most suitable frequency (resonance frequency of the entire mechanical system), the program increased the signal period over time by using fixed frequency steps. The results of the changes were recorded by a MicroSense displacement sensor (model 5810, 5622-LR probe, 20 kHz [36]).

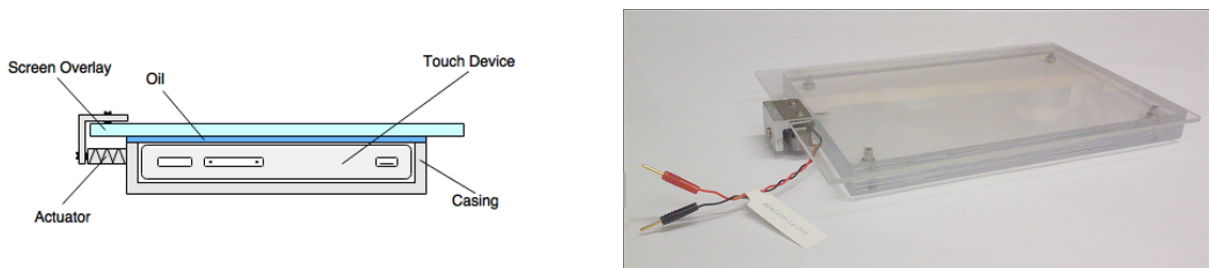


Figure 12: Mockup with affixed piezoelectric actuator

6.1.2 Results

After experimenting with the amplified piezoelectric actuator (APA120S), it can be said that the setup does not provide the intended stick-slip effect. Although it was possible to move a test object with a weight of 100g over the screen overlay, the movements were not stable. Hence the object moved differently depending on its position. As can be seen in Fig. 13, if the object was positioned on the first third of the screen overlay (I), it moved away from the actuator towards the direction of the dotted line. If it was located on the other side (II), the object moved into the opposite direction, towards the dotted line. It was concluded that, due to the actuator construction and the attachment to the screen overlay, vertical vibrations were injected into the system. This behavior indicates that no actual stick-slip effect was generated. It was assumed that parasitic vertical movements are responsible for moving the object instead of the stick-slip effect. The vibrations are injected based on the actuator construction and the screen overlay attachment. This effect reduces or even eliminates the friction between the object and the overlay surface [34] and leads to movements even in the absence of the stick-slip effect. Another evidence of this argument is that the object only moved at very specific frequencies which can be assumed to be the resonance frequency and its harmonics. Always when such a frequency occurred the acoustic noise increased rapidly. In that mode, the prototype produced larger vertical movements and acted like a speaker diaphragm. In addition, the dead spot which was observed on the prototype may be explained by assuming that the vertical vibrations deform the screen overlay in a sinusoidal way. Each time a resonance frequency occurred, a standing wave was created which had its peak value at the dotted line. A sinusoidal deformation would also explain why the object speed decreased, as it approximated the dotted line.



Figure 13: Sliding friction in the presence of vertical parasitic oscillations

In pursuance of minimizing the vertical vibrations, the screen overlay fixation configuration was changed. The force generated by the actuator was directly applied to the screen overlay. Nevertheless the change did not show the expected results as the new mockup configuration demonstrated the same behavior as before. It was assumed that the design of the actuator was not optimal for the task because it was implemented as a spring. This specific design is presumably not stiff enough and can cause vertical vibrations.

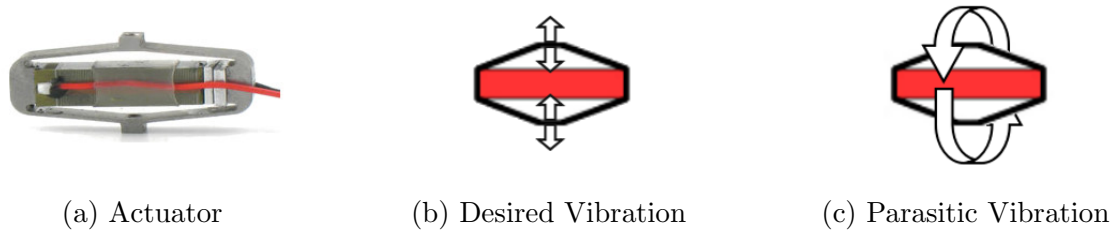


Figure 14: APA120S Piezoelectric actuator and its degree of possible actuation

The last problem which was revealed during the pilot experiments was that the displacements of the object regarding the overlay might be exceedingly low. The APA120S actuator can only produce a maximum displacement of $130 \mu\text{m}$ without load. After the screen overlay was attached to it, no measurable displacement was detected. Nevertheless, the blocking force of the APA120S is 44.4N which should be high enough to create a measurable displacement of the screen overlay.

6.1.3 Discussion

A piezo actuator seemed very promising, however the prototype showed its limitations. The main benefits are the compact format and the easy actuation-to-voltage control. The major drawback is the small stroke size of current stacked piezo actuators. A maximum displacement of $130 \mu\text{m}$ at about 140V can be assumed to be too low. Moreover the spring-like design of the actuator introduces too many vertical vibrations because of the limited stiffness of the frame. To sum up it can be said that available piezo actuators may not be ideal for this application at the moment. A design is required which provides a higher stroke length and reduces the vertical vibrations to a minimum.

6.2 Amplified piezoelectric actuator: mockup 2

The data gathered in the previous subsection indicates that a higher stroke magnitude and reduced component of vertical vibrations may produce better results. All these attributes can be provided by a linear piezoelectric transducer. As described by CEDRAT Technologies [37], this configuration of actuators is able to provide longer strokes, a medium amount of control and a higher stiffness.

6.2.1 Mechanical coupling and energy transmission

The prototype of the linear piezoelectric transducer was adapted from a design described by Chen et al. [38]. The casing was crafted from plexiglas. A stiff iron shaft was used which was coupled with the piezoelectric actuator on one side and an inertial mass which was affixed to the opposite side. To connect shaft and base, high pressure was required. It was impossible to move the shaft while the motor was not running which ensured high stiffness. To provide the transmission of ultrasonic waves along the shaft, a special interface material was required

between casing and shaft. It contained one layer of rubber-like elastic material to distribute the pressure evenly and one more layer of very slippery elastic material to allow the shaft displacements with variable frictional force.

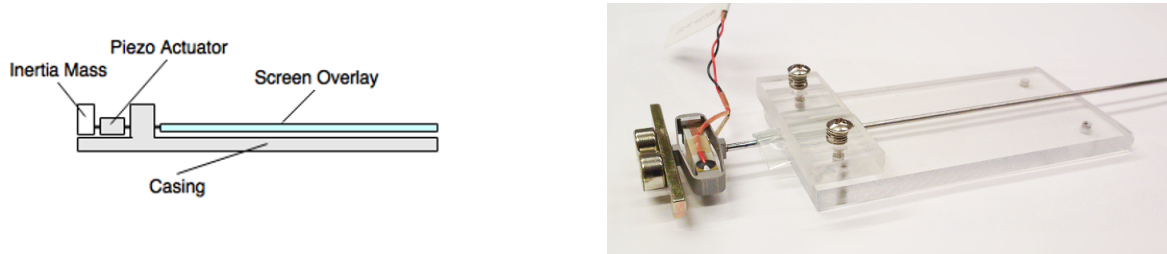


Figure 15: Linear piezoelectric transducer, mockup 2

6.2.2 Results

In general, the linear piezoelectric transducer worked as intended [38]. As a result of changing the direction and frequency of the sawtooth waves applied to the actuator, the direction and speed changed accordingly. As described in the piezoelectric motor specification developed by CEDRAT Technologies [37], long strokes of magnitude of several millimeters were possible to achieve. However, the developed prototype was not able to produce the long strokes with sufficient speed to generate a stick-slip movement.

6.2.3 Discussion

Unfortunately it was not possible to assemble a piezo electric motor as described by CEDRAT Technologies [37]. The stroke length and speed were too low to produce a stick-slip effect in an efficient manner. This limitation was due to the basic design of the prototype. In spite of the limitation, it has been shown that it is possible to generate the required strokes within an appropriate time [37]. It was concluded, that linear piezoelectric transducers may be highly promising in general, however, their application in this thesis was not ideal.

6.3 Electromagnetic actuator: mockup 3

In spite of all the benefits piezoelectric actuators provide, it was not possible to replicate the stick-slip phenomenon within the given setup. For that reason, it was decided to change the type of actuator to an electromagnetic one, more specifically to a pull-type solenoid. This kind of linear actuator is commonly used in various applications such as consumer electronics or door locks and they provide a considerably greater magnitude of strokes which can range from a few millimeters up to about one centimeter. It needs to be taken into account that the length of strokes, applied to the screen overlay, defines the resolution of the final prototype. Therefore, it is essential to choose a solenoid which has just about the right stroke length.

6.3.1 Mechanical coupling and energy transmission

For the electromagnetic pull-type solenoid mockup, the same plexiglas base was used in order to compare it to the piezoelectric actuator. One major difference was that the solenoid was fixed on top of the screen overlay and the plunger was connected to the casing (base). When the solenoid was activated, its plunger retracted by pulling the overlay towards the plunger fixation point. While the solenoid was pulled in, it also worked against a spring. After stopping the actuator, an opposite force was generated from the potential energy stored in the compressed spring. To generate the stick-slip effect, the pulling phase needed to be considerably faster compared to the pushing phase (the release of the potential energy by the compressed spring). In order to obtain the slow pushing action, a specific elastic, spring-like material was used to provide the appropriate sticking speed.

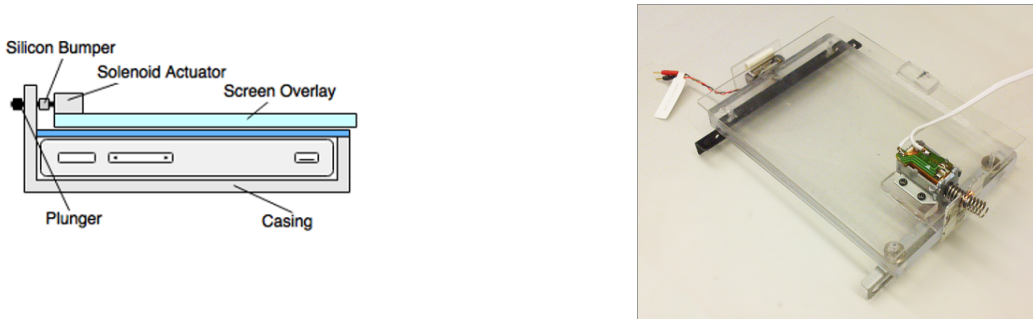


Figure 16: Electromagnetic actuator mechanical coupling, mockup 3

6.3.2 Results

The experiments performed with the electromagnetic actuator were substantially successful. As a result, it was possible to generate a stick-slip motion by applying sawtooth waves with a frequency of about 32 Hz. In addition, the displacement of objects placed on the screen overlay was stable without showing dead spots, as it has been observed in the experiments with the piezoelectric actuator. The force applied by the system was capable of moving an object having a mass of 300g. On top of that it was even possible to make a smaller object of 45g move upwards on an inclined surface having a slope of 20 degrees. This example proves that the movement was not a result of vertical vibrations since such vibrations would have caused the object to slide down instead of moving upwards. This movement shows that the static friction between overlay and object was not decreased.

6.3.3 Discussion

Using the electromagnetic pull-type solenoid, the prototype fulfilled the requirements of generating a stick-slip motion. It was capable of creating continuous directional forces on a plane rigid surface. Compared to the other examined solutions, one drawback was the size of solenoids. These actuators could not be hidden on the side of the casing, as it was possible with the piezo-

electric transducers. Another drawback was the unidirectional (push or pull) type of solenoids design. Such a configuration required the use of a spring or an elastic silicon bumper to generate the push-back motion. If the elastic material pushed back too fast, the object might slip in both directions. If it pushed back is too slow, the stick-slip period may become too long, making the whole system configuration less efficient. An alternative would be to use powerful and miniature bi-directional solenoids (push-pull type). The problem of using those type of actuators is that they are considerably more expensive and it is significantly harder to control them.

6.4 Conclusion

After testing and analyzing all three mockups, it was concluded that the electromagnetic actuator would be appropriate for implementing the final prototype. Despite its drawbacks, such as size and power consumption, it was the only a suitable type of actuator which was able to provide enough strong magnitude (length and force)to generate a stable stick-slip motion.

7 Final system implementation

After investigating different types of actuators, it was concluded that an electromagnetic actuator provides the best way to generate stick-slip motion. This chapter discusses the implementation of the final prototype based on electromagnetic pull-type solenoids. It describes the system as a whole including the mechanical model (Fig. 17 and Fig. B1, in Appendix B), hardware controller (Fig. B4, in Appendix B) and the software algorithm (Fig. A1-A3, in Appendix A) used to control the directional forces and kinesthetic signals. Finally, an application for handwriting learning under continuous supervision is presented (Fig. B3, in Appendix B).

7.1 Delivering kinesthetic signals: a system overview

The system for delivering kinesthetic signals was designed as an overlay for the MS Surface Pro 3 tablet (Fig. 17). Four pull-type solenoid actuators were affixed to the plexiglas plate to create a fully-controllable haptic space augmented via linkage-free, stylus-based interaction over the touchscreen. The solenoid actuators were attached to the screen overlay at the center of each side. By using U-shaped aluminum brackets, the solenoid plungers were affixed to the casing (base). To generate the pushback motion, each plunger was equipped with a silicone rubber bumper.

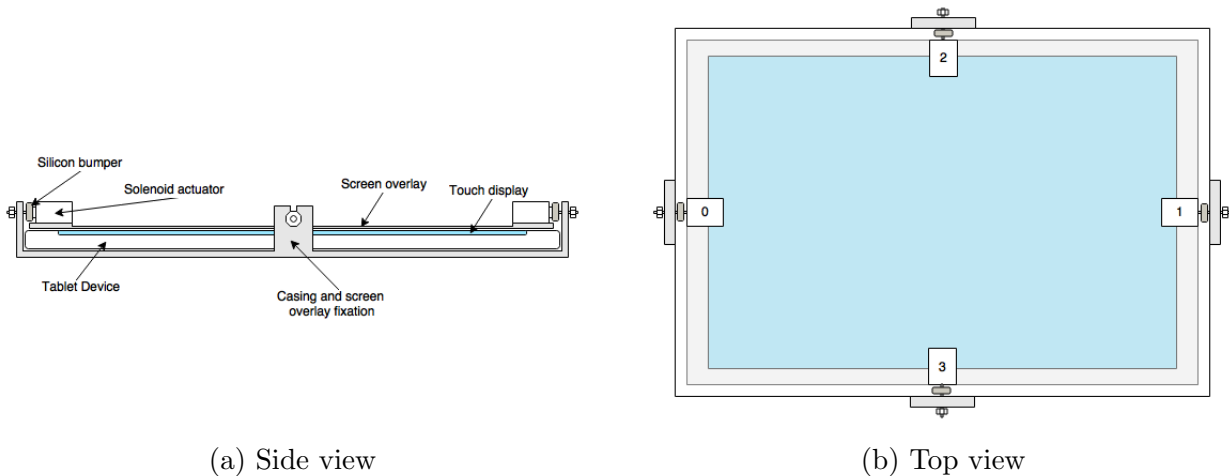


Figure 17: Kinesthetic handwriting learning system, implemented as the overlay of the MS Surface Pro 3 tablet.

To control the kinesthetic signals, a software architecture was designed (Fig. A1, in Appendix A) which contains three main parts: UI thread, hardware thread and the FTDI microcontroller, as explained below.

UI Thread: The UI thread (Fig. A2, in Appendix A) was designed to retrieve the user’s input data from the interactive device. While the user interacts with the touchscreen, the system records the point of interaction (X-Y touch coordinates) and the applied pressure. In addition to this, the system is able to differentiate between various kinds of input devices, such as stylus

or fingertip. Besides the user input, the UI thread analyzes the graphically-presented tasks or instructions based on the image shown on the screen. By interpreting the slope and gradient of the presented image, target coordinates are automatically calculated [12, 39]. As a result, the UI thread is able to calculate a list of actuators required to deliver a three-dimensional object sensation based on kinesthetic signals. This actuator list may vary depending on the type of application and the desired force feedback. To transform the actuator list into a real force sensation, the UI thread passes the list to the hardware thread.

Hardware Thread: The hardware thread (Fig. A3, in Appendix A) was designed to translate the information coming from the UI thread into a format which can be processed by the FTDI microcontroller. The hardware thread receives the list of actuators provided by the UI thread and transforms it into a stick-slip actuation pattern. Therefore, a certain bit is assigned to each actuator (Fig. 17, b). If this bit is set to 0, the corresponding actuator is deactivated. Contrary, if it is set to 1, the actuator is activated. Finally, generated bit configurations are packaged into one byte and sent to the FTDI microcontroller. Electromagnetic solenoids have a specified duty cycle for nominal strokes under normal conditions that limits the amount of force which can be applied to the object on the screen. In order to optimize the control parameters, an extra mode was added to the setup. Specifically, an extra bit (bit 7) was introduced which bypasses the power limitation. If set to 1, the solenoid operates in such a way, that its defined continuous voltage is exceeded by 30%. This mode is set only for a very short time, at the beginning of each period of the solenoids activation. As a result, the force provided, especially at the beginning of the stick-slip phase, is increased significantly.

FTDI microcontroller: The FTDI microcontroller was designed as an interface between the MS Surface Pro 3 tablet and the solenoid controller, built in concrete hardware. The main functionality of the microcontroller is to convert data, which is sent via USB, into a parallel bit pattern to switch the solenoid actuators "On" or "Off". The FTDI uses standard Windows serial port commands to communicate with the tablet. Therefore, the microcontroller has to be configured as a virtual serial port. In order to provide the parallel output necessary to set the actuators simultaneously, the FTDI has to be configured to use the "Bit mode", which bypasses the internal FIFO queue and allows instant serial to parallel conversion.

7.2 Software Specification

The final system setup contains the three main software components which have been mentioned briefly in the previous subsection. In order to fully understand how the kinesthetic signals can be controlled, it is important to describe the system components in more detail. Therefore, the following subsections discuss all three parts and how they interact with each other.

7.2.1 UI Thread

The UI thread contains the user interface implementation. The main goal of this component is to get user-related input and to send it to the hardware thread. C# was chosen as a programming language because it provides both: an easy user interface implementation and direct hardware access with the use of standard Windows libraries. Moreover, C# provides an event-driven approach which allows to collect input data from the user's as they interact with the device. Each time the user touches the display or moves a pointing device over the touchscreen, a new touch event is detected. Using those events, the current stylus (fingertip) position, the pointer pressure and the event type can be extracted. The event type contains the information necessary to recognize and analyze the pointing device and action. The identification of the pointing device can be very important because interacting via fingertip is different from using a stylus, in terms of friction coefficient and material consistency towards the touchscreen overlay. By separating different interaction devices, the forces can be adapted according to each situation. In addition, the event type can be used to indicate whether the user interaction continues or if it is altered i.e. re-directed or stopped. To calculate which actuator has to be activated, the algorithm subtracts the current user touch vector (\vec{C}) from the destination (\vec{D}). Using the result vector (\vec{R}), the object quadrant can be determined (Fig. 18). According to the resultant vector, a list of actuators is calculated which has to be activated to move the object towards the (nearest) destination.

$$\begin{bmatrix} D_x \\ D_y \end{bmatrix} - \begin{bmatrix} C_x \\ C_y \end{bmatrix} = \begin{bmatrix} R_x \\ R_y \end{bmatrix}$$

$$R_x > 0 \Rightarrow \textit{RightActuator}$$

$$R_x \leq 0 \Rightarrow \textit{LeftActuator}$$

$$R_y > 0 \Rightarrow \textit{BottomActuator}$$

$$R_y \leq 0 \Rightarrow \textit{TopActuator}$$

After the actuator list was specified, the algorithm calculates the azimuth angle (α) between the current position and the nearest point of destination, in relation to the main horizontal axis (border). The demonstration prototype currently has a resolution of about 2 mm displacement of the stylus tip at a normal force of about 150 g. This is due to the limited tools which were available for producing the mechanical parts, especially the U-shaped brackets which connect the actuators with the base. Due to the limited resolution achieved, the prototype tends to produce discrete corrections of the supervised trajectory (generating pixelated images, Fig. B2, in Appendix B). Though, to reduce this discreteness, the application is able to activate two actuators simultaneously or sequentially. The decision of activating one or two actuators is based on the Pythagorean Theorem. If the azimuth angle lies between 25 and 75 degrees both actuators can be activated. In that case a corrective directional force is generated diagonally. If the azimuth angle is less than 25 or higher than 75 degrees, only one actuator creates a

force-moment to correct the stylus trajectory.

$$\alpha = \sin\left(\frac{a}{c}\right) * \frac{180}{\pi}$$

$\alpha < 25^\circ \Rightarrow$ Left / Right Actuator

$\alpha > 75^\circ \Rightarrow$ Top / Bottom Actuator

$25^\circ \leq \alpha \leq 75^\circ \Rightarrow$ Both Actuators

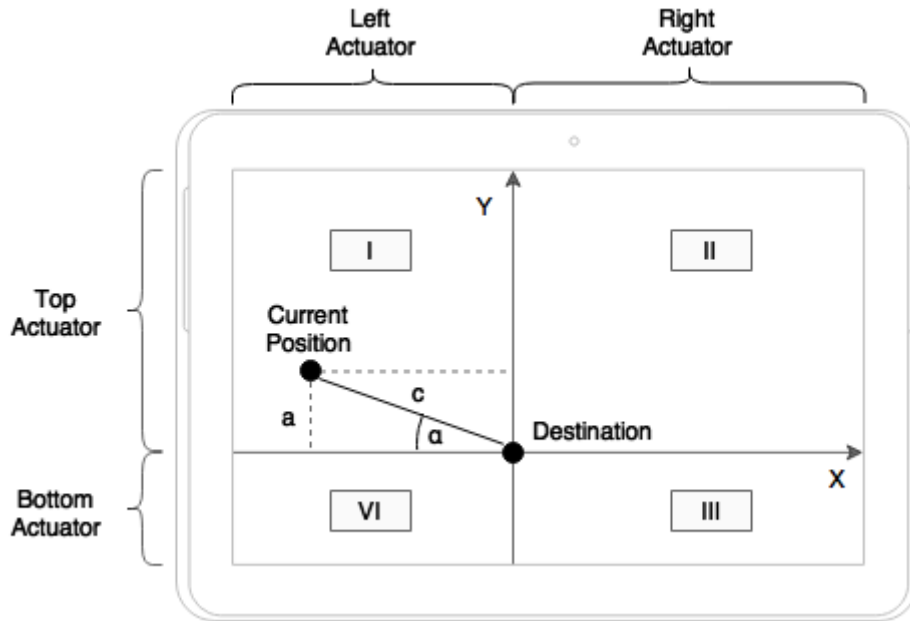


Figure 18: Kinesthetic learning system, path calculation

7.2.2 Hardware Thread

The hardware thread (Fig. A3, in Appendix A) translates the list of actuators calculated by the UI thread into a bit pattern which is sent via USB to the FTDI controller. When the UI thread sends a new actuator list, the list is transformed into a bit mask. Based on the default screen orientation, one specific bit is assigned to each actuator (Fig. 17, b). The assignment was done in the following order:

- Bit 0 - Activates the left actuator
- Bit 1 - Activates the right actuator
- Bit 2 - Activates the top actuator
- Bit 3 - Activates the bottom actuator

In mobile devices and tabletops, top, bottom, left and right sides of the screen are relative. The orientation may change by rotating the device. In order to take this into account, when the algorithm detects a change in orientation, it adapts the bit assignment accordingly. The system position sensor provides an *OrientationChanged* event which notifies the program application when the orientation changes. After the actuators configuration has been correctly transformed, the bit mask is stored in a static variable to allow access from the UI and hardware thread. To ensure a thread-safe environment, the static variable is copied into a new thread-local variable. As already mentioned in subsection 7.1, the system provides a solution to bypass the power limitation. In the first step of the stick-slip actuation cycle, the power limitation is bypassed for 3 ms. This is achieved by setting the bit 7 using the "OR" bit operation. The resulting bit mask is then sent to the FTDI controller. In order avoid damage on the solenoid actuators the power limitation bypass is deactivated after 3 ms. In the second step, the solenoids are operated with a power limitation for additional 8 ms which is done by using the XOR bit operation with the previously calculated bit mask. The result is again sent to the FTDI controller. In the last step, the actuation is stopped for 20 milliseconds by sending a zero bit mask to the FTDI controller. Thus, the solenoid duty cycle was organized as follows:

1. Create a bit mask from actuator list
2. Actuate with power limitation bypass for 3 ms (bit mask OR 0x80)
3. Actuate with power limitation for 8 ms (bit mask XOR 0x80)
4. Stop actuation for 20 ms (0x0)

The timing is extremely crucial. The system has to react in milliseconds and it needs to be as accurate as possible to generate the stick-slip motion. As described by Golomshtok [40], the standard .NET (C#) thread timing is inaccurate. It is highly dependent on the device type and especially mobile devices are not accurate enough. As experiments with the MS Surface Pro 3 tablet have shown, the thread timing error has been recorded to be 8 ms (for timings less than 15 ms). Therefore a specific thread time-handling was designed which is explained further in subsection 7.4.4.

7.2.3 FTDI microcontroller

To establish the communication between the mobile device and the actuators, the UM245R FTDI - parallel bit interface was used [41]. Such a solution provides the possibility to communicate serial data via USB connection and to deliver parallel output to the hardware. To enable the communication, the FTDI uses a virtual COM port. To get access to the FTDI commands from the hardware thread, an external DLL was used (FTD2XX.NET.dll, [42]). After the device was correctly installed, it can be detected by looking for open ports. When the correct COM port has been detected, the so called *Bit Mode* needs to be activated. This communication interface allows asynchronous data transfer between the FTDI and the solenoid actuators.

7.3 Solenoid controller

The solenoid controller is directly controlled by the bits set through the FTDI controller, as can be seen in Fig. 19. To operate the solenoid actuators, a 12V power supply is used. To prevent the microcontroller from getting destroyed by high voltage, the FTDI is physically encapsulated from the solenoid controller by using optocouplers (Fig. B4, in Appendix B). The solenoid behavior is controlled by setting the bits to a certain logic level. First, setting the bits 0-3 to a high logic level, the corresponding actuators are turned on. That means that the solenoid, being energized, is pulling the plunger (a steel core) which pulls the screen overlay in the direction of the actuator. Second, setting a bit to a low logic level, the solenoid gets deactivated and the pulling motion is stopped. In default mode, all actuators are running with a power limitation which means that the original DC voltage is reduced down to 8V (1.4A). Finally, setting the bit 7 to a high logic level, the current limitation can be bypassed. That means that the voltage is increased rapidly from 8V to 12V which leads to an increase in the DC current from 1.4A up to 3A. The additional 4V provide a large power boost but it also causes the solenoids to exceed their power dissipation limitations. Thus, the enhanced mode can only be active for a short amount of time (approximately 10% of the duty cycle).

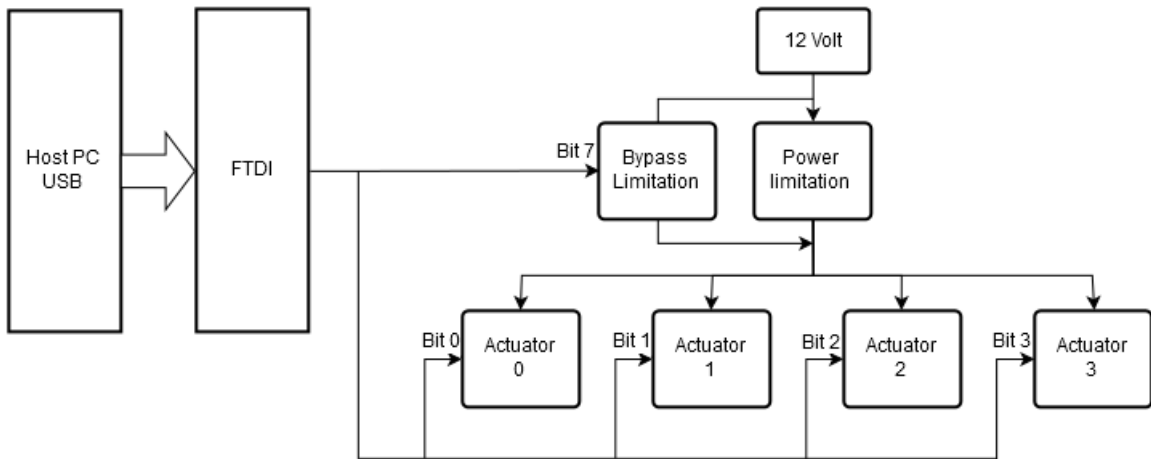


Figure 19: Solenoid controller, block diagram

7.4 Implementing a handwriting support using kinesthetic signals

Handwriting presents a good example where supervised learning can be implemented using kinesthetic signals and force feedback. A standard system implementation would combine the visual representation of a letter or word with spoken instructions. However, observing the way how humans learn to write, shows that this approach is not enough. At the beginning, the process of writing is very slow and exhausting because it requires significant mental effort. In addition, coordinating the arm and hand muscles, in order to draw a recognizable letter, is a very complex process. Only through repetitions, the process becomes easier and more natural. This shift from a process which requires some mental effort towards a nearly automated one can only be achieved by repeating the movement and by "memorizing" the kinesthetic signals.

The main idea of the handwriting system is to support the user's stylus movements in order to speed up the learning process. Therefore, simple shapes, letters or complete words are shown on the screen which need to be redrawn by the user. In order to support the user's movements, the stylus is moved over the display surface by generating directional forces. The so generated kinesthetic signals help the user to speed up the development of a muscle memory and to automate the writing process. As the user becomes more advanced, the system decreases the force generated, allowing the user to gain more control over the movement.

7.4.1 Getting the user input coordinates

In order to calculate the force which has to be applied to the user's input device, three event handlers are registered: StylusUp, StylusDown and StylusMove (Listing 1). All three deliver the current position on the screen (X and Y pixel coordinates) and the pressure used by the user. These events provide the possibility to determine which actuators need to be activated by comparing the user action and the current position with a defined destination point. On the StylusDown and StylusMove events, the directional force feedback is started. On the StylusUp event, the user removes the stylus from the display and the directional force-feedback is stopped. On top of that, all three events are used for determining if the provided force vector generates the desired result and makes the necessary adjustments (Fig. 20, a-c). By comparing two consecutive points, the speed and direction can be calculated which allows to correct the force and direction.

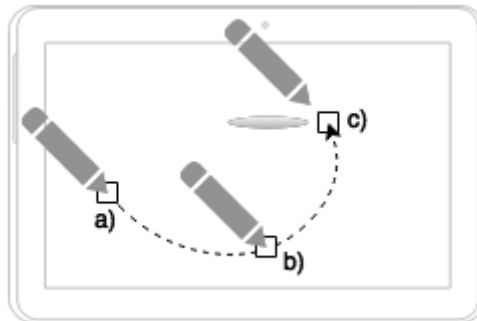


Figure 20: Handwriting system, getting stylus events and input coordinates

```

1 private void touchscreen_StylusUp(object s, StylusEventArgs e)
2 {
3     // stop force feedback
4     stickSlipControl.stopActuation();
5 }
6
7 private void touchscreen_StylusMove(object s, StylusEventArgs e)
8 {
9     // adjust force feedback
10    Point cursorPosition = e.GetPosition(drawingCanvas);
11    adjustForceFeedback(cursorPosition);
12 }
13
14 private void touchscreen_StylusDown(object s, StylusDownEventArgs e)
15 {
16    // start force feedback
17    Point cursorPosition = e.GetPosition(drawingCanvas);
18    adjustForceFeedback(cursorPosition);
19 }

```

Listing 1: Get stylus position and pressure

7.4.2 Calculate active actuators and bit mask

To determine which actuators need to be activated, the user touch quadrant has to be calculated (7.2.1). Therefore, the current user touch location (Fig. 21, point a) is subtracted from the destination point (Fig. 21, point b). The resultant vector is used to determine which actuators need to be activated to deliver the desired kinesthetic signals (Listing 2). As can be seen in Fig. 21, to move the stylus from point a to b (along the directed dotted line), the actuator with the bit 0 and 3 have to be activated. By continuously monitoring the user movement and by comparing them with the expected movements, it can be ensured that the kinesthetic signals are applied correctly (user stays on the dotted line, Fig. 21, point c).

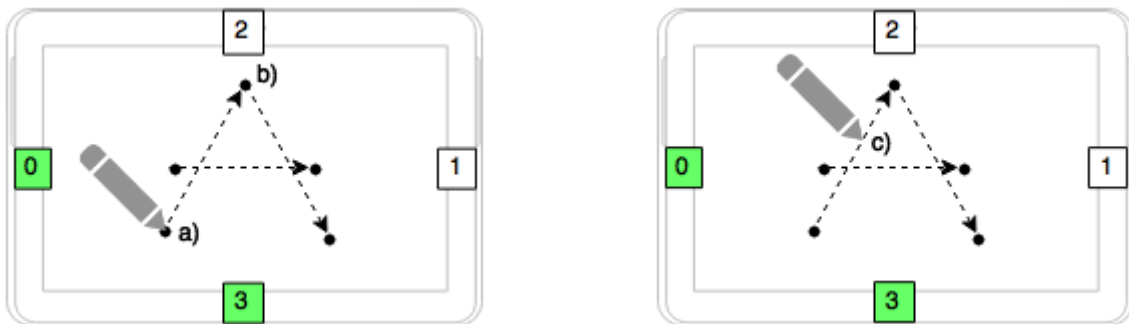


Figure 21: Handwriting system, force-supported stylus movement

```

1 // calculate the difference to determine the required actuators
2 Point difference = PointUtil.subtractPoints(curPos, destination);
3
4 Actuator leftRight = new Actuator();
5 Actuator topBottom = new Actuator();
6
7 // left or right actuator
8 if (difference.X < 0)
9     leftRight.Value = Actuator.Left;
10 else
11     leftRight.Value = Actuator.Right;
12
13 // top or bottom actuator
14 if (difference.Y < 0)
15     topBottom.Value = Actuator.Top;
16 else
17     topBottom.Value = Actuator.Bottom;

```

Listing 2: Calculate active actuator

In order to deliver directed forces in all directions, different actuators need to be activated according to the force vector. To activate or deactivate actuators, a bit mask is calculated and sent to the FTDI controller. Therefore, each actuator holds a bit value which changes according to the screen orientation. All single bit values are passed to a function (*"actuate"*) and packaged into a single byte, using a logic OR operator (Listing 3). The result is stored in a thread-safe variable (*"interThreadBitMask"*) in order to allow inter-thread communication.

```

1 public void actuate(params byte[] actuators)
2 {
3     byte bitMask = 0;
4
5     // add each actuator bit to the bit mask
6     foreach (byte actuator in actuators)
7     {
8         bitMask |= actuator;
9     }
10
11     interThreadBitMask = bitMask;
12 }

```

Listing 3: Calculate actuator bit mask

7.4.3 Connect to FTDI microcontroller

The handwriting system was developed under Windows 8. To connect the FTDI with the operating system, the FTD2XX_NET.dll is used (7.2.3). The FTD2XX_NET DLL is a wrapper library which encapsulates low-level functions and provides them as high-level C# objects. To access an FTDI device, a serial connection needs to be established using a USB port (Listing 4). First, by calling the *"OpenByIndex"* method, a serial port is opened and ready for communication. After that, the microcontroller needs to be configured. By default, the FTDI provides synchronous parallel output using a handshake protocol. To avoid unnecessary overhead, the FTDI is configured to use the *"Bit Mode"* which allows direct manipulation of the parallel output pins without any buffer or queue.

```

1  FTDI device = new FTDI();
2  ftStatus = device.GetNumberOfDevices(ref ftdiDeviceCount);
3  ...
4  // always open only the first FTDI device
5  ftStatus = device.OpenByIndex(0);
6  ...
7  // set the baud rate (defined in a resource file)
8  ftStatus = device.SetBaudRate(uint.Parse(Resource.BOUDRATE));
9  // write to 0x1 with a bit mask of 0xff to activate the BitBang mode
10 ftStatus = device.SetBitMode(0xff, 0x1);

```

Listing 4: Open serial connect to the FTDI microcontroller

7.4.4 Write serial data to FTDI

After a connection with the FTDI microcontroller has been established and the configuration was successful, the system is ready to communicate with the hardware (actuators). Therefore, the UI thread writes a bit mask into a thread-safe variable ("*interThreadBitMask*") which is used for inter-thread communication and passing the bit mask from the UI thread to the hardware thread. At the beginning of each stick-slip actuation cycle, the "*interThreadBitMask*" is read and its value is stored in a local variable. After that, the algorithm performs three steps: First, the power mode is activated by setting the bit number 7 in addition to the bit mask (Listing 5, line 6). After writing the bit mask to the FTDI device, the thread sleeps for a certain amount of milliseconds. Second, the continuous mode is activated by removing the bit 7 and only sending the pure actuator bit mask (Listing 5, line 12). Third, a zero-bit mask is sent to deactivate all actuators (Listing 5, line 18).

```

1  // create a locale, thread-safe copy of the bit mask to write
2  byte writeToController = interThreadBitMask;
3  uint bytesWritten = 0;
4
5  // start with peak voltage for x ms (1000000B | writeToController)
6  writeToController |= 0x80;
7  getFtdiDevice().Write(new byte[] {
8    writeToController }, 1, ref bytesWritten);
9  SleepForMilliseconds(PEAK_TIME_IN_MS);
10
11 // start with limited voltage for y ms (1000000B ^ writeToController)
12 writeToController ^= 0x80;
13 getFtdiDevice().Write(new byte[] {
14   writeToController }, 1, ref bytesWritten);
15 SleepForMilliseconds(ON_TIME_IN_MS);
16
17 // stop actuation for z ms
18 getFtdiDevice().Write(new byte[] { 0x0 }, 1, ref bytesWritten);
19 SleepForMilliseconds(OFF_TIME_IN_MS);

```

Listing 5: Write bit mask to FTDI

It needs to be mentioned that the sleep method is not truly sending the hardware thread to sleep. As experiments with the MS Surface Pro 3 tablet have shown, the thread scheduler is not accurate enough to provide exact sleep periods of multiple milliseconds which caused many issues. As previously mentioned, in order to generate a stick-slip actuation pattern, the timing needs to be very exact. Therefore, a "Stopwatch" counter is used to measure the time passed (Listing 6). This "Stopwatch" traps the program in a loop until the elapsed time is less than the milliseconds to wait. In that way, precise timings can be guaranteed. The drawback of this solution are possible performance issues, as a result of keeping the thread resources locked.

```
1 private void SleepForMilliseconds(int millisecondsToWait)
2 {
3     Stopwatch counter = Stopwatch.StartNew();
4     while (counter.ElapsedMilliseconds >= millisecondsToWait)
5     {
6         // run until x ms have passed
7     }
8     counter.Stop();
9 }
```

Listing 6: None interruptable sleep method

8 Result and conclusion

The purpose of this thesis was to investigate into a new interaction technology which allows to integrate the kinesthetic sense into interactive display surfaces, in the absence of kinematic chains and mechanical linkages. The main objectives were to demonstrate the limitations of haptic systems used in modern interactive devices and to show the need for integrating the kinesthetic sense. Furthermore, it was required to develop a device to prove the technical feasibility of a linkage-free kinesthetic system which delivers directional force-feedback to the user's input device. As a result of the thesis, it can be said that all the main goals have been achieved. It has been shown that the commonly used tactile feedback only provides a very limited amount of information to the user. Therefore, it is required to add kinesthetic signals to deliver a full haptic image to the user. Additionally, this work has demonstrated that there is no solution available at the moment which delivers real linkage-free kinesthetic force-feedback to the user. The only approach which has been researched is how to provide a force sensation by reducing the coefficient of friction between the user's finger and the interactive surface. One of the major contributions of this thesis is the implementation of a fully working system which delivers kinesthetic signals to the user's input device. It has been shown that the stick-slip effect can be effectively utilized to create directional forces on an interactive display surface (Fig. B3, in Appendix B). All in all, it can be said that this thesis provides an alternative approach for integrating the kinesthetic sense into human-computer interaction. In contrast to linkage-based impedance and admittance devices or to the friction coefficient modulation, the stick-slip-based approach seems to be a good alternative. The current results are very promising and will hopefully lead to further research in this area.

9 Limitations and further development

This thesis demonstrated a new interaction technique for integrating directional forces to enhance an interactive display surface in the absence of stiff kinematic chains and mechanical linkages. Although a fully-functional system has been described and built, many details have not been discussed yet. Therefore, the following chapter provides a broad overview about further areas of research especially focusing on current force limitation, manipulation of multiple objects and the integration of direct touch input through the user's fingertip.

Limitations of the force generated

The maximum amount of force which the system is capable to apply towards the input device can be seen as a measurement of efficiency. From this point of view, the current system is relatively inefficient compared to what could be achieved. The generated force is quite limited as a consequence of three factors: the type of solenoid actuator available, the control algorithm and the surface overlay design.

The solenoids used for the current system are not designed to work as actuators. They were developed to be used as single stroke systems with limited linear actuation and short duty cycles. Therefore, their efficiency in a continuous actuating system is rather poor. Hence, additional research needs to be done to find a better solenoid model or actuator technology.

Another area of improvement is the optimization of the stick-slip controller and the actuation algorithm. Based on the fact that the solenoids are mounted on each side of the screen, a push-back motion could be supported by the opposite actuator. By fully controlling the pull and push movement, the actuation signal could be shaped more accurately which would improve the force transmission.

The surface overlay is the third major limiting factor. Because of time constraints, at the moment only a single screen overlay material has been tested: standard antistatic Universal OHP transparent presentation slide (0.1 mm thick). As described in subsection 5.3, the surface properties have a large impact on the stick-slip effect and therefore also on the efficiency of the entire system. For this reason it is important to further research different materials for both the overlay and the stylus tip. Finally, the stiffness of the material needs to be considered to increase the system efficiency.

Manipulation of multiple objects

With the increasing use of mobile devices, people are getting more experienced in the use of interactive displays. This development leads to the increased use of public information screens and collaborative interactive work spaces. One of the main features which allows this development is the increased use of multi-touch screens. By allowing multiple users to interact with the same interactive display, social interaction is promoted between them which can be very

beneficial in work environments as well as in public spaces [43]. All linkage-free kinesthetic systems discussed in this thesis, including the developed system, do not mention multi-user environments. None of these systems is capable to deliver multiple kinesthetic signals independently to different points on a plane display surface. Considering the emerging need of collaborative work spaces, the problem of manipulating multiple objects independently at the same time must be discussed. One possible approach has been shown by Reznik and Canny [20]. They were able to manipulate multiple objects on a plain rigid surface, independently. Therefore, this approach should be examined and adapted to the current system.

Direct manipulation through the user's fingertip

While this thesis only focused on stylus-based interaction, the majority of mobile and interactive devices mainly focus on direct input through the user's fingertip. For this reason, it is also important to investigate if and how the current system could be changed to also support touch input. Thus, many additional properties must be evaluated within the system. As described by Derler and Gerhardt [28], the human skin can be considered as a complex multilayer composite material with many different properties. This is especially valid when talking about the human fingertip. With a high density of sweat glands and a pressure-depending area of contact between the skin and surface, calculating the right stick-slip actuation pattern is largely dynamic and very complex. In addition to the fact that the skins coefficient of friction changes according to the environment is an added complexity. As presented by Derler and Gerhardt [44], the friction coefficient depends on the contact condition. Dry skin has an average friction coefficient of 0.5 while moist and wet skin have a coefficient higher then 1. Furthermore, wet skin, which has a friction coefficient of less then 0.1, behaves yet completely differently. All of these properties need to be classified and taken into account which makes the stick-slip effect very difficult to control. Hence, it can be said that direct interaction through the user's fingertip is a feature which is challenging and further investigation needs to be done to resolve these issues.

Summary

In this chapter, the limitations of the developed system for delivering directional forces on a plane surface were discussed. Even though the current system proves the technical feasibility, the research is still in an early state. As discussed in subsections above, further research needs to be done, especially regarding the actuator technology and the behavior of human skin under the influence of the stick-slip effect. There is still a long way ahead to create an efficient and fully functional system to deliver directional forces in the absence of kinematic chains and mechanical linkages. Nevertheless, when considering the areas discussed in the above, it will be possible to develop the system to a level where it can be tested under normal usage conditions which would be a big step towards integrating the haptic sense in a more efficient manner.

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Appendices

A System Control Diagrams

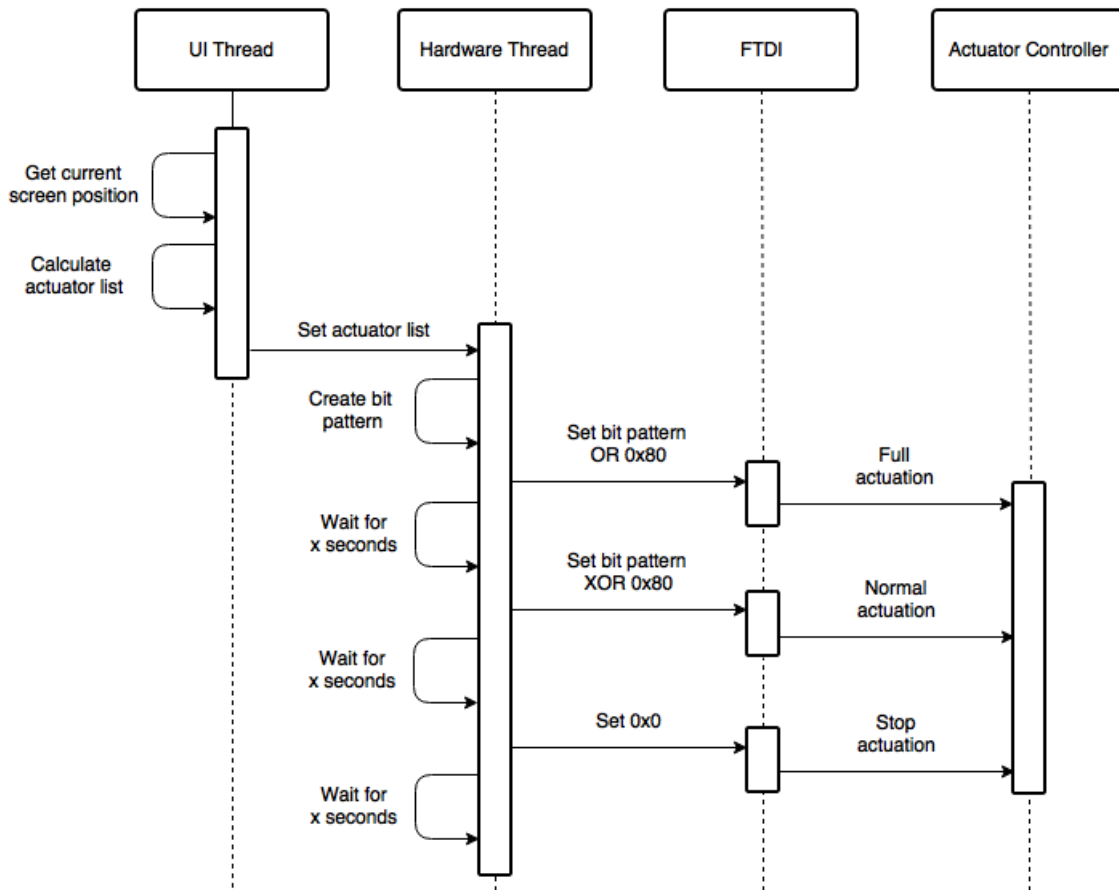


Figure A1: System Sequence Diagram

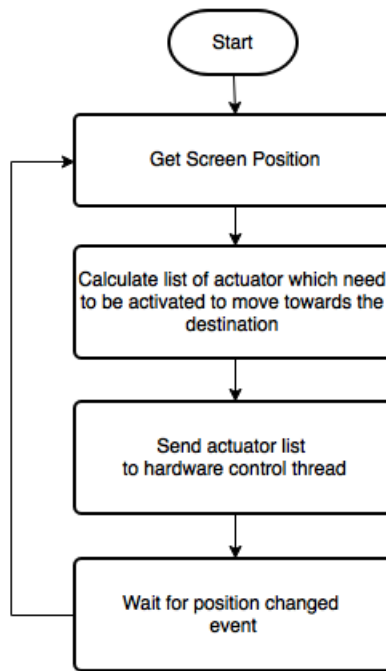


Figure A2: UI Thread Flow Diagram

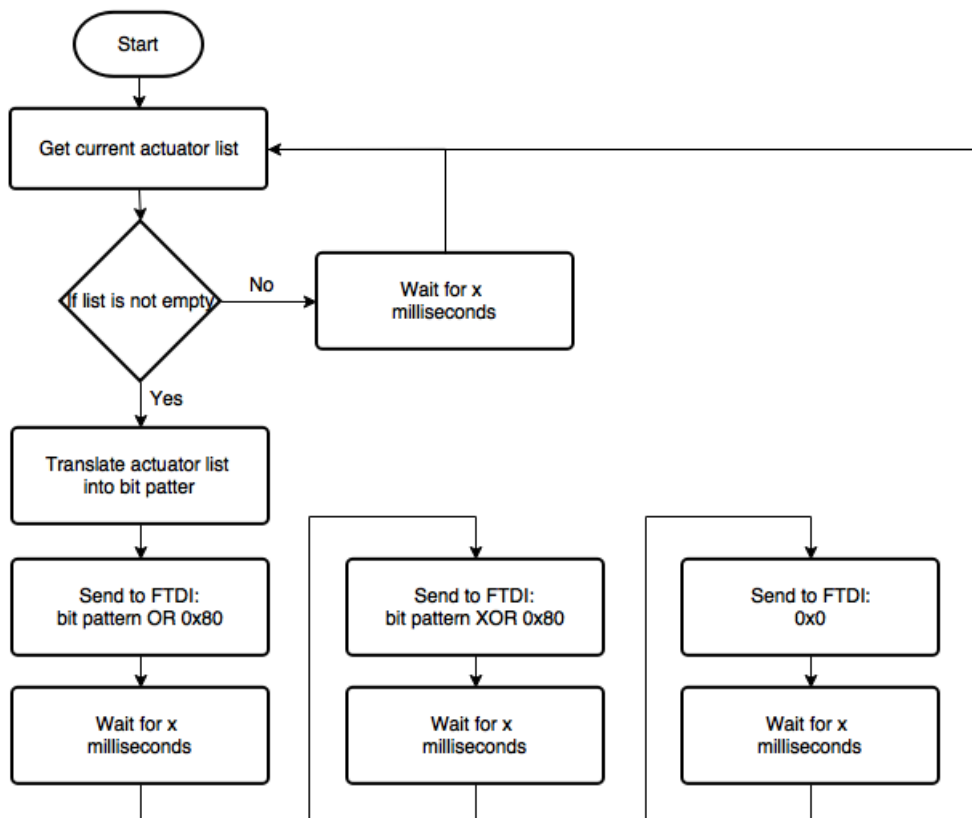


Figure A3: Hardware Thread Flow Diagram

B Final System

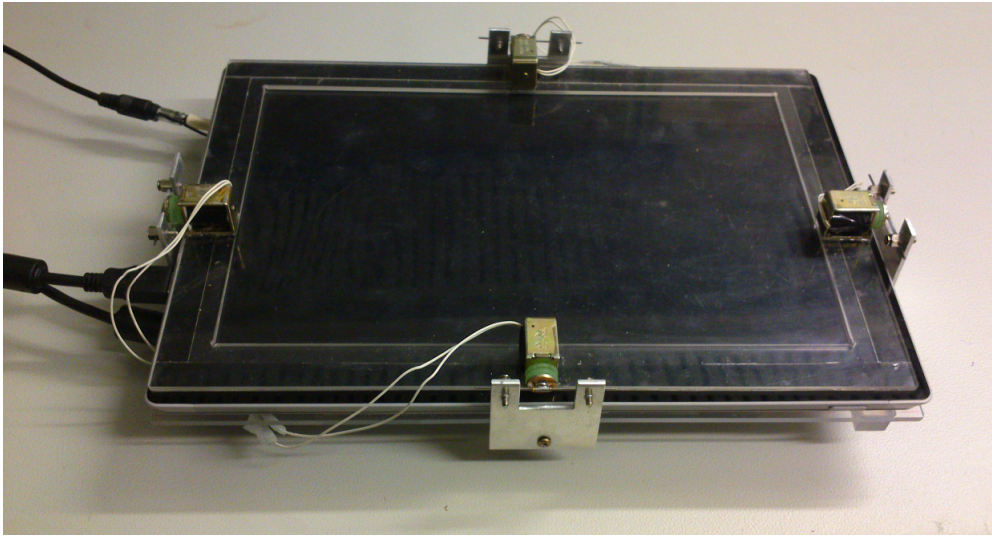


Figure B1: Final System



Figure B2: Kinesthetic handwriting learning system, pixilated picture

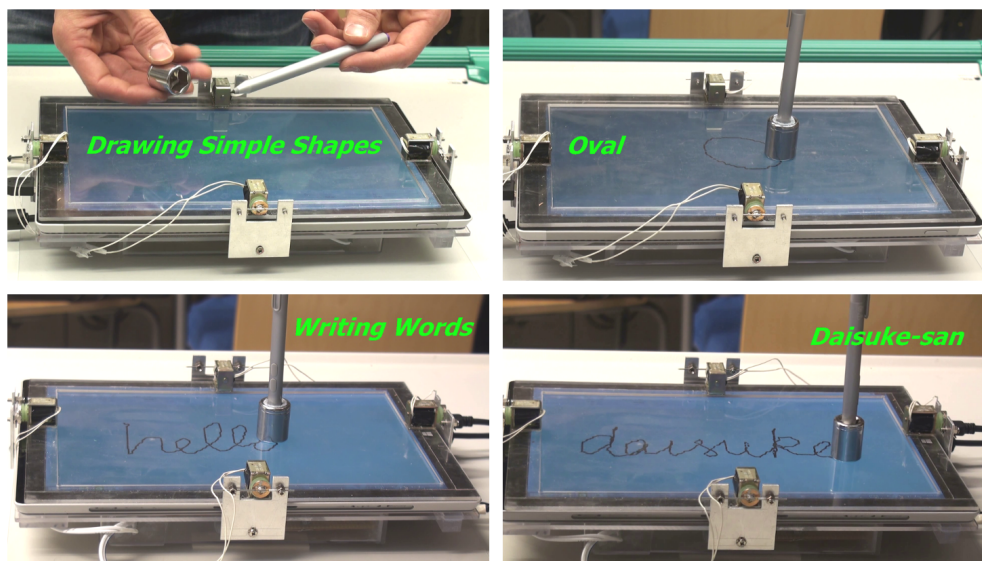


Figure B3: Handwriting system examples

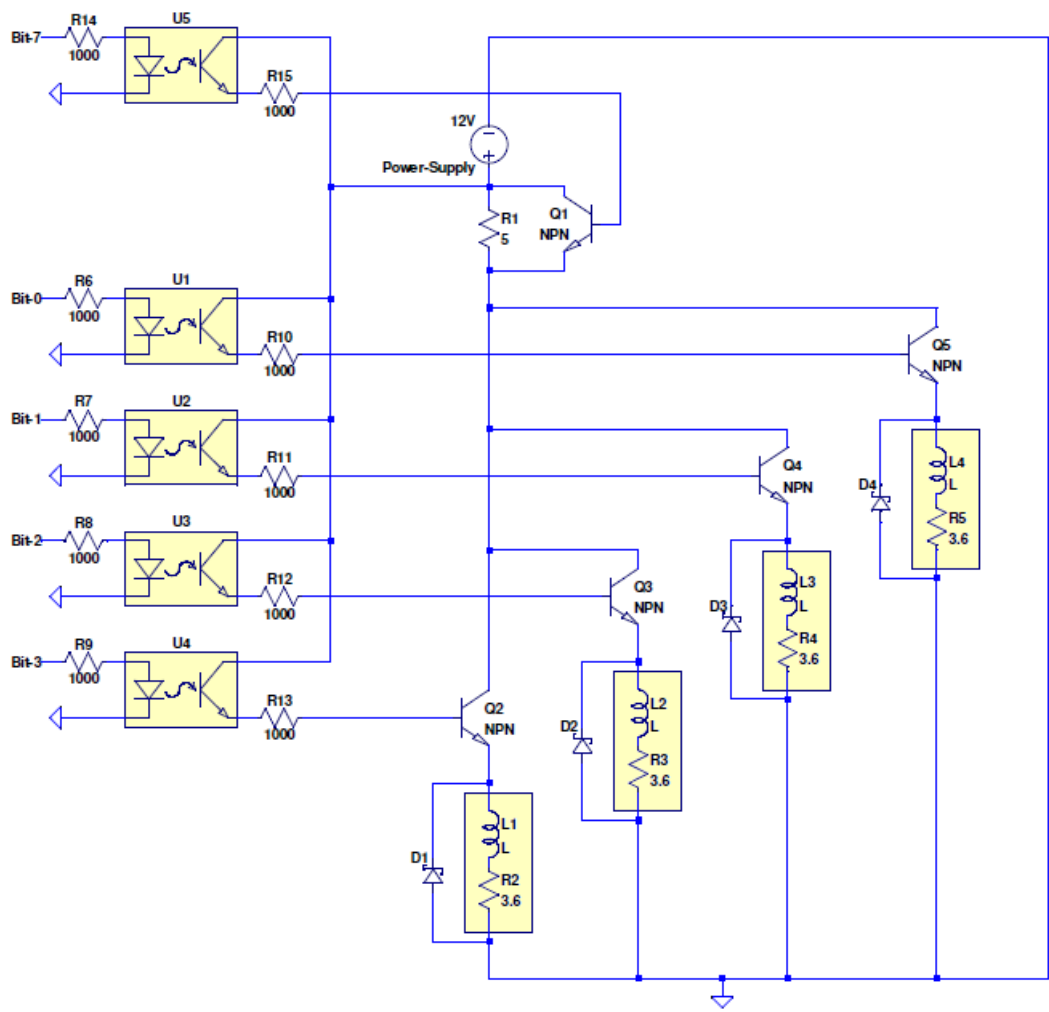


Figure B4: Solenoid Control Circuit