A Touch Based Finger-Motion-Adaptive Control Design for Braille Reading

A Dissertation Presented

By

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Abstract

According to the estimations of the World Health Organization, worldwide, there are approximately 285 million visually impaired people, among whom 246 million have low vision, and 39 million are blind. About 1.3 million of these blind individuals live in the U.S., and only less than 10% of them are Braille literate. As many studies also advocate, Braille literacy has strong impact on opportunities to receive education and join to workforce, which are also linked to confidence, success, self-sufficiency and higher quality of life.

Promoting Braille literacy among the blind requires access to state-of-the-art digital technologies, which can be enabled by developing novel approaches, especially by creating affordable, practical, compact and efficient refreshable Braille reading displays. Unfortunately, existing commercially available products suffer from high-costs mainly because they rely on a large number of piezoelectric actuators in order to display Braille characters. Although many design ideas and actuation mechanisms have been proposed and tested in the literature over the years, there has been no significant change in the commercially available products since 1970s. Hence, there still exists a need for a low-cost, portable and efficient refreshable Braille reading display.

In this dissertation, we focus on developing engineering design rules by which Braille reading devices can be created at low costs and with enhanced user experience. With this aim, a touch based finger-motion-adaptive control design algorithm is proposed for use on a rotating-wheel type Braille reading machine. By taking into account the inherent complexity of Braille reading process, the proposed algorithm estimates user’s hand gestures in real-time without any sensors attached to the hand, and based on this estimation, it can adjust the speed of the wheel bi-directionally in real-time. The finger-motion-adaptive algorithm is tested and its efficacy is evaluated through human subject experiments with sighted and blind people. Results indicate that subjects’ performance metrics improved in the presence of the finger-motion-adaptive algorithm, demonstrating the potentials of utilizing the algorithm in next-generation Braille reading devices.

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Chapter 1

Introduction

It is estimated that about 39 million people in the world are blind, with about 1.3 million of them living in the US [1]. Estimations from World Health Organization indicate that an additional 246 million people in the world have low vision [1], and 2012 American Community Survey reported that about 6.6 million people have visual disability [2]. These figures vary depending on the legal definitions of disability, blindness, and having low-vision. In this dissertation, any individual having challenges with his/her vision, and hence in need of assistive technologies to manage his/her daily-life tasks will be called visually-impaired person, and an individual, who is born with total blindness, will be referred as a blind person.

Braille reading/writing system serves as the primary vehicle for visually impaired people to receive education, advance in their degrees, educate themselves, keep up to date with the news media, and handle day to day tasks [3, 4]. Braille literacy is also the key to accessing information, self-sufficiency, and joining the workforce, thus directly impacts the quality of life of many visually impaired and blind people. In a recent study [5], it was reported that among 85,000 working-age blind adults, 90% of Braille literate people are employed whereas the employment rate among people who do not have Braille literacy is only 33%. Despite the importance of Braille literacy, current numbers for Braille literacy are alarming, around the world and among young generations. A 2009 report estimates
that only 10% of the visually impaired children in the U.S. are learning Braille [6]. Surprisingly, five decades ago, this rate was 50% among the legally blind school-age children [6]. Among many options, one of them that can help reverse this declining trend can be making refreshable Braille displays more affordable for visually impaired people.

Currently, existing devices come with many limitations preventing effective, pervasive, and low-cost Braille education [7, 8]. Existing technology needs to be significantly improved from cost, ergonomics, and usability aspects [9, 10]. Other issues are related to physical size and weight of devices affecting the portability of existing refreshable Braille reading displays. Since in the end all these facts are obstacles to the improvement of Braille literacy, exploring novel approaches that offer reliable solutions to the above mentioned issues, is a critical mission.

The goal of this study is to explore engineering design rules by which Braille reading devices can be created at low costs and with enhanced user experience. Specifically, these design rules will describe ways to create devices that can seamlessly adapt to users’ specific hand gestures which are known to be critical for effective Braille reading.

The remaining of this chapter is organized as follows. Section 1.1 introduces the structure of Braille and commonly used Braille reading and writing devices. Section 1.2 presents a literature survey on various refreshable Braille reading displays developed for the visually impaired as well as finger kinematics during Braille reading. The motivation and significance of the dissertation is discussed in Section 1.4, and contributions are listed in Section 1.5. The chapter is concluded with an outline of the dissertation in Section 1.6.

## 1.1 Braille

Invented by Louis Braille in the first quarter of 19th century, Braille is a universal tactile system for reading and writing used by blind and visually impaired people. A Braille
cell consists of six dots, which are arranged in a 3 by 2 matrix (see Figure 1.1, left). Different combination of Braille dots form letters. The example in Figure 1.1 (on the right) depicts the print and Braille versions of the word 'braille'.

![Braille cell diagram](image)

**Figure 1.1:** Different combinations of Braille dots (on the left) make characters that represent letters (on the right).

The most commonly used tool for Braille writing is slate and stylus shown in Figure 1.2 on the left hand side. In order to write Braille with a slate and stylus, the paper is entrapped between two metal pieces of the slate, and then the stylus is used to punch braille dots on the paper. This writing method is primitive since writing is carried out by typing one dot at a time. Another drawback is that the user has to emboss the mirror image of the characters. On the other hand, it is advantageous in terms of its low cost and portability. Another alternative for Braille writing is using a braillewriter, whose working principle is similar to typewriters. The most popular one is the Perkins braillewriter (middle picture in Figure 1.2), which facilitates embossing a character at a time, and is mostly used in classrooms.

![Braille devices](image)

**Figure 1.2:** Slate and stylus [11] (left), Perkins Brailler [12] (middle), Refreshable Braille display [13] (right).

On the right hand side of Figure 1.2, a commercially available Braille reading device is presented, which is also referred as a refreshable Braille display. Such devices can display Braille characters by means of actuated pins, which react rapidly to input commands to effectively refresh the Braille text by generating a Braille-pin stroke of about 2-3
mm out of plane. These displays can be connected to a personal computer in order to access digital information in Braille. With the buttons provided on the display, users are able to navigate through their computer screen. Depending on the number of displayed Braille characters, the sizes of commercially available refreshable Braille displays vary and their prices range from $3,500 to $15,000 [14].

1.2 Literature Survey

1.2.1 Refreshable Braille Displays

Refreshable Braille displays available in the market make use of piezo-electric actuation, whose working principle is based on bending of piezo-electric bimorph layers under applied voltage to lift and lower the Braille pins [15]. While these devices can display text in real-time by means of high bandwidth of piezo-electric actuators, utilization of multiple bimorph reeds to create 20 to 80 cell displays reflects to costs. These devices also require high voltage such as 200 Volts [16] and in some cases portability can be limited because of the large size of the actuators. In order to overcome these issues and improve existing refreshable Braille displays, various actuation methods such as thermal, electrical and mechanical, have been widely investigated in the literature [17–23].

Among existing actuation techniques, electroactive polymer (EAP) materials have recently gained attention on the development of sheet type Braille displays [24–29], where miniature actuated dots are packed into a densely-packed array form to produce refreshable Braille. Although these actuators hold promise for creating full-page Braille displays, improvements are needed especially by lowering their voltage requirements, enhancing their bandwidth and increasing generated forces [30]. Another promising method for actuation in Braille displays is shape memory alloys (SMA), which are compact and lightweight. The main challenges with such actuation means are the response time and bandwidth [31]. These actuators can be useful in future generation lightweight
Braille displays, especially by enhancing their response speeds for rapid display and refresh of Braille [32, 33].

With the aim to reduce the high costs of conventional displays, electrical stimulation has been used in creating Braille displays [34, 35]. Tests performed with current and voltage stimulation in [36] showed that current stimulation achieved high legibility of Braille characters at the cost of uncomfortable sensations under the fingertip. Although the perceived pain is reduced by voltage stimulation method, it shows lower identification rates of characters. Despite their low power consumption and potential to be manufactured in compact form, electrotactile stimulation does not constitute a reliable option to present Braille due to sensations such as itch, tingle, buzz, pinch and sharp pain reported by human subjects [37]. Another method that has been widely investigated in the literature is vibration based tactile stimulation which presents advantages in terms of power consumption and potential for compact actuator configurations. In studies [31, 38–42], vibrational stimuli is created using different actuation mechanisms such as electric, piezo-electric, smart materials, and coin motors.

Other studies aim to offer an affordable solution to cost issues by creating Braille displays comprising a single Braille cell. In [43], a single Braille cell is mounted at the end effector of a force-feedback haptic interface. In the experiments carried out with blind people, users navigate on a virtual page by placing their fingertip on the single cell and moving it over the workspace of the haptic device. Experimental results indicate slow reading speeds, and emphasize the significance of transitions of the finger between Braille characters, which are essential for tactile perception [44], but are not available on a single Braille cell display. In [19], authors propose a Braille rendering method based on the lateral deformation of the skin using piezo-ceramic actuators. They create virtual Braille patterns that mimic the perception that would occur during brushing a finger against a line of Braille dots. The significance of the study lies in this proposed technique, which solves the adaptation problem present in single-cell Braille displays (further discussed in Section 1.3) due to lack of sufficiently many Braille cells to create a brushing movement between the finger and the display.
Without depending on single cell based design, the study in [45] proposes an approach for creating continuous reading experience by configuring the Braille letters around a rotating drum, which is called by the authors as Rotating-Wheel Braille display. This display, which is not available in the commercial market, is advantageous since it requires only few actuators in a small compact volume (with drum diameter $5 - 10 \text{ cm}$) compared to other existing devices, holding promise toward an affordable and portable device. However, this prototype operates at constant speeds only [46], and moreover, its performance assessment is not available as it was not thoroughly studied in human subjects experiments but only in preliminary piloting, which showed strong promise for further expansion. User feedback obtained from pilot testing indicates the need for a means to control the wheel speed on the fly. Authors also report that users desire to adjust the wheel speed at times when they want to slow down on a word, reread a previously read word or read words faster which have been already guessed from context.

### 1.2.2 Finger Kinematics during Braille Reading

Gaining insight into finger kinematics during Braille reading is important in terms of developing efficient Braille displays. Braille reading tasks performed with human subjects in [47] reveal that the instantaneous velocity of the reading finger does not remain constant but exhibits fluctuations leading to nonuniform finger movements during Braille reading. An important feature of Braille reading is reversals, also referred as “regressions” [48], which are defined by right-to-left movements of the finger in order to reread text whose processing has not been completed yet. In a reversal action, readers move their finger leftward on the same word that is being read or on the preceding word, and during this reversal action no reading takes place. After positioning the finger on the word or part of the word that is desired to be reread, forward reading continues by moving the finger from left to right direction. It is reported that even the most experienced readers perform reversals on a regular basis [49]. Another important observation made on reversals is that during reading whether it is forward- or backward-directed, the finger remains in contact with the reading surface [49].
Velocity changes of the Braille reading finger during scanning Braille characters are also investigated in [50]. In this study, authors simulate the fingertip deformations by using an artificial touch sensor with the aim to investigate haptic discrimination of Braille characters during reading. A probabilistic framework is demonstrated for recognition of Braille characters by modulating the reading velocity of the artificial fingertip in a closed-loop system. Results indicate that fast discrimination of Braille characters is achieved by dynamic adaptation of the finger velocity and accelerations are observed similar as in human subject experiments.

A recent study explores the contribution of sliding motion between the fingertip and the reading surface as well as the proprioceptive cues to Braille reading [51]. For this, authors conduct Braille letter recognition experiments by using different Braille reading configurations, which are created by the combinations of display types (static/sliding) with proprioception conditions (proprioceptive/non-proprioceptive). Experimental results reveal that sliding contact between the fingertip and the display improves Braille reading accuracy when compared to static display mode, whereas proprioception shows no significancy in improving reading performance. In light of these findings, authors also emphasize that single cell displays lacking sliding contact would not be effective for Braille reading.

### 1.3 Challenges with Creating Refreshable Braille Displays

Although various actuation techniques are investigated with the aim to render Braille efficiently and at low costs as discussed in Section 1.2.1, a Braille reading device with actuation mechanisms other than piezo-electric based materials is still not available in the commercial market. Main problems encountered by the proposed designs are high-voltage requirement, lack of portability, high prices, reliability, and long response times preventing real-time operation.
Although an approach based on single cell shows promise for a portable design by addressing the cost and size issues of a standard Braille display, there are some limitations in using them for displaying Braille [10, 51]. On a single cell display, users need to spend time on each fixed single Braille cell in order to perceive each character completely which in turn slows down the reading speed. Rapid reading is inhibited in cases when the user wants to reread a word which can only be achieved through separate buttons to control the refreshing of previously read letters or words. Reading from a single cell also creates the difficulty in constructing a geometric model of the layout of Braille characters since all of them are displayed at the same spot causing conflicts in mental image. In order to better understand this, one can imagine reading a newspaper from a small window displaying one letter at a time which requires retaining the previously read letters in order to build the virtual images of the words and sentences being read. Another limitation is the sensation loss of the tactile receptors on the fingertip after a period of stimulation, which is known as adaptation [52], and occurs due to lack of the sweeping movement between the finger and the Braille text.

The adaptation problem is also reported with vibrotactile stimulation [53] by psychophysical experiments [54, 55] and occurs due to the declining sensitivity with extended exposure to vibratory stimulus. Another issue faced by vibrotactile stimulation is change blindness, which is defined as the inability of people to detect significant changes between visually presented consecutive scenes, when separated by a mask or an empty time interval [56]. Studies in [57, 58] reveal that change blindness observed in vision also occurs in tactile perception. Experiments performed with human subjects on the comparison of two consecutive tactile stimuli, separated by a tactile mask or an empty time interval, presented to their fingertips are reported as leading to erroneous tactile perception of the displayed pattern [57].
1.4 Motivation and Significance of the Study

In the past three decades, personal computers and electronic displays have advanced at an astonishing pace, resulting in ever easier access to digital information. Despite these rapid developments in technology, no significant changes have been observed in the existing refreshable Braille displays since the introduction of the first commercially available products in 1970s. Hence, there still exists a great need for the investigation of novel approaches towards the development of a low-cost, portable, and efficient Braille reading display. The need for such a device together with recent investigations of finger dynamics during Braille reading, as discussed in Section 1.2.2, motivates us for exploring alternative ways to display Braille. In this research study, we propose a hand gesture adaptive algorithm that can be used in a human-machine interface for the blind.

One of the main challenges in designing a versatile Braille reading device is the inherent complexity of the Braille reading process. Braille reading involves finger-rubbing actions across Braille letters for the stimulation of appropriate nerves for proper reading, and intricate finger-motion patterns including accelerations, decelerations and right-to-left movements, namely reversals as discussed in Section 1.2.2. These characteristics of Braille reading point out that a Braille reading device must be adaptable to users’ reading patterns.

In this study, we envision that it would be extremely useful if a Braille reading device could sense a user’s finger gestures in real-time and adjust Braille refresh rate accordingly to accommodate reversals as well as any changes in the reading speed of the user. According to the extensive literature search that we carried out on the proposed techniques for a low-cost Braille display, we found out that one prototype device that has the potential to eliminate the aforementioned challenges discussed in Section 1.3 is the rotating wheel Braille display [46]. Nevertheless, this prototype rotates at constant speeds only, and hence does not accommodate reversals. Also, its performance and efficacy evaluation has not been performed through human subject testing. Moreover, to the best of our knowledge, there has been no study investigating the problems of existing
Braille reading devices with a focus of users’ needs, namely by taking into account the finger dynamics during Braille reading. In this study, we argue that an ideal Braille display device could be the one that has been validated by human subjects testing, and that tailors a continuously refreshing Braille display with refresh speeds that can automatically adapt to user’s finger motion, in real-time. Such a device could be similar to the rotating wheel Braille display or it can be a belt conveyor type system or any type of device that can continuously refresh Braille on a moving surface.

1.5 Contributions

As motivated in the above section, the major contributions of this dissertation are listed as follows:

- A finger-motion-adaptive (FMA) controller is proposed to enhance user experience in Braille reading on a moving surface.

- Real-time adaptation of displayed information to specific hand gestures is performed with a sensorless design using developed disturbance observer under a closed-loop control framework.

- The proposed closed-loop system can produce satisfactory performance for Braille reading dynamics and this framework can be constructed without any explicit knowledge of the mathematical model of the electromechanical system. This makes the control design completely model-free.

- Braille inspired and Braille reading tasks are tested on a rotating-wheel type setup through human subject experiments with sighted and blind participants, respectively. Results and feedback from subjects are reported. Relevant performance metrics are analyzed with statistical tools.
Based on the above contributions, successful results obtained in the presence of finger-motion-adaptive algorithm show strong promise that a continuously refreshing Braille reading device has indeed potential to be a standard Braille display in the future.

1.6 Outline of the Dissertation

This dissertation starts with introducing the development and design of the finger-motion-adaptive (FMA) controller, which is validated with real-time experiments on a machine-to-machine system in Chapter 2. The testing and evaluation of the FMA controller through sighted subjects are presented and discussed in Chapter 3. Chapter 4 studies the utilization of active disturbance rejection control (ADRC) with finger-motion-adaptive dynamics and reports preliminary results on the pilot testing of the proposed controller, performed with blind subjects. An ADRC based switching FMA controller is introduced in Chapter 5. Results of Braille reading experiments carried out with blind subjects and evaluation of ADRC based switching FMA controller with associated performance metrics are presented and discussed in Chapter 6. The dissertation is concluded in Chapter 7 with future research directions.
Chapter 2


2.1 Introduction

Developing an efficient and user-adaptive Braille display requires deep understanding of how blind people move their fingers/hands during Braille reading. As discussed in the previous chapter, accurate reading requires the relative motion between the finger and Braille letters to create the virtual Braille image as well as the reversals, which are performed by blind people in order to recover incomplete processing of words to fully comprehend the text. Based on these finger kinematics during Braille reading, we hypothesize that efficient and rapid Braille reading can be achieved by a device allowing bi-directional motion of the displayed text, which should be adjusted in real-time taking into account changing reading patterns of the reader including reversals. With the aim
to show such an adaptation principle, here we propose a finger-motion-adaptive (FMA) control design, which is employed on a machine that has similar operation principle to the Rotating-Wheel Display presented in [46].

Since the Rotating-Wheel display is not available in the commercial market, and creating a refreshable Braille display is not the main interest here, we first study finger motion adaptation on a setup we built using a DC motor along with a disc attached onto the motor shaft (see Section 2.2). The ultimate goal is to demonstrate adaptation of the disc speed to the user’s finger motions. The working principle behind the finger-motion-adaptive control on a rotating wheel is explained by illustrating several finger positions during reading as shown in Figure 2.1. In this figure, the user performs Braille reading on a rotating-wheel type device, where clockwise (CW) and counterclockwise (CCW) rotation of the wheel correspond to forward reading and reversals, respectively. In order to perform forward reading, user does not need to travel all the way toward right, instead the wheel rotates in CW direction, bringing the text underneath user’s finger. However, user’s finger motions are not restricted on the wheel and s(he) can freely move his/her finger as s(he) wishes to. As the user attempts to move his/her finger toward left for a reversal as demonstrated with the transition of finger from positions 3 to 4 in Figure 2.1 a), the direction of wheel rotation is reversed to accommodate the reversal motion. Once the user positions his/her finger to reread the previously read word (as shown with finger position 5), the wheel speed rotation is set back to CW direction to enable forward reading again (finger positions 6-7).

In this chapter, without any human subjects testing, we study the above described finger-motion-adaptive (FMA) control design on a machine-to-machine system (Section 2.2) along with the theoretical foundation of the control design. Stability analysis of the proposed control system is performed in Section 2.3. Results obtained in experiments are presented and discussed in Section 2.4. Section 2.5 concludes this chapter.

Figure 2.1: Illustration of finger movements during a reversal motion and adaptation of a rotating-type machine to finger dynamics. a) Finger motion demonstrating reading of the word “knowledge”. A sample reversal is depicted at position 3. The finger goes back to the beginning of the word at position 5, and then continues reading toward right passing through positions 6-7. b) Analogous operation with reversal accommodated by the FMA controller. Numbered positions of the finger from panel a) are mapped here. Braille is presented on a rotating wheel. At position 3-4, the subject moves the finger in the opposite direction of the text flow (reversal) in order to reread the part of the word that has not been processed completely. When FMA controller detects the reversal, it slows down the wheel and can even reverse direction to allow the subject enough time to successfully reread the letters. That is, the controller adapts the text flow speed to temporal and spatial changes in user’s hand gestures.
2.2 Design of the Finger-Motion-Adaptive Controller

The rotating-wheel braille display as described in the literature operates bi-directionally at constant speeds only, where the rotation direction and speed are manually set via switch buttons. Here, we propose that the wheel speed of such a device can be regulated according to user’s finger motions by estimating in real-time the frictional forces applied by the user on the wheel surface during Braille reading. In order to implement this, we propose a controller that is inspired by disturbance observers. This controller, called in this dissertation as finger-motion-adaptive (FMA) controller differs in certain aspects from conventional disturbance observers, as detailed below. FMA controller is envisioned to regulate a device similar to Rotating-Wheel display to enhance its utility in order to provide the user with an interactive Braille reading experience by adapting Braille display speed to user’s finger motion.

![Experimental Quanser setup for machine-to-machine system. Top view.](image)

**Figure 2.2:** Experimental Quanser setup for machine-to-machine system. Top view.

Braille reading performed on a rotating-wheel type Braille display is a human-machine system (HMS) where human interacts with the device by touching it. Prior to studying this interaction, we built its analogous version, which is a machine-to-machine system (MMS) (see Figure 2.2). In the MMS, we mimic a finger touching a rotating disc using a belt system which pushes against the disc driven by a DC-motor (Motor-1). In the
Figure 2.3: Block diagram demonstrates the structure of the FMA controller based on disturbance observer.

HMS, the human would introduce the disturbance to the system when s(he) rubs his/her finger on the rotating-wheel. When Braille reading is performed from left-to-right, the disturbance acts in the reverse direction of the text flow, and therefore the rotation speed of the wheel should increase to accommodate user’s intention to read faster in the forward direction. Similarly, in case of a reversal to rescan the text, the disturbance acts in the same direction as the text flow, which must be adapted by slowing down the speed of the wheel to allow enough time for the user to read the text. In the MMS, when belt drive comes in contact with the rotating disc, it creates an analogous disturbance as in the HMS. The discussions made in the remainder of this chapter are based on this MMS.

The block diagram in Figure 2.3 shows the control system structure of the MMS. This structure comprises of a disturbance observer with a feedback-controller $C_2$ in order to regulate the speed of Motor-1 (M1). Disturbance observers are widely used in motion control systems for disturbance rejection purposes [59]. However, in this control system the disturbance observer is implemented to estimate the disturbance $\hat{d}_\tau$, which is then used as an additional “reference” to the speed of M1 ($w_{r1} + w_{r2}$), which must be adapted to, with the help of $C_2 = k_p$ where $k_p$ is the proportional gain of the disturbance
adaptive controller (see Figure 2.3). In other words, when the disturbance is received in the direction of machine rotation, then it is expected that the machine must speed up, analogous to the HMS described above. In conventional disturbance rejection schemes, however, estimated disturbance is used to offset the estimation at the actuation level [60].

In Figure 2.3, $G$, $C_1$, $C_2$, $K_t$, $\omega_{r_1}$, $\omega_{r_2}$, $\tau$, $d_\tau$, $d_\tau\dot{\tau}$ and $d_\tau,0$ represent the plant, controllers, motor torque constant, speed reference of M1, disturbance adaptive speed reference, control input, torque disturbance, estimated torque disturbance, and the offset related to uncertainties in the motor transfer function $G$ (see below for details), respectively. The values of the control system parameters are given on Table 2.1. The plant $G(s)$ is the transfer function between torque and speed of M1, which is given by

$$G(s) := \frac{\Omega(s)}{\tau(s)} = \frac{1}{J_{eq}s + B},$$

(2.1)

where $\Omega(s)$ and $\tau(s)$ are the Laplace transforms of angular speed of M1 and the torque applied to M1, respectively. This speed is controlled via a PI-controller $C_1(s)$ which is in the following form:

$$C_1(s) = \frac{K_ps + K_i}{s},$$

(2.2)
where $K_p$ and $K_i$ are respectively the proportional and integral gains.

The disturbance observer used to estimate the disturbance torque is designed with the inverse of the plant, $G^{-1}(s)$, assuming the plant model (2.1) is accurately known, and a low-pass filter $Q(s)$ which is required to make the inverse plant model realizable [61], where the transfer function of the filter here is given by

$$Q(s) = K \frac{1}{\tau_q s + 1},$$

(2.3)

with $K$ being the DC gain and $1/\tau_q$ being the cut-off frequency of the filter.

Once the torque disturbance $\hat{d}_\tau$ is estimated, it is then multiplied by the proportional controller $C_2(s)$ to form the speed input $\omega_{r_2}$ that needs to be added to the reference speed $\omega_{r_1}$. This is done for the adaptation of the speed of M1, where $\omega_{r_2}$ acts similar to a commanded reference associated with the disturbance, where the disturbance on M1 is applied by a foam material on the belt in Figure 2.2.

We remark that although the model of the motor is given, system identification tests did not match the given model. However, the lack of a precise model of the motor did not play an important role in terms of validating the proposed disturbance adaptive controller. This is because the idea behind the use of the disturbance observer in this study is more to reveal the direction of the friction force during the contact than the disturbance magnitude. This information is then fed back to a proportional controller. Moreover, in such cases, one can also tune the controller $C_2$ in order to create appropriate adaptation of M1 to the estimated disturbance $\hat{d}_\tau$. Further details on implementing a model-free approach to design FMA controller is discussed in Chapter 4.
2.3 Stability Analysis of the Disturbance Adaptive Controller based System

In order to analyze the stability of the FMA controller in Figure 2.3, transfer functions of the multiple input (reference speed $w_{r_1}$ and external disturbance $d_\tau$) single output (controlled speed $w$) system are calculated as follows in Laplace domain.

\begin{align}
\Omega_d(s) &= \Omega_{r_1}(s) + \Omega_{r_2}(s) \quad (2.4) \\
\Omega_{r_2}(s) &= C_2(s)Q(s) (G^{-1}(s)\Omega(s) - \tau(s)) \quad (2.5) \\
\tau(s) &= K_tC_1(s) (\Omega_d(s) - \Omega(s)) \quad (2.6) \\
\Omega(s) &= G(s) (\tau(s) + D_\tau(s)) \quad (2.7)
\end{align}

where Laplace transformation of $w$ is denoted by $\Omega$ with appropriate subscripts, and same symbols in Laplace domain are used for the remaining terms for simplicity. The closed-loop system in Figure 2.3 can be modeled by equations (2.4)-(2.7). By solving for $\Omega(s)$ in terms of $\Omega_{r_1}(s)$ and $D_\tau(s)$, we find the following transfer functions:

\begin{align}
G_{w/w_{r_1}} &= \frac{\Omega(s)}{\Omega_{r_1}(s)} = \frac{K_tC_1(s)G(s)}{1 + K_tC_1(s)G(s)} \\
&= \frac{K_pK_t\tau_qs^2 + (K_pK_t + K_iK_t\tau_q)s + K_iK_t}{CF} \quad (2.8) \\
G_{w/d_\tau} &= \frac{\Omega(s)}{D_\tau(s)} = \frac{G(s)(K_tC_1(s)C_2(s)Q(s) + 1)}{1 + K_tC_1(s)G(s)} \\
&= \frac{\tau_qs^2 + (KK_pK_tK_p + 1)s + KK_iK_tk_p}{CF} \quad (2.9)
\end{align}

where the output is given by

$$\Omega = G_{w/w_{r_1}}\Omega_{r_1} + G_{w/d_\tau}D_\tau \quad (2.10)$$
and the characteristic function $CF$ is formulated as

\[ CF = \tau_q J_{eq} s^3 + (J_{eq} + \tau_q B + \tau_q K_t K_p) s^2 + \left( B + K_t K_p + \tau_q K_t K_i \right) s + K_t K_i \]  

(2.11)

Here, $CF = 0$ represents the characteristic equation of the closed-loop system, which can be further investigated to analyze the stability of the system using Routh’s array [62] as given below.

\[
\begin{bmatrix}
\tau_q J_{eq} & B + K_t K_p + \tau_q K_t K_i & s^3 \\
J_{eq} + \tau_q B + \tau_q K_t K_p & K_t K_i & s^2 \\
B + K_t K_p + \tau_q K_t K_i - \frac{\tau_q J_{eq} K_t K_i}{(J_{eq} + \tau_q B + \tau_q K_t K_p)} & 0 & s \\
K_t K_i & 0 & 1
\end{bmatrix}
\]

Based on the array, the closed-loop system is asymptotically stable if and only if the first column elements of the array are all positive. Since certain physical parameters must be positive (see Table 2.1), one can use these first column elements to further simplify the stability conditions. That is, since $\tau_q > 0$, $J_{eq} > 0$, $B > 0$, $K_t > 0$, the closed-loop system stability conditions reduce to

\[
K_p > \max \left( \frac{-J_{eq} + \tau_q B}{K_t \tau_q}, \frac{\tau_q J_{eq} K_t K_i}{K_t (J_{eq} + \tau_q B + \tau_q K_t K_p)} - \frac{(B + K_t K_p + \tau_q K_t K_i)}{K_t} \right) \quad (2.12)
\]

\[
K_i > 0 \quad (2.13)
\]

Assuming the closed-loop system is stable, i.e., eqns. (2.12) and (2.13) hold, steady state error $e_{ss}(t)$ of the system between $w$ and $w_{r1}$, with $w_{r1}$ being a unit step input, is calculated as follows:

\[
e_{ss}(\infty) = \lim_{t \to \infty} e_{ss}(t) = \lim_{s \to 0} s \frac{1}{1 + K_t C_1(s) G(s)} \Omega_{r1}(s)
\]

\[
= \lim_{s \to 0} s \left( \frac{s (J_{eq} s + B)}{(J_{eq} s^2 + s B + K_t K_p s + K_t K_i) s} \right) \frac{1}{s} = 0 \quad (2.14)
\]
which indicates that the output will track the commanded input $\Omega_r$ with zero steady state error. Similarly, using final value theorem as in eqn. (2.15) we show that for a unit step disturbance $d_\tau$, the output speed of the rotating disc $w$ changes by a factor of $K_k p$, with $K = 1$ being the filter gain.

$$G_{w/d_\tau}(\infty) = \lim_{s \to 0} s \frac{G(s)(K_t C_1(s)C_2(s)Q(s) + 1)}{1 + K_t C_1(s)G(s)} = \frac{\tau_q q^2 + (K_t k_p K K_p + 1)s + K_t k_p K K_i}{(J_{eq} q^2 + (B + K_t K_p)s + K_t K_i)(\tau_q q + 1)} = K_k p$$  \hspace{1cm} (2.15)

Inspecting Table 2.1, we note that any uncertainty in the system will very likely arise in $J_{eq}$ and $B$. In order to next investigate the stability of the system under $\pm 10\%$ uncertainty in $\delta B$ and $\delta J_{eq}$ for respectively $B$ and $J_{eq}$ in the plant, using eqns. (2.4)-(2.6) and (2.17) along with the modified plant in eqn.(2.16) we first extract the characteristic function in terms of $\delta B$ and $\delta J_{eq}$, which is given in eqn. 2.18.

$$\tilde{G}(s) = \frac{1}{(J_{eq} + \delta J_{eq})s + (B + \delta B)}$$  \hspace{1cm} (2.16)

$$\Omega(s) = \tilde{G}(s)(\tau(s) + D_\tau(s))$$  \hspace{1cm} (2.17)

$$CF = (\tau_q J_{eq} + \tau_q \delta J_{eq})s^3 + (\tau_q B + \delta J_{eq} + J_{eq} + K k_p K_t K_p \delta J_{eq} + \tau_q \delta B + K_t \tau_q K_p)s^2$$
$$+ (K k_p K_t K_i \delta J_{eq} + B + K_t \tau_q K_i + K_t K_p + K k_p K_t K_p \delta B + \delta B)s$$
$$+ K_t K_i + K_t K k_p K_i \delta B$$  \hspace{1cm} (2.18)

Applying Routh Hurwitz stability criterion to the characteristic function, we show that the shaded area in Figure 2.4 reflects the stability region with respect to $\delta B$ and $\delta J_{eq}$. By zooming around the origin, we were able to verify that $\pm 10\%$ plant uncertainty around the nominal plant is included in the shaded stability region. As a matter of fact, the
closed loop is robustly stable against much larger deviations from the nominal value, as shown.

![Stability region of the closed-loop system](image)

**Figure 2.4:** Stability region of the closed-loop system given in eqns. (2.19)-(2.22) in terms of plant uncertainties $\delta J_{eq}$ and $\delta B$.

## 2.4 Experimental Results

Real-time experiments are carried out to show the working principle of the FMA controller described above, on the MMS. In the following, we introduce the hardware used for real-time experiments and discuss the results, which were presented in [63].

### 2.4.1 Hardware

The hardware used for the real-time experiments is an industrial mechatronic drives unit by Quanser shown in Figure 2.2. The unit has two motor driven shafts (shaft-1 and shaft-2) that are equipped with optical encoders. Shaft-1 is loaded with an inertia disc driven by M1, four masses and a disc, and shaft-2 driven by M2 is mounted with a gear which drives a belt whose outer side is partially covered with a foam.

Two belt tensioners are used for the belt drive system in which the first one is used to create tension in the belt, and the second one acts like a free-rotating roller. This roller is positioned such that whenever the foam on the belt travels on the roller, the foam comes in contact with the surface of the disc. When the foam comes in contact with the
disc, it gets pressed against it with a normal force, causing friction. Here, the geometric arrangement of the belt drive and the disc roll is aimed to imitate a finger touching Braille letters in both left-to-right and right-to-left directions.

### 2.4.2 Real-time Experiment Results

For real-time experiments with the FMA controller, we considered a scenario including the following events ($E_1 - E_5$):

- $E_1$: There is no contact between the foam and the disc, and M1 starts to rotate clockwise (CW) at a constant speed.
- $E_2$: The first contact occurs where the belt drive moves in the same direction (CW) as M1, causing a friction between the foam and the disc.
- $E_3$: The contact is released between the foam and the disc.
- $E_4$: The belt drive starts to move at a faster speed in reverse direction (counter-clockwise, CCW) and a second contact between the foam and the disc occurs.
- $E_5$: The contact between the foam and the disc is released and M1 continues to rotate at a constant speed.

The implementation of the above scenario is realized using MATLAB/Simulink and Quarc Software on the Quanser setup shown in Figure 2.2 and explained in Section 2.4.1. An update rate of 500 Hz is used in the real-time implementation. Plots in Figure 2.6 from top to bottom represent the speed of M1, speed of the roller driven by M2 and the disturbance torque, respectively. The plots are divided into time intervals $t_0, t_1, \ldots t_8$ to better explain the results of the events explained above (see also Figure 2.5). Throughout the experiments, the speed of M2 is controlled at the desired reference speed, while the speed of M1 is controlled but is adapted to a different reference value depending on in which direction the foam applies friction (disturbance) on the disc that M1 is driving (see Figure 2.6).
Figure 2.5: Several images are captured from the experiment. These are numbered from $t_0$ to $t_7$ and are consistent with the time points shown in Figure 2.6. In the time intervals $[t_2, t_3]$ and $[t_6, t_7]$, during which FMA controller becomes active due to the contact between the foam and the disc, the rotation of motor-1 is colored in red thick arrow indicating the change in the speed due to the adaptation.

One important note here is that, since we know that our model $G(s)$ is not accurate, the disturbance observer may estimate $\hat{d}_r = \hat{d}_{r,0} \neq 0$. To prevent this, the setup is calibrated, simply by offsetting $\hat{d}_r$ by $-\hat{d}_{r,0}$ to zero the observer output, before the experiments. To further investigate this offset, assuming the plant transfer function is first order with uncertainties $\delta J_{eq}$ and $\delta B$ as described above, equations (2.4)-(2.7)
modify to (2.19)-(2.22), from which one can extract the transfer function of the estimated torque \( \hat{d}_r \) in terms of \( w_{r_1} \) being a step input and the external disturbance \( d_r \) being zero. Since the stability of the system under uncertainties is already guaranteed (Figure 2.4), one can then use the final value theorem to estimate the aforementioned offset, which is calculated as given in (2.23) using parameters on Table 2.1.

\[
\begin{align*}
\Omega_d(s) &= \Omega_{r_1}(s) + C_2(s) \hat{D}_r(s) \\
\tau(s) &= K_t C_1(s) (\Omega_d(s) - \Omega(s)) \\
\Omega(s) &= \tilde{G}(s) (\tau(s) + D_r(s)) \\
\hat{D}_r(s) &= C_2(s) Q(s) \left( G^{-1}(s) \Omega(s) - \tau(s) \right)
\end{align*}
\]  

\[
\hat{d}_{r,0} = \lim_{s \to 0} s \hat{D}_r(\Omega_{r_1}) = \lim_{s \to 0} s \frac{-\delta B K}{(Kk_p \delta B + 1)} 1 \frac{1}{s} = \frac{\delta B}{2\delta B - 1}. 
\]  

where \( \hat{d}_r(w_{r_1}) \) stands for the estimated torque disturbance \( \hat{d}_r \) calculated in terms of the input \( w_{r_1} \), when the external torque disturbance \( d_r \) is set to zero. Under the assumption that the uncertainty of the plant \( G \) is bounded, the offset \( \hat{d}_{r,0} \) calculated as in (2.23) depends only on the uncertainty in viscous damping coefficient of the plant \( G \).

Next, we investigate the time points marked with \( t_1..t_8 \) in Figure 2.6:

- At \( t = t_0 \), M1 starts to follow a step input of 5 rpm in CW direction and M2 moves in the same-direction as M1 causing the roller to rotate at a speed of 25.6 rpm in CW direction. Until \( t = t_1 \) there is no contact between the foam and the disc, therefore torque disturbance is around 0 Nm.

- At \( t = t_1 \), the foam comes in contact with the disc and gets pressed against it, causing the torque disturbance on M1 to grow. The disturbance has a negative sign
since the disturbance torque acts against the rotation direction of M1. The speed of M1 therefore automatically increases, as desired, in relation to the estimated disturbance.

- From $t = t_2$ to $t = t_3$ the roller continues to rotate and the foam remains in contact with the disc causing the disturbance torque to remain negative. During the contact, the disturbance torque does not remain constant but fluctuates around $0.035 \, Nm$. This is a result of the variation of the generated force at the contact point due to the uneven surfaces of both the disc and the foam, and also a result of the stick-slip friction that occurs during the contact.
• At $t = t_3$, the contact is released which causes a sudden jump in both of the speeds of M1 and the roller. The estimated disturbance torque immediately drops around $0 \, Nm$ since there is no contact anymore. The speed of M1 returns to its initial value of $5 \, rpm$ and remains at that speed in the absence of contact.

• At $t = t_4$, the roller is stopped. At $t = t_5$ it starts to rotate in CCW direction at a speed of $64 \, rpm$.

• At $t = t_6$, another contact with the foam occurs, and the disturbance torque starts to increase due to the force applied in the direction of the motion of M1. The speed of M1 therefore decreases, as desired, and as commanded by $C_2$, in relation to the estimated disturbance.

• The time interval $[t_6, t_7]$ during which the disc and the foam remains in contact is shorter when compared to the first contact occurred during $[t_1, t_3]$. This is due to the higher speed of the roller ($-64 \, rpm$) which causes a tangential velocity of $0.067 \, m/s$ at the point of contact which is higher than the tangential velocity of M1 ($0.031 \, m/s$), causing a force applied to M1 in the direction of its motion.

• At $t = t_7$, the contact with the foam is removed, and thus a sudden jump in both of the speeds of the M1 and the roller occurs due to removal of friction. The estimated disturbance torque returns to $0 \, Nm$ since no torque is applied to M1. M1 returns to its initial speed of $5 \, rpm$ and remains at that speed until the end of the experiment ($t = t_8$). During this time, the disturbance torque remains around $0 \, Nm$ in the absence of contact with the foam.

2.5 Conclusion

In this chapter, we proposed a finger-motion-adaptive (FMA) controller, its design and application on a machine-to-machine system. The FMA controller is implemented in real-time and its working principle is explained on the machine-to-machine system.
Within the FMA control framework, a disturbance observer is used to estimate the external disturbance to the machine and then adapt its speed in relation to the estimated disturbance with the help of a feedback controller, which makes it different than conventional disturbance observer based control architectures. Real-time implementation results showed potential for applying the designed FMA controller to a human-machine system.
Chapter 3

Evaluation of
Finger-Motion-Adaptive (FMA)
Controller through Human
Subjects Experiments with
Sighted People

3.1 Introduction

In this chapter, we perform the feasibility analysis of the finger-motion-adaptive (FMA) controller with sighted subjects. The controller is implemented on both a mechanical setup, and a touchscreen monitor. This controller does not need any sensors to be attached to the subjects’ hands, and functions only by estimating variations in certain physical variables in the mechanical setup and the touchscreen monitor, specific to how the user’s finger interacts with the machine/device. Since the feasibility of FMA controller is first studied with sighted subjects, to maintain the connection of the study
with Braille reading, Braille-inspired tasks were designed requiring subjects to perform

certain “tracking” activities by interacting with the machine/device with their fingers
at speeds consistent with Braille reading. In the design of these tasks, two criteria are
taken into account: a) task performance must be measurable via some metrics such that
differences, if any, with and without FMA control can be studied, b) tasks should require
similar horizontal finger motion as in Braille reading including backward direction, to
account for reversals.

This chapter starts with introducing the experimental design and protocol in Section 3.2.
Section 3.3 presents the outcomes of the human subject experiments, which are further
discussed in Section 3.4. Section 3.5 ends this chapter with concluding remarks.

3.2 Methods and Materials

We first designed a task in which subjects are asked to track some curves drawn on
a paper wrapped around a disc that either rotates at a constant speed or at speeds
adaptive to the subject’s horizontal finger motion. This setup (see left picture on Fig-
ure 3.1), which is analogous to rotating wheel Braille display, enables us to evaluate
FMA controller. On the other hand, in this setup, it is not possible to measure the
absolute position of the finger on the curves. Hence, another setup (see right picture
on Figure 3.1) was also designed to study FMA controller, this time in digital setting,
namely, on a touchscreen monitor where the absolute position of a subject’s finger can
be accurately recorded. In all the experiments, subjects are shown some curves that flow
from right to left, and are asked to track as many curves as they can while maintaining
accuracy by keeping their fingers on the curves.

Since our experiments are inspired by Braille reading, subjects’ performances in these
experiments are evaluated based on the metrics used to assess Braille reading speed,
which is measured as words per minute with accuracy [64–66]. To accomplish this
connection, the following steps were taken in the design of the experiments. First of
all, the experiments here are designed for sighted people, hence a curve tracking task is created where subjects need to move their fingers as visually impaired people would do during Braille reading. Curves include forward and backward tracking directions which respectively mimic forward reading and reversals observed in Braille reading. Each curve is thought as a Braille sentence, and the performance in the experiments with the disc (see Figure 3.1) is evaluated by the number of curves that are completely tracked from left to right by the subject. Curves are kept in appropriate lengths to be consistent with words per minute measure in Braille reading, so that subjects’ finger motion is continuous on a curve, again similar to what is known in Braille reading that readers do not lose contact with Braille letters even during reversals [47].

Accuracy is another important factor in measuring Braille reading speeds [65–67], since it is associated with text comprehension. We also use accuracy as a measure in the experiments with the touchscreen monitor, where we are able to record finger position of the subjects. The accuracy metric here, measured as lateral deviations from horizontal parts of the presented curves, is calculated based on how closely a subject’s finger has completed tracking these curves. This measure helps to penalize a subject’s performance when the subject tries to complete more tasks in a given time at the cost of sacrificing
accuracy.

### 3.2.1 System

The hardware used in the experiments are an industrial mechatronic drive unit by Quanser and the ST2220T 21.5” multi-touch monitor by DELL. Experiments carried out with the Quanser DC-motor and the touchscreen are referred to as mechanical experiment (ME) and touch screen experiment (TE), respectively, throughout the chapter. For the mechanical setup, the controller is implemented in Simulink, whereas the controller used on the touchscreen monitor is coded in Matlab.

**Mechanical Experiments (ME) with DC-Motor**

The goal in ME is to track with the finger as many curves presented on the rotating wheel as possible within the given time of 45s. Duration of the task is determined such that the subjects complete the task without losing interest, or encountering fatigue. A scaled-down version of the curve path drawn on the wheel is shown in Figure 3.2 with the original aspect ratio. As discussed in the previous section, left-to-right and right-to-left movements of the finger along the designed curves here are inspired from those found in Braille reading, where the parts of the curves folding backwards are considered as reversals. In order to design the length and frequency of the reversals, the study in [47] is investigated, where it is reported that reversals are observed often during Braille reading, almost in each sentence. The results of the cited study show that reversals ranged from 0.5cm to 7cm for the sentences used in those experiments. In light of this, in our experiments, we chose the length of the reversals around the average of these two values (3±2cm), and the frequency of the reversals is chosen to be approximately 1/6 of the total length of the curve path along the horizontal direction. Since during Braille reading activity, words and sentences are read sequentially in a given order, curves in ME are located on the paper such that they can be tracked only sequentially. Subjects
Figure 3.2: The curve path used in ME. For different experimental conditions the sequence of the curves are changed in order to prevent subjects from memorizing the order. The curve path is printed on a paper and wrapped around the rotating disc. Curves are given in the same aspect ratio as they are seen on the rotating wheel. This figure is reduced in dimension to fit the margins. As the wheel rotates clockwise, curves flow from right to left. Each curve is designed such that tracking the curve with the index finger imitates reading of a short Braille sentence. The parts of the curve with arrows pointing left mimic reversals observed during Braille reading. Subjects start tracking with the first curve (marked with red circle), and proceed with the next one. After completing seven distinct curves, they repeat tracking the same path. The red arrow at curve 7 guides the subject to proceed to curve 1, to repeat the path.
are provided help via sequential numbers on each curve indicating the tracking order. Each experimental condition has different sequence of curves to prevent learning.

Subjects take the following two experimental conditions in balanced order, each preceded by a short training session to familiarize the subjects with these conditions:

- **No finger motion adaptive algorithm (NAA):** The wheel rotates clockwise at a constant speed. A controller is used to keep the speed constant during the experiments. This controller is necessary especially when subjects touch the disc.

- **Finger motion adaptive algorithm (AA):** In the absence of finger contact with the wheel surface, the wheel rotates clockwise at the same speed as in the NAA. When the finger touches the wheel, the wheel speed is controlled based on the direction of the finger motion relative to the disc, as applied with normal pressure on the paper. Speed is increased upon the subject’s intention to track upcoming curves faster by moving his/her finger upstream of the curve flow, and decreased when the subject moves downstream. The algorithm also lets the subject to reverse the direction of rotation if the curve-path needs to be rewound back.

**Control Principles in ME**

The speed control of the wheel is implemented based on the disturbance adaptive controller as explained in our study in [63] where the controller was tested on a mechanical setup without any human subjects experiments. Specifically, the controller used here is able to regulate disc speed by sensing how much assistive/resistive torque is being exerted on the disc by the finger. One part of the controller has a predictor to sense this torque and its direction, and the other part regulates the voltage sent to the motor so as to regulate speed as demanded (see Chapter 2).

Based on the pilot studies, a curve flow speed of 6 cm/s, corresponding to 8 RPM of the disc is found to be comfortable enough to accomplish the given curve tracking tasks, and is therefore chosen as the reference speed in the experiments. Higher speeds were
avoided as this would cause subjects to track the curves only partially in NAA since subjects would not be able to control the disc speed.

**Performance Assessment in ME**

Subjects’ performance denoted by $P_{ME}$ is determined by the number of curves tracked *completely* from the beginning to the end of each curve. Since it is impossible to measure finger position in ME, performance is solely based on this measure.

**Touchscreen Experiments (TE)**

In TE, the goal of the subjects is to track as many curves as possible with sufficient accuracy within the given 90s time. Curves are displayed on a touch monitor which enter the screen from right hand side and flow toward left. Figure 3.3 shows a scaled-down version of the curve path keeping the original aspect ratio. The curves are displayed to the subjects within the window shown in the figure, fixed with respect to the screen, and whose size was determined so that the complete body of the curves fit inside it. The curves are not numbered as in ME, since there is no space restriction on the touch screen, and curves flow sequentially. Also, since finger strokes are continuously captured, subjects are allowed to release their fingers from the screen and re-touch/re-track the same curve. This is because, in TE, we have the flexibility to record finger positions in real time. The order of the curves and reversals are designed using the same guidelines as in ME.

Four experimental conditions are tested with the subjects as explained next, with each condition being preceded by a brief training session, and the first two conditions in balanced order:

- **No finger motion adaptive algorithm (NAA):** Predefined curves flow on the screen of the touch monitor at a constant speed from right to left. FMA control is inactive.
Figure 3.3: The curve path used in TE. The curves in the curve path are given in the same order as in NAA. For each condition the sequence of the curves are changed in order to prevent the subject from memorizing the order. The curve path repeats itself with the same sequence until the subject completes tracking within the given time. Curves are given in the same aspect ratio as they are seen on the touch monitor. This figure is reduced in dimension to fit the margins. Curves flow from right to left. As in ME, each curve is designed such that tracking the curve with the index finger imitates reading of a short Braille sentence. The parts of the curve that point to left mimic reversals in Braille reading.
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- **Finger motion adaptive algorithm (AA):** Unless there is contact with the screen, curve flow is at the same speed as in NAA. When the subject traverses the finger on a curve from left to right, then the speed of the curve flow is increased appropriately, enabling the subject to cover the curves faster. As the finger approaches to a corner on the curve, the speed is reduced back so that accurate tracking can be maintained while changing the direction of finger motion. Speed reduction also occurs when the subject wants to move on parts of the curve that point to the left, corresponding to reversals.

- **Finger motion adaptive algorithm with increasing speed (AA+):** Finger strokes of some subjects in AA reached the right half of the screen, which caused those subjects to wait for the upcoming curves. In order to provide subjects an opportunity to catch the curves toward the middle of the screen, thereby to be more efficient in performing the tasks, in AA+ experiments, the base speed of the curve flow was made variable within FMA control; it was automatically increased if the finger strokes reached the right half of the screen.

- **No finger motion adaptive algorithm, increased speed (NAA+):** The average speed of the condition AA+ is calculated for each subject, and then is set as the new constant baseline speed. FMA control is inactive. This condition is identical to NAA except it is performed at a higher baseline speed specifically selected for each subject.

**Control Principles in TE**

FMA controller used in TE consists of two parts: a position controller and a real-time nearest point search algorithm available in MATLAB (The MathWorks). The working principle of the position controller is as follows: When a subject’s finger interacts with a curve at a point $p_t$, two independent position controllers, one in x direction and the other in y direction, are used, with proportional gains denoted by $k_{px}$ and $k_{py}$. The controller first calculates the traveled distance along x- and y-coordinates relative to the first interaction point $p_t$, and these distances are introduced to the controller as errors
denoted by $\delta x$ and $\delta y$. Then, the horizontal position of the curve path is regulated based on the error $\delta x$ penalized by the controller gain $k_{px}$ whereas the regulation along vertical direction is performed only on the particular curve that the subject is interacting, and is calculated based on the error $\delta y$ penalized by the controller gain $k_{py}$. When the interaction with the touch screen is removed at any instance, then the position controllers are reset to zero, and curve flow speed resumes its baseline value.

The nearest point algorithm is employed to enhance the tracking speed of the subject, see Table 3.1 for definitions:

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_i$ $i = 1, 2..$</td>
<td>The region where the curve of interest is located</td>
</tr>
<tr>
<td>$b_{R_i l}$ $i = 1, 2..$</td>
<td>Left vertical boundary of region $R_i$ (dashed)</td>
</tr>
<tr>
<td>$b_{R_i r}$ $i = 1, 2..$</td>
<td>Right vertical boundary of region $R_i$ (dashed)</td>
</tr>
<tr>
<td>$C_i$ $i = 1, 2..$</td>
<td>Curve of interest</td>
</tr>
<tr>
<td>$p_k$ $k = 1..101$</td>
<td>Points on the curve</td>
</tr>
<tr>
<td>$s_{pk}$</td>
<td>Approximate slope of the curve at point $p_k$</td>
</tr>
<tr>
<td>$c$</td>
<td>Corner locations of the curve</td>
</tr>
<tr>
<td>$m$</td>
<td>Offset between curves in x direction</td>
</tr>
<tr>
<td>$p_t$</td>
<td>Point touched by the subject</td>
</tr>
<tr>
<td>$p_n$</td>
<td>Nearest point on the curve to $p_t$</td>
</tr>
<tr>
<td>$d$</td>
<td>Distance between $p_n$ and $p_t$</td>
</tr>
</tbody>
</table>

Table 3.1: Notations used for the implementation of FMA controller in TE

The curve path is divided into regions $R_i$ via vertical boundaries $b_{R_i}$ not seen by the subject (dashed in Figure 3.4). Each region $R_i$ contains a curve $C_i$ which was created in Matlab as an interpolating cubic spline that consists of points $p_k, k = 1..101$. Each curve $C_i$ is offset by a horizontal distance $m$. The slope $s_{pk}$ at each point $p_k$ of the
curves is calculated using $p_{k+1}$ in first order Taylor expansion. According to $s_{pk}$ value, $p_k$ is determined to be either on a vertical segment (if $|s_{pk}| > 0.34$), or on a horizontal segment of the curve. This range for slopes was determined in pilot studies based on what the subjects in general perceived to be horizontal or vertical finger motions.

The start and end point of each vertical part is considered as a corner $c$ of the curve. Region boundaries $b_{R_l}$ and $b_{R_r}$ for each curve $C_i$ are determined such that they are located on the left and right of the curve by an offset of $m/2$. For each touched point $p_t$ by the subject, the curve region $R_i$ containing $p_t$ is found in order to determine the active curve $C_i$ that is the closest to the touched point $p_t$. Then, using the nearest point search algorithm in Matlab, the closest point $p_n$ to the touched point $p_t$ is calculated. This way the error in position tracking can be calculated.

Following action is taken if $p_n$ is on a horizontal part of the curve: The gain $k_{px}$ of the position controller is increased such that the curve flows faster underneath subject’s finger. As $p_n$ approaches the corner $c$ of the curve, $k_{px}$ is reduced in real-time to its previous value in order to prevent subject’s finger to overshoot the corner of the curve and undesirably deviate from the curve. When $p_n$ is on the vertical part of the curve, the position controller gain $k_{py}$ is increased at each time step up to a predetermined value and kept at that value until the finger reaches a corner on the active curve.

**Performance Assessment in TE**

The performance of a subject in TE is measured using two metrics $P_{TE1}$ and $P_{TE2}$, determined respectively based on what percentage of the curves the subject is able to cover within the given time and how accurately the curves are tracked. In order to calculate the coverage percentage, nearest search algorithm is used to find the points on the actual curve that are the closest to the path tracked by the finger (see Figure 3.5). The closest points on the actual curve provide a measure of how closely the subject is able to track the actual curve. $P_{TE1}$ is calculated by the ratio of the number of unique closest points to the total number of points on the actual curve path. In order
to calculate $P_{TE_2}$, which is the normalized error, the total distance between the closest points and the tracked path is divided by the number of closest points.

![Sample Curve](image)

**Figure 3.5:** Evaluation of subjects’ performance in TE. Figure represents a sample curve and a trace path generated by the researcher. The actual points of the curve are colored blue whereas the generated trace path/points are seen in green. In order to evaluate subjects’ performance in TE, two metrics are studied: the accuracy and the percentage of the tasks accomplished within given time. Using a closest-point algorithm, the closest points on the actual curve for each point in the subject’s trace path are found. The sample in the figure shows the distances between those closest points and the tracked path colored in red. A good performance is represented in the first upper half of the curve where the distance between the closest points and user points are relatively shorter indicating that the user was able to track the path as close to the actual path as possible.

### 3.2.2 Ethics Statement and Participants

The study was approved by the Institutional Review Board at Northeastern University (IRB Protocol Number: 13-08-32). Experiments are announced through flyers that were hung around Northeastern University campus. The experiments were open to volunteering sighted and healthy subjects who were at least 18 years old with sufficient literacy level in English. No compensation is paid to subjects for their participation in the experiments. Prior to the experiments, written consent was obtained from each participant. The experiments are carried out with thirty sighted subjects among whom there were 12 females and 18 males with ages ranging from 23 to 33 years.
3.2.3 Protocol

After obtaining written consent, participants are asked to sit comfortably in front of the rotating wheel and touch monitor in ME and TE, respectively. They are instructed to use their index finger of their dominant hand to follow the curves, and rest their elbows on the table in case their arm gets tired. For ME, they are asked to move their fingers only in their field of view without leaning over to forecast the upcoming curves. The goal in the experiments is explained to the subject. A training session is completed by the subject prior to each experimental condition. The curve paths given in the training sessions are different than the curve paths used in the actual experiments. In both ME and TE, in order to study the effect of order of different experimental conditions, half of the subjects are given the NAA first whereas the other half start with the condition AA. Conditions AA+ and NAA+, when applicable, are taken subsequently. Moreover, the sequence of the curves is different in each condition to prevent learning. Each subject is given a NASA TLX survey after completing each condition, where subjects evaluated mental, physical, temporal demands, performance, effort and frustration by a score from 0 to 100. A questionnaire is completed by each subject after finishing the whole experiment. The questionnaire is aimed to determine if the subject had any issues adapting the AA condition and if s(he) had any recommendations on FMA controller. For TE, subjects are also asked to fill out a motion sickness questionnaire before and after the experiments. In ME, subjects’ hand movements are recorded with a camera upon their consent. These recordings/videos are used for the evaluation of subjects’ performance as a group.

3.2.4 Statistical Analysis

Statistical analysis is performed to study any significant differences in performance metrics between experimental conditions. The analysis is carried out using SPSS.
In ME, the difference scores $P_{ME}$ were normally distributed, as assessed by Shapiro-Wilk’s test ($p = 0.396$). Two-tailed paired-samples t-test is used to analyze statistical significance between conditions AA and NAA.

In TE, curve coverage performance scores $P_{TE1}$ for conditions NAA, AA, AA+ and NAA+ were not normally distributed as evaluated by Shapiro-Wilk’s test ($p < 0.05$, for score samples in all conditions). Since data transformation did not succeed in normally distributed samples, a non-parametric method alternative to the repeated measures ANOVA test, namely the Friedman test, is used for statistical analysis. Post-hoc comparison tests are performed with a Bonferroni correction for multiple comparisons. Error samples, $P_{TE2}$ are also found to have non-normal distributions for all conditions ($p < 0.05$, Shapiro’s Wilk). One-way repeated measures ANOVA test is used to determine any statistical significance in $P_{TE2}$ between all conditions. $P_{TE2}$ samples are log transformed to meet the normality and sphericity assumptions of the repeated measures ANOVA test. Normality and sphericity has been validated by Shapiro-Wilk’s and Mauchly’s tests, respectively. Post-hoc comparison tests with Bonferroni adjustment are performed to reveal any statistical significance between pairwise combinations of all conditions. As analyses were performed in logarithmic scale, results are reported as back-transformed means (geometric mean) with 95% confidence intervals.

In order to reveal any statistical significance in NASA TLX scores between different conditions, a two-tailed paired-samples t-test is performed in ME, and one-way repeated measures ANOVA tests are used in TE, where pairwise comparisons are evaluated by post-hoc tests with a Bonferroni correction.

The significance level for all statistical tests is set to $p < 0.05$. Values reported in the next section with $\pm$ represent mean $\pm$ standard error. Raw data can be accessed at [68] and the results presented in the next section are accepted for publication in [69].
3.3 Results

FMA controller helps to accomplish more tasks per time in ME

Subjects’ scores in ME are presented on Table 3.2. The values presented under attempt and success for conditions NAA and AA indicate how many curves subjects started tracking, and how many of these they completed successfully. Both conditions correspond to a success rate around 95%, where 5% failure rate is due to the fact that, within the given time, the last attempted curve was not completed.

The performance score $P_{ME}$ indicating the task completion percentage is calculated by normalizing the number of successfully tracked curves where the subject among the 30 that achieved tracking of the maximum number of curves is given the maximum score of 100 points. The comparison of $P_{ME}$ between NAA and AA shows that subjects completed 1.6 times more tasks in AA when FMA control was active. The two-tailed paired-samples t-test shows that task completion percentage $P_{ME}$ in AA with the mean of normalized score $73.1 \pm 2.4\%$ is significantly higher than in NAA with the mean of normalized score $46.3 \pm 0.4\%$, with an increase of $26.83\%$ ($t(29) = 11.15, p < 0.0005, d = 2.04$).

Figure 3.6: Mean workload metrics for different experimental conditions performed in ME. Results are based on NASA–TLX. Error bars represent standard error. Mental demand scores in NAA and AA are found to be statistically significant at the 0.05 level while no statistical significance is observed for the remaining workloads.
Figure 3.6 shows the NASA TLX results for conditions NAA and AA where the mean load for each task is higher in AA. While the mental demand is significantly higher in AA by a score of $10.2 \pm 3.6$ when compared to NAA (two-tailed paired-samples t-test, $t(29) = 2.8, p = 0.008$), variations in other task load metrics do not permit to draw any statistical significance.

**FMA control is used effectively for increased curve coverage in TE**

Results from TE are presented in Figures 3.7-3.8. Figure 3.7 shows the mean curve-coverage-percentage $P_{TE_1}$ for different experimental conditions. In order to calculate $P_{TE_1}$, the highest achieved curve-coverage-percentage is found among the four conditions (NAA, AA, AA+, NAA+), and is taken as 100 points, and all the remaining scores are normalized based on this value. Statistical analysis is performed using the non-parametric related-samples Friedman’s test due to the non-normal distribution of $P_{TE_1}$ scores, as assessed by Shapiro Wilk’s test ($p < 0.05$ for all conditions), and failed data transformation. Curve-coverage-percentage was statistically significantly different between different conditions (Friedman’s test, $X^2(3) = 79.56, p < 0.0005$). Post-hoc analysis is performed with two-tailed Bonferroni correction for multiple comparisons, and revealed statistically significant differences in $P_{TE_1}$ scores from NAA ($Mdn \pm SE = 54.6 \pm 0.7\%$) to AA ($Mdn \pm SE = 63 \pm 1.1\%$) ($p = 0.016$), as well as from NAA+ ($Mdn \pm SE = 79.6 \pm 2.2\%$) to AA+ ($Mdn \pm SE = 88.8 \pm 1.2\%$) ($p = 0.031$). When FMA controller is used with the increased base speed setting (AA+), subjects performed the highest scores, with significant differences in comparison to other experimental conditions (two-tailed Bonferroni correction for multiple comparisons, between NAA and AA+ $p < 0.0005$, and between NAA+ and AA+ $p = 0.031$).
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Figure 3.7: Median percentage of the curve path covered by the subjects for each experimental condition in TE. Error bars represent the standard error. Different letters on error bars indicate statistical significance in pairwise comparisons performed with Bonferroni post-hoc tests.

FMA control is used effectively without losing accuracy in TE

A one-way repeated measures ANOVA was conducted to determine whether there were statistically significant differences in lateral deviations, $P_{TE}$, between experimental conditions NAA, AA, AA+ and NAA+. $P_{TE}$ values were not normally distributed (Shapiro-Wilk’s test, $p < 0.05$ for all conditions). Hence, normality was achieved by log-transformation of the data. Sphericity assumption was met as assessed by Mauchly’s test, $X^2(5) = 8.62, p = 0.125$. One-way repeated measures ANOVA test is performed on the log-transformed data and showed statistically significant changes in lateral deviations $P_{TE}$ between conditions NAA, AA, AA+ and NAA+, $F(3, 87) = 11.46, p < 0.0005$, partial $\eta^2 = 0.35$. Figure 3.8 presents the mean lateral deviations of subjects’ fingers from the horizontal parts of the actual curve path, which are calculated as 1.84mm (95% CI, 1.65 to 2.05mm), 1.94mm (95% CI, 1.75 to 2.15mm), 1.97mm (95% CI, 1.8 to 2.16mm) and 2.24mm (95% CI, 2.05 to 2.5mm) for NAA, AA, AA+ and NAA+ conditions, respectively. Notice that the means presented in Figure 3.8 are calculated by the anti-log of the means of the log-transformed data, therefore representing the geometric means of the
original data. Pairwise comparisons between conditions are presented next, which are performed using post-hoc tests with a Bonferroni adjustment. The increase of 0.1mm in $P_{TE_2}$ from NAA to AA is found to be not statistically significant ($p = 0.446$), as well as the increase of 0.13mm from NAA to AA+ ($p = 0.242$). In other words, such deviations from the horizontal segments of the curves were not significantly different with increased average curve flow speeds in AA+ when compared to lower speeds in NAA and AA. However, accuracy dropped significantly as the curve flow speed is increased in the absence of FMA control in condition NAA+, where the mean deviation of the finger, $P_{TE_2}$ increased significantly by 0.27, 0.3 and 0.4mm when compared to NAA ($p < 0.0005$), to AA ($p = 0.012$), and to AA+ ($p = 0.01$). Since the vertical parts of the curves are used only to connect the horizontal segments, performance along vertical segments of the curves was not of interest, and was found to not show any statistical significance.

![Figure 3.8](image)

**Figure 3.8:** Mean lateral deviations from the horizontal parts of the curve paths in TE. Mean values are geometric means calculated by antilog of transformed data. Different letters on bars indicate statistical significance in pairwise comparisons performed with Bonferroni post-hoc tests.
Subjects perceived increased mental demand with FMA control

For each task subjects evaluated mental, physical, temporal demands, performance, effort and frustration via NASA TLX, where a workload score is ranged from 0 to 100. As seen in Figure 3.9, mental demand was lower in experimental conditions AA (18.5 ± 2.6) and NAA (19 ± 3.1) than in conditions AA+ (24.2 ± 2.6) and NAA+ (40.3 ± 3.4). With increased mental demand in AA+, the performance reaches higher value but noticeably decreases under the condition NAA+ in which the mental demand is the highest and the performance is the poorest based on $P_{TE_1}$ and $P_{TE_2}$. A one-way repeated measures ANOVA test revealed statistical significance in mental demand between conditions NAA, AA, AA+ and NAA+ ($F(3, 87) = 25.5, p < 0.0005$). Pairwise comparisons with a Bonferroni correction showed that the increase in mental demand from NAA, AA and AA+ to NAA+ is statistically significant (for all comparisons $p < 0.0005$), as well as from AA to AA+ ($p = 0.045$). Physical demand (PD), temporal demand (TD), performance (PF), effort (EF) and frustration (FR) are also found to be statistically significant between different conditions by one-way repeated measures ANOVA tests (PD: $F(3, 87) = 6.4, p = 0.001$, TD: $F(3, 87) = 6.14, p = 0.001$, PF: $F(3, 87) = 6.54, p = 0.0005$, EF: $F(3, 87) = 8.23, p = 0.001$, FR: $F(3, 87) = 5.97, p = 0.001$). Post-hoc tests with a Bonferroni correction for pairwise comparisons revealed that mental demand, physical demand and effort are significantly higher in NAA+ when compared to NAA, AA and AA+ (for all $p < 0.01$). The remaining three workloads, namely, temporal demand, performance and frustration showed statistical significance in some pairwise comparisons as reported in Figure 3.10.

3.4 Discussion

In this study, a finger-motion-adaptive (FMA) controller is proposed, tested, and evaluated with sighted subjects. Based on the experimental results and statistical analysis, we have the following observations and discussions:
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Figure 3.9: Average mental demand vs. performance graph for TE based on NASA–TLX. Pairwise comparisons with a Bonferroni correction showed that mental, physical demands and effort are significantly higher in NAA+, when compared to NAA, AA and AA+. See Figure 3.7 for significance in performance metrics.

ME results show that when curve flow speed related to wheel rotating speed varied adaptive to subject’s finger motion, rather than being at a constant value, subjects were able to track more curves within the given time. Since in AA it is possible to reduce the curve flow speed on reversals, and even reverse the curve flow direction if needed, it was unknown to us whether or not subjects would be able to complete as many tasks as they could in NAA. However, our findings show that, with little training, subjects used FMA control effectively in AA in a way to compensate for the time they lost at lower speeds, by accelerating the curve flow whenever they were comfortable.

One may argue that the reason subjects performed poorer in NAA in ME is that the pre-set constant curve flow speed for NAA is too high which may have caused subjects to fail tracking some of the curves. This is however not the case as seen from the
success/attempt rates on Table 3.2 for both AA and NAA conditions, where subjects were able to successfully complete approximately 95% of all the attempted tasks in NAA and AA conditions. This indicates that the constant speed in NAA as well as the base speed in AA were convenient for the subjects to complete their tasks.

When we inspect the performance levels $P_{ME}$ and the subjective workload assessment presented respectively on Table 3.2 and in Figure 3.6, we observe that the performance and the mean mental workload are both increased in the presence of FMA control. An
interpretation of this increase can be that subjects were more engaged and alert with the tasks when FMA control was active, causing increased attention and thus relatively higher mental workload which in turn helped subjects concentrate and perform better in AA. In other words, mental workload increase was sufficient enough to guide the users to increased performance, without overwhelming them in their tasks.

Although ME results indicate that subjects accomplished more tasks using FMA control, we wanted to further investigate whether the accuracy along the tracked path has dropped significantly in the presence of FMA control due to temporally increasing speeds. For this, we designed similar tasks but to be performed on a touchscreen monitor so that we could record finger positions of the subjects. The results obtained from TE were consistent with ME results, showing that subjects covered a higher percentage of curves when FMA control was active. The accuracy in the presence (AA) and absence (NAA) of FMA control did not differ significantly although AA on average had a higher curve flow speed than NAA.

While analyzing the results for NAA and AA, we noticed that the recorded finger positions of some subjects concentrated further on the right hand side of the screen. This indicated that at some time instants, subjects waited for the upcoming curves to enter the screen, which indicated inefficiency, and raised the question of whether or not subjects would be able to track the curves at a speed higher than the given base speed. In order for the subjects to catch the curves further to the middle of the screen, we designed another experimental condition AA+, a modified version of AA, where the initial curve flow speed is the same as the base speed in AA, but is increased if the finger position of the subject starts to settle toward the right half of the screen. In AA+, we tested whether the subjects would be able to take advantage of FMA control and cover a higher percentage of curves at a higher base speed than in AA and NAA. We also inspected whether there would be significant loss in accuracy along the horizontal direction due to higher base speed. After analyzing the results of AA+, we found that subjects performed significantly better in AA+ than they did in NAA and AA. Accuracy in the horizontal segments of the curves in AA+ did not differ significantly from NAA and AA.
either. Contrary to our expectation, accuracy did not drop with the increased speed in AA+, but almost remained the same when compared to AA (0.05% difference).

FMA control allows subjects to track curves faster on horizontal lines that are in left-to-right direction, while it automatically reduces the base speed as a reversal is approached so that finger tracking is accommodated. Although subjects are asked to complete tracking of each curve from start to end, and research personnel observed fair play, one concern here might be that subjects may still achieve high scores by tracking the curves only in the left-to-right directions, and skipping the reversals. This concern may exist in TE, since in ME, the performance $P_{ME}$ is evaluated based on full completion of the curves, without partial credits. To address this in TE, we investigated completion rates on reversals, Table 3.3. For this, each subject’s ability to touch as many points as possible on reversals are calculated as a ratio to all such points on reversals, up to the particular termination point in the experiments. As seen on Table 3.3, subjects were able to touch a large portion of the reversals presented to them (92% and 88% of all possible reversal points in AA and AA+, respectively), and hence subjects reflected this in their performance metrics.

After completion of experiments with conditions NAA, AA, and AA+ in a single session, during analysis of the collected data, the need has arisen to investigate whether or not subjects would be able to perform better than in AA+ if they were given the condition NAA but at a higher constant speed. For this, we designed the condition NAA+, and contacted the subjects to request for participation in an additional experiment with the condition NAA+, first preceded by a training session. All the same subjects agreed to participate. In NAA+, the finger-motion-adaptive controller was not active, and the average curve flow speed in AA+ for each subject was calculated separately, and set as the constant curve flow speed in NAA+. The results of NAA+ showed that the performance was significantly lower when compared to AA+, and the accuracy also dropped significantly with respect to the other conditions. When we compare the results of NAA and NAA+, we observe that there is a trade-off between the task completion rate and the accuracy. The increased speed in NAA+ helps subjects complete more
tasks when compared to NAA, however, it also causes considerably increased lateral deviations in the horizontal segments of the curves, sacrificing accuracy.

Overall, when we investigate the experimental results, we observe that subjects tend to benefit from FMA control to complete more tasks while maintaining accuracy. This is the case in both ME and TE. With regard to ME, subjects completed 1.6 times more tasks in the presence of FMA control. In TE, when FMA controller is used with increased speed setting (AA+), we reached the same performance factor of 1.6 when compared to NAA. This indicates that although the initial base speeds were the same for conditions NAA and AA+, in AA+ subjects took the opportunity to execute the tasks at higher speeds, without sacrificing accuracy in any noticeable way.

Some of the above findings can also be linked to Yerkes–Dodson law [70]. In TE, the performance increases with mental workload up to a maximum, and starts to decrease after that point in the presence of much higher mental workload. Results in Figure 3.9 are consistent with this law, where mental demand from NASA-TLX surveys is plotted with respect to performance. Increased performance and mental demand in AA+ indicates that subjects are more engaged with the tasks in AA+ with positive outcomes, however, they are overwhelmed with too much mental workload in NAA+ which causes them to perform worse in the given tasks. Statistical results clearly support this discussion. Pairwise comparisons with a Bonferroni correction are performed between different experimental conditions for workloads, and, mental, physical demands and effort found to be significantly higher in NAA+ when compared to NAA, AA, and AA+. These metrics between experimental conditions NAA vs. AA, and NAA vs. AA+ however did not show any statistical significance, while subjects’ performance were significantly higher in AA and AA+, when compared to NAA, as shown in Figure 3.9.
3.5 Conclusion

In this chapter, the feasibility of a finger-motion-adaptive (FMA) controller is assessed by sighted human subjects in experiments with finger-tracking tasks in a machine/device, inspired by Braille reading and “reversals”. Based on the experimental results and statistical analysis of performance metrics pertaining to task accuracy and task completion, it is found that in the presence of FMA control, subjects’ performance metrics associated with the tasks have significantly improved as supported by statistical analysis. FMA control in accordance with experimental results presented in this chapter shows potential for its further study with visually impaired subjects, and its utilization on a rotating wheel-type Braille displays, with the goal to enhance Braille reading experience by creating an adaptive device for human finger gestures.
Chapter 3. Evaluation of FMA controller through Human Subjects Experiments with Sighted People

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| Mean     | 8.4     | 7.9    | 93.5 | 13.1   | 12.4   | 94.9 | 46.3 | 73.1 |
| Std. error| 0.1    | 0.1    | 1.1  | 0.4    | 0.4    | 0.8  | 0.4  | 2.4  |
| t-test   |         |        |      |        |        |      | p<0.0005 |      |

Table 3.2: Curve tracking performance of subjects in ME.
Chapter 3. *Evaluation of FMA controller through Human Subjects Experiments with Sighted People*

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<td>Mean</td>
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<td>Std. error</td>
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Table 3.3: Reversal completion rate in TE.
Chapter 4

Active Disturbance Rejection Control (ADRC) and Pilot Testing with Blind Subjects

4.1 Introduction

In this chapter, the disturbance adaptive controller is redesigned in order to improve controller dynamics of the rotating wheel system. System identification tests performed in time and frequency domains to identify the model of the motor responsible to drive the wheel showed that the motor exhibits dead zone nonlinearity at low voltages and the motor response does not follow a linear trend while operating at speeds corresponding to average Braille reading speed of blind people. Since the response of the acquired model by system identification tests could not be verified by repeated experiments, active disturbance rejection control (ADRC) is implemented in order to deal with the unknown and unmodeled dynamics and to achieve satisfactory performance in creating finger motion adaptive dynamics.
In Section 4.2, we introduce the ADRC framework for the rotating wheel system, whose real-time experimental results are presented and discussed in Section 4.3. Section 4.4 studies tuning of the presented controller for human subjects and also presents pilot testing of the proposed controller with two blind subjects. A brief summary concludes this chapter in Section 4.5.

4.2 Active Disturbance Rejection Control of a First-Order System with Unknown Input Disturbance

ADRC is a method that performs an online estimation of the total disturbance (external disturbances, unknown and unmodeled dynamics combined), which is then compensated using the control law. Since ADRC does not require prior knowledge of the system model, it is an attractive control method. In principle, in ADRC the system model is expanded with a fictitious state variable representing the total disturbance, which is then estimated online by a state observer. This real-time estimation is then offset in the control law to simplify the control design process.

For the control problem at hand however, ADRC is not trivial. This is because the unknown external disturbance (user’s finger touch) must be separately estimated. The following approach has been developed to address this issue. Let us start with the dynamics of the rotating wheel system, which can be approximated by a first order model given by:

\[
\dot{w}(t) = g(w(t), u(t), t) + \alpha u(t) + d_e(t) = f(w(t), d_e(t), u(t), t) + \alpha u(t)
\] (4.1)

where \(w\) is the speed of the motor, \(g\) is a nonlinear smooth function representing the unknown system dynamics, and \(f(t) = g(t) + d_e(t)\) is the total disturbance comprising
of internal (unknown and unmodeled parts of the system) and unknown external disturbances, and \( \alpha \) is a constant to be designed. Here, \( d_e \) is introduced to the system by the user when s(he) touches the surface of the rotating wheel.

**When** \( d_e = 0 \).

The control mission when \( d_e = 0 \) recovers the original ADRC and is given as follows: design \( u = u(w(t)) \) such that \( |\text{error}| = |w_d(t) - w(t)| \leq M \) as \( t \to \infty \), where \( w_d \) is the desired speed and \( M \) is the finite error bound.

As per the guidelines of ADRC, we first create an extended state vector, denoted by \( x \), and given by \( x = [x_1 \ x_2]^T = [w \ f]^T \), where \( w \) is the output in (4.1), and the unknown nonlinear function is \( f = g \) since \( d_e = 0 \). The objective now is to estimate the state \( x_2 = f \) using an observer. For this, the following state space representation is utilized:

\[
\begin{align*}
\dot{x} &= Ax + Bu + E \dot{f} \\
y &= Cx
\end{align*}
\]  

(4.2) \hfill (4.3)

\[
A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} \alpha \\ 0 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 \end{bmatrix}, \quad E = \begin{bmatrix} 0 \\ 1 \end{bmatrix}
\]

where the nonlinearity \( f \) cannot be measured but can be estimated by an extended state observer (ESO)

\[
\dot{z} = Az + Bu + L(x_1 - z_1)
\]  

(4.4)

where \( z = [z_1 \ z_2] = [\hat{w} \ \hat{f}]^T \) is the state estimate vector, matrices \( A \) and \( B \) are the same as those in (4.2), and the observer gain vector \( L = [l_1 \ l_2]^T \) can be designed based on the well known principles of full state observers [62].

Using the estimated variables \( z_1(t) = \hat{g}(t) \) and \( z_2(t) = \hat{f}(t) \), we can implement the control law \( u \) in a way to eliminate the nonlinearity in 4.1. Assuming that the observer is effective, \( \hat{f} \to f \), which can be guaranteed with fast observer dynamics, this elimination
is possible by selecting
\[
u(t) = \frac{u_0(t) - \hat{f}(t)}{\alpha},
\]
which revises to
\[
\dot{w} = u_0
\]
in ideal conditions. Noting further that \( \dot{w} \) is the estimate of \( w \), \( \dot{w} \approx w \), we can then select \( u_0 \) as a proportional controller with gain \( k_p \),
\[
u_0(t) = k_p(w_d(t) - \dot{w}(t))
\]
which aims to vanish the error \( w_d - w \approx w_d - \dot{w} \) with an appropriate selection of \( k_p \). Consequently, closed-loop system (4.6)-(4.7) becomes:
\[
\dot{w}(t) \approx k_p(w_d(t) - w(t))
\]
which has a stable pole when \( s = -k_p < 0 \). Since (4.8) is a first-order process, the value of \( k_p \) can be calculated by the known relationship between the settling time \( t_s \) and the time constant \( \tau \) of the system, \( t_s \approx 4\tau = 4/k_p \).

---

1One can design a more sophisticated controller such as PID.
Next, using the bandwidth parametrization method [71], we can pick two identical observer poles $s_{eso1,2}$ and solve for the gains of $L$. This is done by pole placement method, where we equate the characteristic polynomial of the observer dynamics to the desired characteristic polynomial as follows:

$$ |sI - (A - LC)| = s^2 + l_1 s + l_2 = s^2 - 2s_{eso}s + s_{eso}^2 $$  \quad (4.9)

From (4.9), the observer gains are calculated as $l_1 = -2s_{eso}$ and $l_2 = s_{eso}^2$. For fast observer dynamics, in this study the observer poles are selected 3 times further to the left of the system’s stable closed loop pole at $s = -k_p$.

**When $d_e \neq 0$.**

The above framework cannot be directly implemented when one wishes to estimate $d_e$ and the nonlinearity $f$ in (4.1) at the same time, since both quantities are unknown. To the best of our knowledge, an ADRC implementation in this context has not been reported in the literature.

Ultimately, the objective is to estimate $\hat{f}$ so that we can form the finger-motion adaptive dynamics (see Figure 4.1). With this, we can determine how much the basespeed $w_{ref}$ must be varied by the adapted speed $w_{ad}$. Here, the basespeed $w_{ref}$ represents the average speed at which a task is accomplished, i.e., if the task is Braille reading, $w_{ref}$ corresponds to average Braille reading speed of the user, whereas the adapted speed $w_{ad}$ determines how much $w_{ref}$ should be increased/decreased to meet user’s needs based on the disturbance applied by user’s finger on the wheel, $d_e \neq 0$.

The challenging part of the above control problem is to extract $\hat{g}$ from $\hat{f}$ so that the adapted speed input $w_{ad}$ can then be computed. Since $d_e$ and $f$ are both unknown, here we propose to differentiate them in real-time, as follows:

1. Choose a design parameter $\alpha$ and build the control law as given in (4.5).
2. Select $k_p$ in (4.8) and calculate the observer gains using (4.9).
3. Measure $\hat{f}$ while $d_e = 0$ to find $\hat{g}$.

4. Offset $\hat{f}$ by $\hat{g}$ using $\hat{d}_e = \text{sign}(w)\hat{g}$ when $d_e \neq 0$.

5. Form the adapted speed as $w_{ad} = C(s)d_e$.

6. Calculate the desired speed as $w_d = w_{ref} + w_{ad}$.

In other words, we propose to use ADRC for identification purposes to calculate $\hat{g}$ (step 3), so that we can later on remove it from the control loop, and hence we can estimate $d_e$ (step 4). See Figure 4.1 for the block diagram representation of the control architecture.

Remark: We note that the above procedure takes a zero-order approximation of $g$ that is it identifies $g$ in steady state, which is $\hat{g}$, and uses this $\hat{g}$ value to offset it from $\hat{f}$ in order to estimate $d_e$. Further studies that identify higher order dynamics of $g$ can be implemented to enhance the dynamic response of the system.

### 4.3 Results

The results presented in the next subsections are accepted for publication in [72].

#### 4.3.1 Experimental Setup

The experiments are carried out on an industrial mechatronic drive unit by Quanser (shown in Figure 4.2). A cylinder is attached to one of the motorized shafts on the unit, which is loaded with an inertial disk. The wheel’s surface is used to display information to user based on the task to be accomplished. For instance, if the task is Braille reading, a Braille text is attached on the surface of the wheel. The shaft position is measured with an optical encoder available on the output shaft. The real-time implementation of the controllers presented in the following sections is performed using Simulink (The MathWorks). The integration method is selected as Euler with a sampling frequency of 500 Hz.
Chapter 4. ADRC and Pilot Testing with Blind Subjects

Figure 4.2: Quanser setup with the rotating wheel system used in the real-time pilot experiments with blind subjects

Figure 4.3: One-way ANOVA showed no statistical significance between mean values of internal disturbance $\hat{g}$ measured in steady state at different speed levels ($F(5,24) = 0.56, p = 0.732$).
Table 4.1: Calculated mean values of internal disturbance at different speed levels in steady state. M±st.err. stands for mean±standard error.

### 4.3.2 Internal Disturbance Estimated by ADRC

In order to control the motor speed in an adaptive way to human finger gestures, we need to separate the external disturbance applied by the human $d_e$ from the total disturbance $\hat{f}$ estimated by the extended state observer of ADRC. This can only be possible if the estimated disturbance $\hat{f}$ follows a certain pattern in the repeated experiments, when no external disturbance $d_e$ is acting on the system. The experiments performed in the absence of $d_e$ showed that $\hat{f}$ remains approximately constant in steady state, which we refer to, as the estimated internal disturbance, $\hat{g}$. Before we can remove $\hat{g}$ from the system, we need to prove that there is no significant difference between the mean values of $\hat{g}$ captured at different speeds when $d_e = 0$. For this, experiments are run at speeds of 0.1, 0.5, 0.8, 1, 1.5 and 2 rad/s (n=6, for each speed level), where $\hat{g}$ is measured for a duration of 60s in steady state. Moreover, since $\alpha$ affects the results, these means are recorded after $\alpha$ has been fixed. Speeds over 2 rad/s are not considered since those speeds are too high for accomplishing any Braille reading task displayed on the wheel’s surface.

One-way ANOVA is conducted next, to determine if the calculated mean values of $\hat{g}$ are different at different reference speeds. The mean values of $\hat{g}$ were normally distributed for speed levels, as assessed by Shapiro-Wilk’s test ($p > 0.05$), and there was homogeneity of variances, as evaluated by Levene’s test of homogeneity of variances ($p = 0.212$). One-way ANOVA showed no statistical significance between the mean values of $\hat{g}$ at different speeds (Figure 4.3, $F(5,24) = 0.56$, $p = 0.732$). The mean±standard error values of $\hat{g}$

<table>
<thead>
<tr>
<th>Speed levels [rad/s]</th>
<th>M±St.err. of $\hat{g}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>-11.9±0.49</td>
</tr>
<tr>
<td>0.5</td>
<td>-12.3±0.44</td>
</tr>
<tr>
<td>0.8</td>
<td>-12.7±0.76</td>
</tr>
<tr>
<td>1</td>
<td>-12.9±0.29</td>
</tr>
<tr>
<td>1.5</td>
<td>-12.7±0.30</td>
</tr>
<tr>
<td>2</td>
<td>-12.5±0.31</td>
</tr>
</tbody>
</table>
are calculated as given on Table 4.1, and for the experiments with FMA controller, \( \hat{g} \) is found to be \(-12.5\) by taking the mean of the values on the table.

Based on the above statistical analysis, we assume that the zero-order approximation of the internal disturbance \( g \) can be a starting point. Therefore, \( g \) can be removed from the closed-loop system in order to then estimate \( d_e \). Subsequently, this estimation is used to form the adapted speed as \( w_{ad} = C(s)\hat{d}_e = C(s)\text{sign}(w)(\hat{f} - \hat{g}) \).

Note that the statistical analysis presented above do not reveal any strong influence of speed on the estimation of \( g \). This does not mean that the rotating wheel dynamics functions independent of speed. It means that for the speed levels that have been conducted, the influence of the speed on the wheel dynamics in steady state does not strongly vary.
4.3.3 Experiments with FMA Controller using ADRC

The disturbance adaptive speed control of the system shown in Figure 4.1 has been implemented using the control structure discussed above. Following the methods presented in the previous sections, we selected $\alpha = 80$, $C(s) = 0.003$, $k_p \approx 40$ corresponding to a settling time $t_s$ of 0.1s and the observer pole locations 3 times further to the left of the closed-loop system pole, $s_{eso_{1,2}} = -120$, which yield the observer gains, $l_1 = -2s_{eso} = 240$ and $l_2 = s_{eso}^2 = 1440$. 

Experimental results are presented in Figure 4.4. Plots in this figure respectively demonstrate the disturbance-adaptive speed control, disturbance estimation, tracking error and a close-up of controlled speed. In the experiments, disturbance is introduced to the system by the research personnel by applying force on the rotating wheel’s surface. As the wheel rotates CW, disturbance is applied in both assistive and resistive directions of motor rotation to demonstrate the disturbance adaptive speed control. The estimated external disturbance introduced to the system can be observed in the top right plot in Figure 4.4. Notice that this plot does not represent the estimated total disturbance $\hat{f}$, instead following the methods presented in the previous section, it shows only the value of estimated external disturbance $\hat{d}_e$ applied to the system by the user.

Moreover, while the wheel rotates CW direction as seen in the first plot of Figure 4.4, rubbing the finger from left to right on the surface of the wheel causes a resistive motion against the motor rotation, and therefore estimated as negative disturbance, whereas a finger motion from right to left is estimated as a positive external disturbance, since it acts as an assisting motion to the motor during its CW rotation. Since the speed control is carried out based on the disturbance estimation, the same pattern as in the disturbance estimation is observed in controlled speed profile. Furthermore, we observe from the error plot that it remains bounded, and $\text{error} \leq |0.1|$ except at the peaks when the finger direction hence disturbance direction changes. The bottom right plot in Figure 4.4, zoomed-in shot of controlled speed, shows the instant when the finger-motion changes direction. In order to investigate the tracking performance of ADRC, we can
calculate the time difference between the peaks in this plot, which gives an approximate period of $13.33 - 13.27 = 0.06s$. The tracking occurs under $0.1s$, which is desirably fast, and the controlled speed does not exhibit noticeable overshoot. This is important in terms of perception felt by the user underneath his/her finger. An overshoot would cause undesired motion and lack of control with the finger.

4.3.4 Comparison between ADRC and PI-Control

In this section, we compare the tracking performance of ADRC and PI-control, which is given in the following form:

$$u(t) = K_p(w_d(t) - w(t)) + K_i \int_0^t (w_d(t) - w(t)) dt$$  \hspace{1cm} (4.10)
Both controllers are tuned based on the following performance criteria while no external disturbance is applied to the system: a) no overshoot should be present, b) settling time of the system should not exceed 1s.

Tuning the PI-controller with the Ziegler-Nichols heuristic method did not result in satisfactory tracking in terms of pre-determined criteria, which may be because the unknown model does not approximate satisfactorily a linear system. Therefore, tuning of the PI-controller has been carried out empirically. The tuned gains for the PI-controller are found as $K_p = 0.6$ and $K_i = 2.5$. Tuning of controller and observer gains of ADRC has been performed using the pole placement technique as discussed in the previous section. For the experiments, the settings used in Figure 4.4 are also used here for $K_p$, $l_1$ and $l_2$. Investigating the plots in Figure 4.5, we observe that results with ADRC converge to the desired trajectory faster than those with PI. The PI-controlled system produces an output with larger deviations around the reference trajectory. This variation can also be observed in error plots in Figure 4.5. While we also made efforts to improve the response speed with the PI controller, this led to overshoot in the system, and hence those cases are suppressed here.

Finally, note that, although the measured signals are noisy, approximate settling times for ADRC and PI can be observed from speed tracking close-up plots, where $t_s$ for ADRC and PI are respectively about 0.1s and 0.3s. Further evaluations on these controllers can be made with the integral of the squared controller error (ISE) and the integral of the squared controller effort (ISC) on Table 4.2. Based on these, ADRC regulated system response is found to be more satisfactory in speed tracking when compared to PI-control.

<table>
<thead>
<tr>
<th>Control Method</th>
<th>ISE</th>
<th>ISC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADRC</td>
<td>0.0086</td>
<td>0.230</td>
</tr>
<tr>
<td>PI</td>
<td>0.0252</td>
<td>0.264</td>
</tr>
</tbody>
</table>

Table 4.2: Controller effort and error for $t \in [0, 6]$ in Figure 4.5
A comparison between ADRC and PI-control has not been investigated while the finger-motion adaptation is active since estimating the external disturbance in the case of PI-control is not possible due to unknown plant dynamics.

4.4 Pilot Testing with Blind Subjects

Braille reading tasks are designed for pilot testing and performed by blind subjects on the rotating wheel system. With these pilot experiments, we aimed to identify any problems that we might have with the experimental design, hardware and the finger-motion-adaptive controller.

4.4.1 Tuning of the ADRC based FMA Control Parameters

The control scheme used in the pilot experiments was as demonstrated in Figure 4.1. As seen in this figure, the FMA control enters the system to generate the desired speed $w_d$ along with $w_{ref}$. For this, $w_{ad}$ creates a speed input varying around the baseline speed $w_{ref}$ to adapt to instantaneous finger motion changes during forward reading, and to slow down the system during reversals to help users catch a missed word. The varying speed input $w_{ad}$ is designed to be of different magnitude for forward reading and reversals, since during a reversal the baseline speed may need to be reduced to become negative to reverse the wheel rotation, whereas during forward reading it would be sufficient to adjust $w_{ad}$ within a boundary of $\pm20\%$ of $w_{ref}$. Although this may be implemented by using two different proportional controllers, one for forward reading, and another for reversals, there is one more condition that the controller $C(s)$ should satisfy. Since the amount of external disturbance $d_e$ applied by the user changes from user to user, and $w_{ad}$ depends on $d_e$, the controller $C(s)$ should form a speed input regardless of the differences in user-applied force. Therefore, here we use a gain scheduling based approach to generate the adaptive speed input $w_{ad}$. 
The gain-scheduled FMA controller automatically adjusts the gains based on the range of applied external force. Lookup tables are used in order to specify gain values as a function of external disturbance. Figure 4.6 represents the Simulink diagram used in the pilot experiments. The lookup tables used for gain scheduling for forward reading and reversals are shown in Figure 4.7, which represents the subsystem “adaptation” shown in Figure 4.6.
4.4.2 Preliminary Results and Observations on Pilot Experiments

To the best of our knowledge, no study exists in the literature that proposes the concept of finger-motion-adaptive Braille reading, hence there also exists no human subject testing on this topic. Although the idea of the rotating wheel design has been proposed 15 years ago, no human subject testing has been reported\(^2\). Because of this reason, before the experiments, we had no clue how subjects would interact with the rotating wheel when they would be introduced to the machine for the first time, and whether they would be able to read Braille on it while the text flows underneath their fingers. In order to prevent any potential issues, which could arise during the experiments, we carried out pilot experiments with blind volunteers.

The experiments are conducted with two blind volunteers who have been working as proofreaders at National Braille Press (NBP). For subjects’ convenience, we carried out the experiments at NBP. The pilot testing is conducted under the approval of the Institutional Review Board at Northeastern University (IRB Protocol Number: 13-08-32). Before the experiments, subjects listened to the audio version of the consent form. The experiments started after the written consent is signed by the subject in the presence of a witness. During experiments, in order to be able to analyze and study subject’s Braille reading in detail, we recorded subjects’ hand motions on camera upon their approval.

In the experiments, we asked subjects to read Braille sentences, which are taken from study [47] and consisted of low-frequency words. Here, with low-frequency words we aimed to attract reversals during Braille reading which would help us evaluate the real-time response and efficacy of the proposed controller based on changing finger dynamics of the subject. The Braille sentences are embossed on adhesive labeling tape using slate and stylus. The tape is cut at the end of each sentence, and attached on a wheel (diameter of \(d_{\text{wheel}} = 14.5\) cm) using the adhesive side of the tape. Twelve sentences fit on the wheel’s surface with two sentences on each row. Markers are placed between the

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\(^2\)Here, we mean that there are no human subjects experiments under approved IRB based on certain protocols, metrics and statistical analysis.
lines to simplify line switching during the experiments. These are prepared by punching a line of Braille dots on a small piece of labeler tape and are attached diagonally on the surface such that when perceived by the subject, they are aimed to direct subject’s finger to the beginning of the next sentence on the next bottom row. The picture in Figure 4.8 illustrates the experimental setup as well as the sentences embossed in Braille, and markers used for line-switching.

![Figure 4.8: Picture shows the rotating wheel used in the pilot experiments and Braille text wrapped around it as well as line switching markers placed in between the lines.](image)

Before the experiments, subjects’ average Braille reading speed in words per minute (wpm) is determined by measuring the time they spent to read a Braille text embossed on paper. The angular speed of the rotating wheel is set based on this measured reading speed. After analyzing the video recordings, our observations point out to the following facts and issues:

- Before starting with reading tasks, we asked subjects to explore the experimental setup with their hands. Prior to the experiments, subjects had no experience reading on a rotating wheel type Braille display before. Nevertheless, they did not
have any difficulty in reading the Braille text on the rotating wheel. Since subjects
read the given texts out loud, we were able to evaluate their reading accuracy. As
we increased the wheel rotation speed during reading, we observed that besides
reading on the rotating wheel comfortably, subjects even exceeded their average
wpm.

- Subjects were able to identify line switching markers on the wheel’s surface, how-
ever sometimes they missed the markers, which caused them to keep reading the
sentences on the same row. And in some cases, although they aimed to read the
next row, they skipped a line and proceeded reading from two lines below.

- The length of the Braille text was too short. And in the cases of missing lines due
to line switching problems, experiments finished too soon.

- Subjects mentioned that they perceived an unusual sensation towards the end of
each sentence, therefore, had difficulty in reading the last word of the sentences.
This can be explained as follows. The high tactile acuity on fingertips allows sub-
jects to distinguish the frictional changes during transition from paper to labeler
tape and vice versa. And the difference in the perception of surfaces with different
textures may be affecting subjects’ performance during reading.

- Since finger motion adaptive dynamics is implemented based on the estimation
of the external torque disturbance, slowing down of the wheel during reversals
is achieved only if a direction change occurs on the force applied on the wheel’s
surface. Therefore, in order for the rotating wheel to respond to finger motions
accurately, some pressure needs to be applied on the wheel during transitions from
left to right and right to left. During experiments, we asked subjects to pretend
like they missed a word and asked them to try to catch it while FMA controller
was active on the rotating wheel. By doing this, they would be able to explore
how much pressure they needed to apply during transitions from forward reading
to a reversal and vice versa. Although they tried to practice the transitions, this
method of training did not turn out to be very effective since after a while subjects kept reading in forward direction without practicing any reversals.

• While training reversals, instead of rubbing the finger from right to left with slight pressure, subjects pressed down vertically on the wheel without any swiping motion with the intention to slow down the wheel. However, this caused the wheel to speed up in the forward reading direction, which led to an undesired response. Due to these issues, in some cases we observed subjects having difficulty in reading the given text.

• After the experiments, subjects are asked to evaluate the efficacy of the FMA controller on a scale from 1 to 10, 1 being the most undesirable, and 10 being very satisfactory. Subjects ratings were 3/10 and 5/10. After the experiments, one of the subjects reported slight arm pain, but she indicated that this did not affect her Braille reading activity during experiments.

• According to subjects’ feedback, the pressure dependent feature of FMA control should be adjusted to better accommodate user’s needs. If possible, FMA control should be made more sensitive to small pressures applied by the finger, whereas it should be made less sensitive against large pressures. The wheel can be paused for a short duration during reversals. The rotating wheel should be positioned on a flat surface allowing the text to be read horizontally. As we asked subjects whether the changing dynamics of the wheel based on their finger motions annoyed them, they mentioned that they found FMA controller useful in catching any missed words.

Pilot testing aimed to reveal any issues we might have in the design of the experimental setup and the finger-motion-adaptive controller, therefore, above we mostly focused on the arising problems instead of our positive observations. In next chapter, we propose solutions to these issues and explain how we applied knowledge from pilot testing to full scale experiments.
4.5 Conclusion

In this chapter, we presented how ADRC framework can be adapted to differentiate two unknown disturbances, one due to finger touching on a rotating wheel and the other due to unknown/unmodeled rotating wheel dynamics. Repeated experiments and statistical analysis show that the unknown/unmodeled dynamics can be removed from the estimated total disturbance, which then allows to predict the disturbances associated with finger touching. With this prediction at hand, it becomes possible to regulate the speed reference accordingly for successful implementation of finger-motion-adaptive dynamics. Real-time experiments conducted for trajectory tracking while finger-motion adaptation is active, as well as for differences in trajectory tracking between ADRC and PI-control under no external disturbance demonstrate the efficacy of the control approach and that the control performance with ADRC is better when compared to PI-control in terms of reference tracking metrics.

Pilot testing is carried out with participation of two blind subjects. We presented a gain-scheduled FMA controller, which is utilized with ADRC to be used in the real-time experiments with human subjects. We report preliminary results and pilot study observations, which were successful in identifying the necessary modifications we needed to apply on the experimental design and the controller for the full scale experiments.
Chapter 5

Design of an ADRC based Switching Finger-Motion-Adaptive Controller

5.1 Introduction

In this chapter, taking into account human subjects’ feedback, we introduce a switching controller, which adapts to users’ finger-motion dynamics during Braille reading. This controller is designed based on what we have learned from pilot testing carried out with blind volunteers. Based on this knowledge, the finger-motion-adaptive controller presented in the previous chapter is redesigned with the aim to provide users with a better and more comfortable Braille reading experience on the rotating wheel. The designed switching controller is used in different experimental conditions and tested by blind volunteers as presented in the next chapter. This chapter is organized as follows. In Section 5.2, we discuss how we addressed the issues identified in pilot testing. Section 5.3
Chapter 5. Design of an ADRC based Switching FMA Controller

presents the design and structure of the switching FMA controller and explains its tunable features to customize Braille reading experience on the rotating wheel for each subject. Chapter ends with concluding remarks in Section 5.4.

5.2 Design Considerations

Our observations during pilot testing helped us to redesign the FMA controller as well as the experimental design and setup. Below we list and discuss the proposed solutions to the issues detected during pilot testing and explain the modifications carried out.

- We enlarged the wheel diameter. One of the reasons of switching to a wheel with a larger diameter was to have more space on the wheel’s surface which would allow putting a longer text, and the other was to increase the sensitivity of the system to human touch. The latter is helpful in terms of torque estimation based control, since the same amount of external force acting on a wheel with a larger diameter generates a larger torque on the system.

- Subjects had difficulty in switching lines by following the markers attached on the wheel’s surface. Therefore, in the new design we discarded the markers and instead we embossed the sentences on a continuous labeler tape, which was then wrapped around the wheel spirally. This aimed to also eliminate the awkward feeling subjects perceived due to frictional changes during transitions between paper and labeler tape.

- While reading Braille, blind people position their hands horizontally on the paper or the display, which is positioned horizontally on a flat table. Since this is the conventional way of reading Braille for the blind, and since on the rotating wheel subjects read by holding their hand in a vertical position, one of the subjects reported slight arm pain after completing pilot testing. Subjects recommended positioning the rotating wheel system in a horizontal configuration, and mentioned
that this would ease Braille reading from the rotating wheel. However, since placing the Quanser unit horizontally on the table might have caused the gravitational forces to affect speed control and could pose a safety concern, to fix this problem, we slightly leaned the setup unit toward subject so that subjects did not have to keep their hands vertically but at an inclined position.

- Subjects experienced some difficulty during reversals. When they wanted to do a reversal, instead of using their natural swiping motion toward left, they first tried to stop the wheel by applying a large amount of force on the wheel surface. However, this caused the system to spin faster instead of slowing it down. Based on these issues, subjects recommended to make FMA control less dependent on the applied force during reversals.

- In order to make training sessions more efficient and the working principle of the FMA controller easily understandable by the subjects, we labeled the finger motions needed for reading Braille on the rotating wheel, namely the left- and right-gesture. The descriptions of the gestures and their usage are discussed in detail in the next section. The Braille text used in the training sessions consisted of self-explanatory instructions, which guided subjects to practice these gestures.

Next, we present how we updated the FMA controller in the light of the above discussions.

### 5.3 Structure and Design of the Switching FMA Controller

The initial implementation of FMA control was based on gain-scheduling approach as discussed in Section 4.4.1. In order for FMA controller to function properly during reversals, this type of control requires the user to conserve the lateral force applied from right to left, until the leftmost location on the text that the user wants to travel to, is arrived. If finger is released from the wheel surface or swiped towards right, the system returns back to its baseline speed. System’s tendency to converge to the baseline speed,
when the pressure applied by the user was insufficient, was one the factors, which caused confusion in subjects’ perception of the finger motion adaptive dynamics. Therefore, we redesigned the adaptive controller $C(s)$ presented in Figure 4.1 as a switching controller, whose states are activated using specified finger motions, which we refer to as left- and right-gestures throughout the remaining of the text.

![Figure 5.1: Illustration of left- and right-gestures. The cylinder represents the rotating wheel, and the arrows on top show the rotation direction of the rotating wheel system. The pictures demonstrate how the gestures are used to switch between forward reading and a reversal.](image)

The left- and right-gestures can be defined as swiping or rubbing the finger respectively toward left and right while applying slight pressure on the wheel surface. The usage of these gestures are illustrated in Figure 5.1. While the wheel rotates CW, the user reads in forward direction. Whenever user wants the wheel to rotate backwards to catch a missed word, he/she uses the left-gesture to activate CCW rotation of the wheel. When the reversal is completed, in order to switch back to forward reading subject uses the right-gesture to activate the CW rotation of the wheel. Next, we introduce the Simulink model used in the experiments with the blind subjects and explain controller states enabling switching between forward reading and reversals and vice versa.

The Simulink model shown in Figure 5.2 is used for real-time implementation of switching FMA controller in the experiments with the blind subjects presented in Chapter 6. This model makes use of ADRC to control the speed $w$ of the rotating wheel. Here, FMA control is represented with the switching controller, which forms a desired speed $w_d$. A manual switch is available to activate/deactivate FMA controller. If FMA controller is deactivated, speed tracking input $w_d$ is set to a constant via a ‘step’ block.
The controller parameters associated with ADRC are selected following the methods presented in Section 4.2. These parameters are designed with an inertial disc and a wheel with a diameter of 22.3 cm attached to the motor shaft on the Quanser unit. ADRC is implemented by selecting the design parameter and settling time as $\alpha = 20$ and $t_s = 0.15$ s, respectively. The proportional controller gain corresponding to $t_s$ is calculated as $k_p \approx 26.7$, which leads to a closed loop pole at $s_{cl} = -26.7$. Selecting extended state observer poles three times further to left of $s_{cl}$ led to $s_{eso_{1,2}} = -80$, $l_1 = -2s_{eso} = 160$ and $l_2 = s_{eso}^2 = 6400$.

The working principle of the switching controller is described using the stateflow diagram illustrated in Figure 5.3. Definitions of the parameters used in the switching controller are given on Table 5.1. Here, $w_{bd}$ and $w_r$ respectively represent baseline speed and the speed set for reversals. Both speeds are determined based on user’s comfort in Braille reading and during reversals. According to the diagram, until the user touches the
rotating wheel, system state is set to ‘NO MOTION’, where the desired speed is $w_d$.

As the user touches the wheel, the absolute value of external disturbance $d$ starts to rise. Once it exceeds a predetermined $d_{\text{min}}$, the state is switched to ‘TRANSITION’, where $w_d$ is set to zero. As its name implies, this state serves as a transition between the states ‘REVERSAL’, and ‘RAMP’. While in this state, if the user chooses to use the right-gesture, state ‘RAMP’ gets activated. In this state, function ramp() is used to generate $w_d$, which is illustrated in Figure 5.4 a). The ramp input is created by taking the integral of a constant $m_{\text{ramp}}$, which at the same time determines the slope of the ramp. Each time ‘RAMP’ state is activated, a rising signal ‘reset’ triggers the integrator

\begin{figure}
\centering
\includegraphics[width=\textwidth]{stateflow_diagram.png}
\caption{Stateflow diagram of switching FMA controller shown in Figure 5.2}
\end{figure}
### Notation

<table>
<thead>
<tr>
<th>Notation</th>
<th>Parameter Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$</td>
<td>External disturbance applied by the user</td>
</tr>
<tr>
<td>$d_{\min}$</td>
<td>Minimum external disturbance to initiate system motion</td>
</tr>
<tr>
<td>$w_d$</td>
<td>Desired speed</td>
</tr>
<tr>
<td>$w_{bl}$</td>
<td>Baseline speed representing user’s comfortable Braille reading speed</td>
</tr>
<tr>
<td>$w_r$</td>
<td>Reverse speed</td>
</tr>
<tr>
<td>$m_{\text{ramp}}$</td>
<td>Slope of ramp</td>
</tr>
<tr>
<td>$\text{init}_{\text{ramp}}$</td>
<td>Initial value of ramp</td>
</tr>
<tr>
<td>$b_1$</td>
<td>Disturbance threshold for left-gesture</td>
</tr>
<tr>
<td>$b_2$</td>
<td>Disturbance threshold for right-gesture</td>
</tr>
</tbody>
</table>

**Table 5.1:** Stateflow parameters shown in Figure 5.3

**Figure 5.4:** Simulink functions used in the stateflow diagram of switching FMA controller (Figure 5.3). The model shown in a) on the left hand side illustrates the ‘ramp()’ function and b) on the right hand side shows the ‘gainscheduling()’ function.

reset to be started at an initial value $\text{init}_{\text{ramp}}$, which is enabled via the external source of the integrator. Once $w_d$ reaches $w_{bl}$, ‘FORWARD READING’ state is activated, where $w_d$ is created by the gainScheduling() function, which is depicted in Figure 5.4 b). The function makes use of a lookup table to create a disturbance based adaptive speed input to be added to $w_{bl}$ to generate $w_d$. While in state ‘TRANSITION’, if the user chooses to use a left-gesture, state ‘REVERSAL’ gets activated. In this state, $w_d$ is set to $w_r$, which initiates the wheel rotation in CCW direction to help the user with the reversal motion. Switching conditions between states are given in Figure 5.3.
5.3.1 Real-time Implementation of the ADRC based Switching FMA Controller

Real-time experiments are carried out to demonstrate the operation of the switching FMA controller and state transitions discussed in the previous section. Experiments are performed with a wheel of diameter $d_{\text{wheel}} = 22.3$ cm and control parameters given in Section 5.3. During the experiments, an external force is applied to the wheel by the research personnel to activate different states of the controller. A part of the results is presented in Figure 5.5. We first investigate system’s response to a left-gesture, which is presented in the left hand side of the figure. For forward reading of a text on the wheel, the rotation direction should be CW, in which wheel speed $w$ is considered positive. Therefore, time interval $[10, 12]$ corresponds to reading in forward direction, where the applied force on the wheel acts in the opposite direction of wheel rotation and therefore estimated as negative as seen in the figure. During this time, switching controller’s state is set to ‘FORWARD READING’. In the experiment, baseline speed is selected as $w_{bl} = 0.5$ rad/s, hence $w$ tracks $w_d = w_{bl}$ during $t = [10, 12]$. After $t = 11$ s, we observe the increase in the estimated disturbance, where the research personnel moves her finger on the wheel from right to left to mimic a left-gesture. As the disturbance exceeds a predetermined threshold, which is selected here as $b_1 = -0.9$, the desired speed $w_d$ is set to the reversal speed $w_r$ and state is changed to ‘REVERSAL’. Based on subjects’ feedback during pilot testing, $w_r$ is designed to be a constant value, which lets the wheel rotate CCW to rewind the text for a reversal and whose value is to be customized according to each subject to meet his/her comfort level during reversals. During pilot testing both subjects mentioned that they would prefer a $w_r$, which is lower than their forward reading speed. Therefore, here $w_r$ is selected as $-0.3$ rad/s. All the parameters used in this experiment are chosen for illustration purposes only, actual values are obtained in the training sessions of the experiments carried out with blind subjects and presented in the next Chapter. We observe that after using left-gesture, the wheel keeps rotating CCW at $w_r$ until a right-gesture is used at approximately $t = 16.7$ s. With the right-gesture, estimated external disturbance $d$ starts to decrease.
due to change of force direction applied on the wheel’s surface. As $d$ drops below the predetermined threshold of $b_2 = -1.1$, state changes to ‘RAMP’, where $w_d$ starts to follow a ramp input, whose slope $m_{ramp}$ and initial value $init_{ramp}$ are selected as 0.2 and 0, respectively. After following the ramp input, as $w$ reaches $w_{bl}$, state changes to ‘FORWARD READING’ and $w$ settles around $w_d = w_{bl}$. Here, scheduled gains are selected as 0, therefore $w$ tracks a constant $w_d$ after $t = 19.3$ s. Next, we discuss how the controller dynamics is effected by the tunable parameters $b_1$, $b_2$, $m_{ramp}$, and $init_{ramp}$.

The selection of controller parameters $b_1$ and $b_2$ is important in terms of tuning the responsiveness of the switching FMA controller, since any attempt by the user for reversals is detected based on these values without having a measurement of finger position. In a system, where a measurement of external disturbance is not available but it is estimated, several methods are possible for detecting reversals. One of them is to detect a reversal based on the sign-change of the estimated disturbance. This can be performed by detecting zero-crossings of external disturbance after removal of the internal disturbance from the system as suggested in Chapter 4. Another technique is to measure the internal disturbance $g$ of the system corresponding to CCW and CW rotation of the wheel, to determine the interval $[-g, +g]$, in which external disturbance can be assumed zero.

![Figure 5.5: Experimental results with the switching FMA controller](image-url)
while any values outside the interval would indicate user-applied force. Although these methods are valid and tested through experiments, in order to realize a fast responding controller upon a reversal, it is necessary to detect it even before estimated external disturbance exhibits a zero-crossing. While forward reading, external disturbance \( d \) is negative and remains below a certain value due to applied force on the wheel. However, whenever the user intends to do a left-gesture, \( d \) starts to rise towards zero, which can be taken as a clue of user’s intention to do a reversal. This is how we implemented the switching controller in this experiment, where we set the reversal detection boundary as \( b_1 = -0.9 \). One can better understand the importance of selection of this boundary by investigating the plots presented in Figures 5.5 and 5.6. As we measured the internal disturbance of the system under no external applied force, we found that it remains around 3 as shown in Figure 5.6 with \( d_2 \). If we would have implemented the reversal detection based on the sign-change of the external disturbance as discussed previously, we would have to wait until the estimated disturbance overcomes the internal disturbance to ensure that it is now in the positive range indicating finger motion from right to left. In our experiment, this corresponds to the data point \([X=12.21, Y=3.022]\) on the estimated disturbance plot in Figure 5.5. However, if we had selected \( b_1 = 3.022 \), there would be a time lag of \( \Delta t \approx 12.21 - 12.06 = 0.15 \) s in the reversal detection. This would cause the system to respond sluggishly to finger motion of the user.

Detection of right-gesture, in other words switching from a reversal to forward reading, is implemented using the same logic. Whenever a right-gesture is performed by the user, the estimated disturbance starts to decrease from its positive value. In this experiment, we set the threshold for detection of a right-gesture as \( b_2 = -1.1 \). From Figure 5.5 we observe that the switching from reversal to forward reading occurs as \( d \) crosses \( b_2 \) boundary at \( t = 16.75 \) s. Again here, without waiting \( d \) to overcome the internal disturbance (\( \hat{g} \approx -3 \)) the controller state is updated. The selection of \( b_2 \) boundary above \( \hat{g} = -3 \) makes it possible to detect the right-gesture in advance by \( \Delta t \approx 16.88 - 16.75 = 0.13 \) s.

We want to note that an important fact, which facilitated the realization of the controller
with the above given gesture-thresholds, is that during Braille reading all movements are made while in contact with the reading surface [48]. In the contrary case, where contact with the surface would be released to make a reversal, disturbance based detection of a reversal would be only possible after the user comes in contact with the surface again. Since this would cause latency in state transitions, it would also affect the response of the switching controller. However, Braille reader’s finger remaining in contact with the surface while reading allows us to develop a fast-acting user adaptive controller as presented here. Another fact we should mention is that in order to be able to select \( b_1 \) and \( b_2 \) as discussed above to create a fast-responding controller, we omitted a state to detect the finger release of the user. In order to detect it, we need to assume the estimated disturbance interval of \( d = [-3, 3] \) as no touch occurs on the wheel and set the speed of the wheel \( w_d = 0 \) \( \text{rad/s} \). However, in the experiments with blind subjects, we asked them to continuously read some passages, where they did not need to release their finger from the surface. Therefore, lack of a state for detecting finger-release was not important in terms of human subject experiments. However, we want to note that adding this feature is trivial.

In the experiments with the blind subjects, presented in Chapter 6, the same values presented in this section for \( b_1 \) and \( b_2 \) are used and controller parameters \( w_{bl}, w_r, m_{ramp}, \) and \( init_{ramp} \) are tuned according to subjects’ needs prior to experiments. Since subjects’ average Braille reading speed varies, the baseline speed \( w_{bl} \) is determined according to each subject. Subjects prefer different wheel speeds during reversals; therefore, the speed \( w_r \) at which the wheel rewinds the text during reversals, is also determined based on subject’s preference. The controller parameter \( m_{ramp} \) enables a smooth transition from a reversal to forward reading by adjusting the slope of the ramp to be followed during this transition. Choosing \( m_{ramp} < 0.5 \) creates a pause effect before the controlled wheel speed returns to the baseline speed \( w_{bl} \) providing the user with a gradual text flow speed. In case subjects prefer a more rapid transition to forward reading, the initial value of the ramp can be adjusted by \( init_{ramp} \). Selecting \( init_{ramp} \) larger than zero lets the controller converge to \( w_{bl} \) in shorter time by increasing the step difference in \( w_d \) during transition.
from reversal to forward reading.

![Graph](image)

**Figure 5.6:** Real-time experimental results with wheels of different diameter. Plot represents control speed and estimated disturbance for two distinct experiments carried out with wheels of diameter 14.5 cm and 22.3 cm. Parameters \([w_1, d_1]\) and \([w_2, d_2]\) are captured in the experiments with the small and large wheel, respectively.

### 5.3.2 Effects of using Wheels of Different Size and Weight

Real-time experiments are carried out to compare the effects of two different sized wheels on the disturbance estimation and speed control. The wheel with smaller diameter \((d_{\text{wheel}} = 14.5 \text{ cm})\) is the same wheel used in the experiments in Chapter 4. The larger wheel with a diameter of \(d_{\text{wheel}} = 22.3 \text{ cm}\) is made from the same material as the smaller wheel and weighs three times heavier. Using the larger wheel we were able to wrap 1.6 times more text around the wheel in the experiments. Other advantages of increasing the size and weight of the wheel are investigated with experiments, which have been carried out with each wheel. In both experiments, speed is controlled to track a step input under no external disturbance while FMA control is inactive. Both experiments are implemented using the same system parameters as above, except \(\alpha\).

We observed that change in the system’s physical properties necessitated to adjust \(\alpha\). Experimental results for controlled speed \(w\) and estimated internal disturbance \(d\) are demonstrated in Figure 5.6. Results obtained with the smaller wheel are shown with \(w_1\) and \(d_1\), whereas \(w_2\) and \(d_2\) correspond to results with the larger wheel. Comparison of controlled speeds shows that \(w_2\) varied less around the reference \(w_d\), which in turn
reduced the measured error between the input and output speed. Estimated internal disturbances $d_1$ and $d_2$ both exhibited oscillatory behavior around a value. However, the amplitude of oscillations in $d_2$ was much smaller when compared to $d_1$. This is important in terms of disturbance based control decisions, which are more reliable if based on a less noisy signal, in this case $d_2$. In summary, with the larger wheel a better speed tracking performance is achieved, and noise in disturbance estimation is reduced greatly.

5.4 Conclusion

A switching FMA controller is proposed with the aim to improve controller dynamics for speed adaptive rotating wheel system whose mathematical model is not available. Real-time implementation showed successful estimation of the external disturbance introduced to the system by the user’s touch on the wheel. Finger gestures available to user by FMA control are introduced and explained. Discussion has been made on how the proposed controller allows user-specific tuning for enhanced Braille reading experience.
Chapter 6

Evaluation of
Finger-Motion-Adaptive
Controller through Human
Subjects Experiments with Blind
Volunteers

6.1 Introduction

This chapter presents the design, evaluation and results of the Braille reading experiments carried out with blind subjects. Based on the experimental results and the feedback of subjects participated in the experiments, we aimed to answer the following questions: Can blind people read Braille text while it flows underneath their fingers on a rotating wheel system? How does the finger-motion-adaptive (FMA) control contribute to Braille reading on a rotating wheel system? Does having FMA controller inactive during Braille reading affect reading accuracy?
The remaining sections are organized as follows. Section 6.2 explains mechanical system used in the experiments, experimental design, participants, and experimental procedure. Results of the experiments are presented in Section 6.3 and are further discussed in Section 6.4.

6.2 Methods and Materials

One of the aims in developing the FMA controller was to provide blind users with a novel, and user-adaptive Braille reading experience. Therefore, the efficacy of FMA controller is evaluated with the help of blind subjects through Braille reading tasks. Next, we present information about subjects and their Braille reading characteristics and discuss the mechanical system used in the experiments and details of experimental design.

6.2.1 Ethics Statement and Participants

Before recruiting participants for the experiments, we took into consideration the fact that the rotating wheel design utilizing FMA controller presents a nonconventional reading experience for blind people, where users interact with the experimental setup in a different way when compared to standard Braille reading devices. Based on this fact, we decided that the efficacy of FMA controller can be best tested and evaluated by advanced Braille readers. This was the most logical first step because we did not want other factors, such as lack of Braille reading experience, to mask our understanding of how FMA control works. Therefore, we have collaborated with the National Braille Press (NBP), where experiments were announced among blind people working at NBP as proofreaders. The experiments were open to volunteering blind subjects, who are Braille literate and at least 18 years old with sufficient literacy level in English. Six blind people volunteered for participating in the experiments, which are carried out at NBP for the convenience of volunteering subjects. All the participating subjects have
learned Braille at a very early age and have been reading Braille for at least 20 years. Among the six subjects (4 females and 2 males), five of them completed all the experimental conditions, and their ages and other information related to their Braille reading are given in Table 6.1.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>S₁</th>
<th>S₂</th>
<th>S₃</th>
<th>S₄</th>
<th>S₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>29</td>
<td>24</td>
<td>65</td>
<td>24</td>
<td>34</td>
</tr>
<tr>
<td>Years of Braille reading experience</td>
<td>26</td>
<td>20</td>
<td>60</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Average uncontracted Braille reading speed $v_{p_{avg}}$ in wpm</td>
<td>77</td>
<td>71</td>
<td>64.2</td>
<td>45.5</td>
<td>72.8</td>
</tr>
<tr>
<td>Hands used during reading Braille</td>
<td>left</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>right</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>both</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Dominant hand used for reading Braille</td>
<td>left</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>right</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fingers used during reading Braille</td>
<td>single</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>multiple</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1: Information collected from blind subjects in pre-experiment surveys

In order to conduct experiments with blind subjects, the study was approved by the Institutional Review Board at Northeastern University (IRB Protocol Number: 13-08-32). No compensation is paid to subjects for their participation in the experiments. Prior to experiments, each participant listened to an audio version of the consent form, and written consent form is signed by the participant in the presence of a sighted witness, as well as the witness himself.

6.2.2 System

For the experiments, the Quanser setup introduced in the previous chapters is used. As discussed in Chapter 5, the wheel with diameter $d_{wheel} = 14.5\ cm$ used in the pilot experiments is replaced with a larger wheel with diameter $d = 22.3\ cm$. This
modification allowed us to use a Braille text that is 1.6 times longer than the one used in pilot experiments. Using a larger wheel also contributed to a more sensitive way of estimating the external disturbance as discussed in detail in Section 5.3.2.

The rotating wheel speed is controlled using ADRC based switching FMA controller, which is presented and discussed in detail in Chapters 4 and 5. For real-time implementation of the controller the Simulink model shown in Figure 5.2 is used, where the controller has been updated at a frequency of 500 Hz by Euler’s method. Tuning and selection of the ADRC based FMA controller parameters are performed as discussed in Chapter 5. The selected and calculated values are as follows: \( \alpha = 20, t_s = 0.15 \, s, \)
\( k_p = 26.7, s_{cl} = -26.7, s_{eso,2} = -80, l_1 = 160, l_2 = 6400, b_1 = -0.9, \) and \( b_2 = -1.1. \)

Remaining parameters of the FMA controller, namely \( w_r, \ init_{ramp}, \) and \( m_{ramp}, \) are customized for each subject, which are reported in Section 6.3.1.

![Quanser setup used in the experiments with blind subjects. Setup components marked on the picture are explained on the right hand side with matching letters.](image)

**Figure 6.1:** Quanser setup used in the experiments with blind subjects. Setup components marked on the picture are explained on the right hand side with matching letters.
6.2.3 Experimental Design

As discussed in Chapter 1, we know from literature that during Braille reading finger motions do not remain constant, however change frequently. These finger motions include reversals, which are performed by swiping the finger from right to left in order to position the finger at the beginning of a previously read word to complete its processing for full comprehension. FMA control has been developed taking into account these reversal motions. Therefore, with the human subject experiments, we aim to explore how the rotating wheel system responds to subjects’ changing finger motions during reversals in real-time. This can be investigated by asking subjects to read a Braille text displayed on the rotating wheel and observe the system response during any potential reversals. Although the future version of the rotating wheel system is envisioned to present a user-adaptive refreshable Braille display, producing such a device is not the main interest of this study. Instead, here we focus on showing the proof of concept of FMA controller. Since we do not have any refreshable cells available on the rotating wheel, a static text is displayed to the user by wrapping it around the wheel. Therefore, there is an upper limit of the Braille text length that can be used in each experimental condition, which also determined the difficulty level of the Braille text displayed to the subjects during the experiments. In the design of the experiments, one of the challenges is to create a text, which has the potential to invite reversals, with limited number of words. Based on this, we borrowed a text from a medical journal which contained low frequency words. In order to induce more reversals, some of the high frequency words are replaced with low frequency words, some of which were intentionally not consistent with the context.

In order to evaluate the efficacy of FMA control in Braille reading, different experimental conditions are designed. In each experiment, subjects are asked to read the given Braille text out loud and focus on the reading accuracy rather than the reading speed. Prior to experiments, subjects are given training sessions to practice reading on the rotating wheel as well as left- and right-gestures of FMA controller, which are introduced in
Section 5.3. The texts to be read by the subjects in the first two experimental conditions are different from each other to prevent learning. Following experimental conditions are taken by the subjects in the given order:

- **Finger Motion Adaptive Dynamics (AD):** Subject’s finger is positioned on the start of the Braille text. Experiment starts as the wheel begins to rotate in clockwise (CW) direction. The wheel speed is set to the baseline speed $w_{bl}$, which is determined based on subject’s comfortable reading speed (determination of this speed is discussed in detail in the following sections). The ADRC based switching FMA controller, presented in Chapter 5, is used to adjust the wheel speed in real-time adaptive to subject’s finger gestures during Braille reading. The experiment ends when the subject completes out loud reading of the given Braille text.

- **No Finger Motion Adaptive Dynamics (NAD):** Subject’s finger is positioned on the start of the Braille text. Experiment starts as the wheel begins to rotate in clockwise (CW) direction. FMA control is deactivated and the wheel speed is kept constant at the baseline speed $w_{bl}$ corresponding to subject’s comfortable Braille reading speed (determination of this speed is discussed in detail in the following sections). The experiment ends when the subject completes out loud reading of the given Braille text.

- **Finger Motion Adaptive Dynamics - 2nd Condition (AD-2):** This condition is identical to AD, except the same Braille text is used as in NAD.

**Pre-training session - Determination of subjects’ average Braille reading speed**

In order to determine the average Braille reading speed of each subject, we asked him/her to read an article borrowed from the daily newspaper ‘The New York Times’ (NYT) and measured the time they needed to complete reading the article. The first two
paragraphs of the article are embossed on a Braille paper using slate and stylus. Braille text is produced using uncontracted Braille.

In the remaining of this chapter, the average uncontracted Braille reading speed is referred as $v_{P_{\text{avg}}}$, where subscript $P$ indicates reading from paper. In order to determine $v_{P_{\text{avg}}}$ in words per minute (wpm), the total number of the words in the article is multiplied with 60s and then divided by the measured time in seconds. The part of the article borrowed from NYT is given below and $v_{P_{\text{avg}}}$ values for each subject are presented in Section 6.2.1 on Table 6.1.

"Catfish Whiskers, pH Detectors, Help Track Prey

Japanese sea catfish have an unusual advantage when hunting in pitch-dark waters, a new study reports: Their whiskers can detect minute changes in the water’s acidity. John T. Caprio, a physiologist at Louisiana State University, was studying how chemical stimuli were encoded by a catfish’s taste system when he noticed a strong reaction from the whiskers. Further study revealed that previously undetected sensors on the whiskers were responding not to the chemical itself, but rather to the effect it was having on the water."

After measuring $v_{P_{\text{avg}}}$, in order to translate this speed to the angular speed to be used on the rotating wheel, the following calculation is performed. The wheel rotation speed corresponding to $v_{P_{\text{avg}}}$ is calculated by multiplying the ratio between the article length, which is 360 cm, and the measured time $t$ (s) with $2\pi$ rad and then dividing it by the wheel’s circumference 70 cm. Hence, the average angular speed of the rotating wheel $w_{RW_{\text{avg}}}$ corresponding to $v_{P_{\text{avg}}}$ is found as:

$$w_{RW_{\text{avg}}} = \frac{360 \text{ (cm)}}{t \text{ (s)}} \times \frac{2\pi \text{ (rad)}}{70 \text{ (cm)}} = \frac{32.3 \text{ (rad)}}{t \text{ (s)}}$$
Training Session

In the training session, the rotating wheel system is introduced to the subjects for the first time (except the two subjects, who participated in the pilot experiments). Subjects explored the rotating wheel and the Braille text placed around it by using their touch. The Braille text used in training sessions is embossed on a continuous labeler tape using a Braille labeler. This tape is then spirally wrapped around the wheel as shown in Figure 6.1. In order to save space for more and longer words, contractions for monosyllabic words, which were available on the Braille labeler, are used, which contain the following: ‘with’, ‘of’, ‘and’, ‘to’, ‘the’. Remaining words are written in uncontracted form. The purpose of using uncontracted Braille throughout the experiments was to keep the length of the words longer which would encourage longer traverses toward left on the text during reversals and hence facilitate observation and evaluation of FMA control. Since evaluation of Braille reading during reversals partially depends on the analyses of videos captured during the experiments, it is important that the distances moved by the finger were clearly observable by the naked eye.

The directives given within the text, when followed by the subjects, aimed to familiarize them with reading on the rotating wheel as well as left- and right-gestures that are made available by the FMA controller. The text presented to subjects consists of high-frequency words, numbers, some low-frequency words, and pseudowords. The wheel speed is set to half of the measured $w_{RW_{avg}}$ and then gradually increased up to $w_{RW_{avg}}$. Subject is asked whether s(he) feels comfortable reading at $w_{RW_{avg}}$ and whether s(he) wants this speed to be increased further. The final speed determined according to subject’s comfort is referred as baseline speed and represented by $w_{bl}$. Other parameters tuned according to each subject’s comfort level are: $w_r$, $m_{ramp}$, and $init_{ramp}$, which are previously discussed in Chapter 5. The text used in training is as follows:

“In order to practice left- and right-gestures please return to the beginning of each sentence to read it one more time. Here I practice going backwards using the left-gesture. Sentences will keep getting shorter. This is a shorter
sentence. I do shorter reversals. I keep reading. Getting shorter. Two words. Shortest. Let’s quit rereading sentences and try to read some numbers: 3,405,607 1045 67800 87401 or maybe low-frequency words such as palliative, complacence, adenovirus and indefatigably. Here are some pseudowords: regimenement, misp, defificobs. Chiquimulilla is a municipality in Guatemala.”

**Braille texts used in the experiments**

The Braille text is embossed on a tape labeler using a Braille labeler. Contractions are only used for some monosyllabic words as discussed in the previous section. Two different texts are generated to be used in AD and NAD conditions. The goal was to create a text with high difficulty level in terms of reading which would encourage more reversals. In order to keep the text suitable for fluent reading and prevent it from being too difficult, which could cause subjects to lose interest in completion of the task, sequential sentences are chosen to have the same context. Texts used in AD and NAD are taken from the same article, which is published in a medical journal [74]. In order to attract more reversals, some high frequency words are replaced with some random low frequency words. The degree of complexity of the phrases are made comparable by balancing the percentage of low-frequency words in both texts. The frequency data is checked based on [75] using The Corpus of Contemporary American English, which indicated both texts to have 41% low frequency words. The length of the texts are chosen to be approximately same when embossed on the labeler tape to allow subjects to travel the same distance on the rotating wheel.

The texts used in the experiments in AD and NAD are given below in the respective order. For AD-2, the same text as in NAD is used. Underlined text represents the low-frequency words.

“A 56-year old man presented to the hospital with **weakness, fatigue, body aches** and an **elevated serum creatinine level** (1.2 mg per deciliter). Review
of his recuperative record implied erstwhile creatinine level of 4.5 mg per deciliter. He had no proteinuria or hematuria. The urine segment was remarkable for the poise of abundant calcium oxalate crystals. He did not have a peculiar history of kidney stones or any family history of kidney disease. He conveyed not consuming ethylene glycol. He had no malabsorptive symptoms or history of gastric surgery. Worsening renal failure with uremic symptoms necessitated the initiation of dialysis.”

“Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.”

6.2.4 Evaluation of Experiments

The results presented in Section 6.3 are analyzed using the video files, which are recorded upon subjects’ consent. Investigating the finger motions of subjects during the experiments, we were able to analyze their approximate reading speed (in wpm), how often they did reversals and which words they have read accurately/inaccurately or skipped. The guidelines followed for data analysis are listed as follows:

- **Words read accurately/inaccurately**: A word is accepted as accurately read if it is read out loud correctly by the subject. If a word is partially or completely read incorrectly in the first pass, but read accurately after a reversal is made on that word, then it is counted as read accurately. If only a part of the word is
read, independent from how accurately that part is read, it is evaluated as read inaccurately.

- **Skipped words:** Since subject’s goal in the experiments is reading the given text out loud with accuracy, if a word is touched but not spoken out loud, it is not possible to know whether that word is silently read and processed by the subject. Therefore, if a word is perceived by the subject by touching but is not read out loud, then it is evaluated as being skipped.

- **Reversals:** A reversal is made if a previously scanned word is partially or completely rescanned by the subject to decode it. The accuracy of the reread word during reversal is evaluated in the same way as discussed in the above items.

- **Reading speed:** The average reading speed is referred as $s_{avg}$ and is calculated in wpm as follows:

$$s_{avg} = \frac{60 \ n_{accurate}}{\text{total time spent for reading}} [\text{wpm}]$$

where $n_{accurate}$ represents the number of accurately read words.

In experiments AD and AD-2, time lost on and during reversals, during which no reading takes place, are not excluded from the calculations of $s_{avg}$ [wpm].

In Section 6.3, the analysis of reading accuracy is visualized by coloring and highlighting the texts used for each different experimental condition. Table 6.2 shows how the coloring and highlighting information is used to display reading accuracy. Words colored in green, red and gray respectively show the words which are read accurately, read inaccurately, and skipped. If any reversal is made, this is indicated by highlighted text. In case of a reversal, colored words in green, red and gray respectively mean that the reread word is read accurately, read inaccurately, and is not read out loud. If the subject decided to quit reading and therefore did not attempt to read the word/words, this is demonstrated by strikethrough word/words.
Table 6.2: Key for reading accuracy analysis (when viewed in color). The word “Braille” is used as a sample to show the coloring/styling of the words based on the analysis.

<table>
<thead>
<tr>
<th>Description</th>
<th>Braille</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accurately read word</td>
<td>Braille</td>
</tr>
<tr>
<td>Inaccurately read word</td>
<td>Braille</td>
</tr>
<tr>
<td>Skipped word</td>
<td>Braille</td>
</tr>
<tr>
<td>Accurately reread word (reversal)</td>
<td>Braille</td>
</tr>
<tr>
<td>Inaccurately reread word (reversal)</td>
<td>Braille</td>
</tr>
<tr>
<td>Not read out loud after reversal is made</td>
<td>Braille</td>
</tr>
<tr>
<td>No attempt to read the word</td>
<td>Braille</td>
</tr>
</tbody>
</table>

6.2.5 Protocol

The experiments are conducted at NBP with volunteering blind subjects at prescheduled times. Before starting the experiments, subjects are asked to sit comfortably in front of the rotating wheel. After obtaining written consent from each participant in the presence of a sighted witness, experimental protocol and goals are explained to each subject by the research personnel. While reading Braille on the rotating wheel system, subjects interacted with the Braille text presented on the wheel surface by holding their reading hand about $45^\circ$ above their viewplane. Subjects expressed comfort in using a single finger for Braille reading, and in the experiments, they used a single finger in their dominant hand to read Braille. In order to determine the average Braille reading speed of each subject, s/he is asked to read the article given in Section 6.2.3. Training sessions are completed by the subject prior to experiments. Subjects were encouraged to take as many training sessions as they needed until they felt comfortable with reading Braille on the rotating wheel. However, research personnel paid attention not to exceed the time devoted for the experiments as reported in the consent form. On the average training sessions took about 13 min. After completing the training session, subjects subsequently took experimental conditions AD, NAD and AD-2. Some of the conditions are repeated upon subject’s wish. Experiments ended when subjects completed reading the given text. Their hand motions are recorded during experiments.
Chapter 6. Evaluation of FMA Controller through Human Subjects Experiments with Blind Volunteers

by the research personnel without revealing their identity. The recorded videos are used for the evaluation of subjects’ performance in different experimental conditions. Before and after the experiments, subjects are asked some survey questions to evaluate their general comfort and subjective assessment on the efficacy of FMA controller.

6.3 Results

In Section 6.3.1, subjects’ performances are analyzed and presented individually. Each subsection presents measured and calculated values of $v_{P_{\text{avg}}}$, $w_{RW_{\text{avg}}}$, and $w_{\text{bl}}$, reading accuracy and reading speed analysis for each experimental condition. Recorded data of the closed-loop control system in Simulink during each experiment is used to calculate the mean wheel speed $\bar{w}$, as well as the mean CW and CCW wheel speeds $w_{CW}$, and $w_{CCW}$, respectively corresponding to forward reading and reversals. FMA controller parameters customized for each subject are also reported. Reading accuracy analysis is demonstrated on the corresponding text read by the subject using the styling information given on Table 6.26. In most of the repeated experiments for NAD, the wheel speed $w_{RW_{\text{avg}}}$ has been reduced in the second trial, which is also reported in the results. During experiments AD and AD-2, in some cases due to inefficient use of the finger gestures presented by FMA controller, subjects spent extra time during experiments, which also affected their measured average Braille reading speed $s_{\text{avg}}$. In order to investigate this further, we selected several time frames of 20 s from the total duration of the experiment. In these time frames, reading fluency and efficiency in the use of the finger gestures are observed to be better when compared to the remaining time intervals. Therefore, reading speed analysis is repeated for the selected time frames and reported in the corresponding subsections. For comparison purposes between subjects, experimental results of different conditions are summarized in the plots given in Section 6.3.2. Subjects’ feedback on the rotating wheel system and assessment on the efficacy of FMA controller are reported in Section 6.3.3.
6.3.1 Evaluation of Subject Performances

Subject 1

The average Braille reading speed $v_{P_{avg}}$ of the subject is calculated as 77 wpm in the pre-training session. The angular speed of the rotating wheel $w_{RW_{avg}}$ corresponding to $v_{P_{avg}}$ is found to be 0.45 rad/s. At the start of the training session, the angular speed is set to 0.225 rad/s, and slowly increased up to $w_{RW_{avg}}$. Upon subject’s request, $w_{RW_{avg}}$ is increased further to 0.50 rad/s, which is used as the baseline speed $w_{bl}$ in all experimental conditions. Tunable parameters of the switching FMA controller are customized according to subject’s comfort in reading, which are selected as follows: $w_r = -0.5 \text{ rad/s}$, $\text{init}_{\text{ramp}} = 0.1$, and $m_{\text{ramp}} = 0.2$.

AD: A 56-year old man presented to the hospital with weakness, fatigue, body aches and an elevated serum creatinine level (1.2 mg per deciliter). Review of his recuperative record implied erstwhile creatinine level of 4.5 mg per deciliter. He had no proteinuria or hematuria. The urine segment was remarkable for the poise of abundant calcium oxalate crystals. He did not have a peculiar history of kidney stones or any family history of kidney disease. He conveyed not consuming ethylene glycol. He had no malabsorptive symptoms or history of gastric surgery. Worsening renal failure with uremic symptoms necessitated the initiation of dialysis.

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Table 6.3: Reading accuracy and reversal analysis of AD-experiment for subject 1

In AD, $\bar{w}$, $w_{CW}$, and $w_{CCW}$ are calculated as 0.28 rad/s, 0.43 rad/s, and -0.48 rad/s, respectively. Subject has completed reading in 118 s leading to a reading speed $s_{avg}$ of
50.8 wpm. Time intervals, during which subject read faster than the measured $s_{avg}$ are given below:

23 words/20sec = 69 wpm:
A 56-year old man presented to the hospital with weakness, fatigue, body aches and an elevated serum creatinine level (1.2 mg per deciliter).

18 words/20sec = 54 wpm:
The urine segment was remarkable for the poise of abundant calcium oxalate crystals. He did not have a

20 words/20sec = 60 wpm:
He did not have a peculiar history of kidney stones or any family history of kidney disease. He conveyed not

**NAD - First trial:** Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with *Averrhoa carambola*, *bilimbi* (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

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**Table 6.4:** Reading accuracy and reversal analysis of NAD-experiment (first trial) for subject 1

In NAD (first trial), subject has completed reading in 69 s leading to a reading speed of 46 wpm.
NAD - Second Trial: Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

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Table 6.5: Reading accuracy and reversal analysis of NAD-experiment (second trial) for subject 1

NAD is repeated with the same wheel baseline speed $w_{bd}$ of 0.5 rad/s. Subject has completed reading in 69 s, and the reading speed is calculated as 64.3 wpm.

AD-2: Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

In AD-2, parameters $w_{bd}$, $w_r$, $init_{ramp}$, and $m_{ramp}$ are selected the same as in AD. Values for $\ddot{w}$, $w_{CW}$, and $w_{CCW}$ are found as 0.27 rad/s, 0.43 rad/s, and -0.48 rad/s,
Table 6.6: Reading accuracy and reversal analysis of AD-2-experiment for subject 1

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respectively. Subject has completed reading in 126 s leading to a reading speed \( s_{avg} \) of 45.7 wpm. Time intervals, during which subject read faster than the measured \( s_{avg} \) are given below:

26 words/20sec = 78 wpm:
Owing to the rapidly progressive nature of the patients failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with

14 words/20sec = 42 wpm:

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22 words/20sec = 66 wpm:
The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with

15 words/20sec = 45 wpm:

Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as

**Subject 2**

The average Braille reading speed \( v_{P_{avg}} \) of the subject is calculated as 71 wpm in the pre-training session. The angular speed of the rotating wheel \( w_{RW_{avg}} \) corresponding
to $v_{P_{\text{avg}}}$ is found to be 0.42 rad/s. At the start of the training session, the angular speed is set to 0.21 rad/s, and slowly increased up to $w_{RW_{\text{avg}}}$. Upon subject’s request, $w_{RW_{\text{avg}}}$ is increased further to 0.55 rad/s, which is used as the baseline speed $w_{bl}$ in all experimental conditions (except second trial of NAD). Tunable parameters of the switching FMA controller are customized according to subject’s comfort in reading, which are selected as follows: $w_r = -0.3$ rad/s, $init_{\text{ramp}} = 0.2$, and $m_{\text{ramp}} = 0.3$.

AD (First trial): A 56-year old man presented to the hospital with weakness, fatigue, body aches and an elevated serum creatinine level (1.2 mg per deciliter). Review of his recuperative record implied an earlier creatinine level of 1.5 mg per deciliter. He had no proteinuria or hematuria. The urine segment was remarkable for the presence of abundant calcium oxalate crystals. He did not have a peculiar history of kidney stones or any family history of kidney disease. He conveyed not consuming ethylene glycol. He had no malabsorptive symptoms or history of gastric surgery. Worsening renal failure with uremic symptoms necessitated the initiation of dialysis.

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Table 6.7: Reading accuracy and reversal analysis of AD-experiment (first trial) for subject 2

In AD, $\bar{w}$, $w_{CW}$, and $w_{CCW}$ are calculated as 0.31 rad/s, 0.5 rad/s, and -0.28 rad/s, respectively. Subject has completed reading in 104 s, and subject’s reading speed $s_{\text{avg}}$ is found as 51.3 wpm. Time intervals, during which subject read faster than the measured $s_{\text{avg}}$ are given below:

26 words/20 sec = 78 wpm:

A 56-year old man presented to the hospital with weakness, fatigue, body aches and an elevated serum creatinine level (1.2 mg per deciliter). Review of his
Chapter 6. Evaluation of FMA Controller through Human Subjects Experiments with Blind Volunteers

23 words/20 sec = 69 wpm:

The urine segment was remarkable for the poise of abundant calcium oxalate crystals. He did not have a peculiar history of kidney stones or any family history of oxalate crystals. He did not have a peculiar history of kidney stones or any family history of kidney disease. He conveyed not consuming ethylene glycol. He had no malabsorptive symptoms or history of gastric surgery. Worsening renal failure with uremic symptoms necessitated the initiation of dialysis.

AD - Second trial: A 56-year old man presented to the hospital with weakness, fatigue, body aches and an elevated serum creatinine level (1.2 mg per deciliter). Review of his recuperative record implied erstwhile creatinine level of 1.5 mg per deciliter. He had no proteinuria or hematuria. The urine segment was remarkable for the poise of abundant calcium oxalate crystals. He did not have a peculiar history of kidney stones or any family history of kidney disease. He conveyed not consuming ethylene glycol. He had no malabsorptive symptoms or history of gastric surgery. Worsening renal failure with uremic symptoms necessitated the initiation of dialysis.

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Table 6.8: Reading accuracy and reversal analysis of AD-experiment (second trial) for subject 2

Upon subject’s request AD-experiment is repeated with the same $w_{ld}$, $w_r$, $init_{ramp}$, and $m_{ramp}$. Values of $\bar{w}$, $w_{CW}$, and $w_{CCW}$ are calculated as 0.26 rad/s, 0.48 rad/s, and -0.29 rad/s, respectively. Subject has completed reading in 110 s, and subject’s reading speed $s_{avg}$ is found as 52.4 wpm. Time intervals, during which subject read faster than the measured $s_{avg}$ are given below:

27 words/ 20 sec = 81 wpm:

hospital with weakness, fatigue, body aches and an elevated serum creatinine level (1.2
mg per deciliter). Review of his recuperative record implied erstwhile creatinine level of 4.5.

21 words/ 20 sec = 63 wpm:

The urine segment was remarkable for the poise of abundant calcium oxalate crystals. He did not have a peculiar history of kidney stones or any family history of kidney disease. He conveyed not consuming ethylene glycol. He had no malabsorptive

NAD - First trial: Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

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Table 6.9: Reading accuracy and reversal analysis of NAD-experiment (first trial) for subject 2

In NAD, the baseline speed $w_0$ of the rotating wheel was set to 0.55 rad/s. Subject has completed reading in 51 s leading to a reading speed of 42.4 wpm.

NAD - Second trial: Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis
of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

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Table 6.10: Reading accuracy and reversal analysis of NAD-experiment (second trial) for subject 2

Upon subject’s wish NAD is repeated with the reduced baseline speed \(w_{bl}\) of 0.45 rad/s. Subject has completed reading in 64 s leading to a reading speed \(s_{avg}\) of 40.3 wpm.

AD-2: Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

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Table 6.11: Reading accuracy and reversal analysis of AD-2-experiment for subject 2
In AD-2, parameters $w_{bl}$, $w_r$, $init_{ramp}$, and $m_{ramp}$ are selected the same as in AD. Values of $\tilde{w}$, $w_{CW}$, and $w_{CCW}$ are found as 0.21 rad/s, 0.46 rad/s, and -0.28 rad/s, respectively. Subject has completed reading in 163 s, and subject’s reading speed $s_{avg}$ is measured as 33.1 wpm. Time intervals, during which subject read faster than the measured $s_{avg}$ are given below:

23 words/20 sec = 69 wpm:
Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial

17 words/20 sec = 51 wpm:
The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with

**Subject 3**

The average Braille reading speed $v_{P_{avg}}$ of the subject is calculated as 64.2 wpm in the pre-training session. The angular speed of the rotating wheel $w_{RW_{avg}}$ corresponding to $v_{P_{avg}}$ is found to be 0.4 rad/s. At the start of the training session, the angular speed is set to 0.2 rad/s, and slowly increased up to $w_{RW_{avg}}$. Upon subject’s request, $w_{RW_{avg}}$ is increased further to 0.45 rad/s, which is used as the baseline speed $w_{bl}$ in all experimental conditions (except third trial of NAD). Tunable parameters of the switching FMA controller are customized according to subject’s comfort in reading, which are selected as follows: $w_r = -0.4$ rad/s, $init_{ramp} = 0.3$, and $m_{ramp} = 0.5$.

**AD:** A 56-year old man presented to the hospital with weakness, fatigue, body aches and an elevated serum creatinine level (1.2 mg per deciliter). Review of his recuperative record implied erstwhile creatinine level of 4.5 mg per deciliter. He had no proteinuria or hematuria. The urine segment was remarkable for the poise of abundant calcium oxalate crystals. He did not have a peculiar history of kidney stones or any family history of kidney disease. He conveyed not consuming ethylene glycol. He had no malabsorptive symptoms or history of gastric surgery. Worsening renal failure with uremic symptoms necessitated the initiation of dialysis.
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Table 6.12: Reading accuracy and reversal analysis of AD-experiment for subject 3

In AD, $\bar{w}$, $w_{CW}$, and $w_{CCW}$ are calculated as 0.16 rad/s, 0.46 rad/s, and -0.4 rad/s, respectively. Subject has completed reading in 202 s, and subject’s reading speed $s_{avg}$ is found as 29.4 wpm. Time intervals, during which subject read faster than the measured $s_{avg}$ are given below:

11 words/ 20 sec = 33 wpm:
A 56-year old man presented to the hospital with weakness, fatigue

18 words/ 20 sec = 54 wpm:
deciliter). Review of his recuperative record implied erstwhile creatinine level of 4.5 mg per deciliter. He

19 words/ 13 sec = 87.7 wpm:
crystals. He did not have a peculiar history of kidney stones or any family history of kidney disease. He

11 words/ 13 sec = 50.1 wpm:
He had no malabsorptive symptoms or history of gastric surgery

**NAD - First trial:** Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been
previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

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Table 6.13: Reading accuracy and reversal analysis of NAD-experiment (first trial) for subject 3

In NAD (first trial), the baseline wheel speed is set to 0.45 rad/s. Subject has completed reading in 38 s leading to a reading speed of 37.9 wpm.

**NAD - Second trial:** Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

Upon subject’s request, NAD-experiment is repeated by the subject with the same baseline speed $w_{bd}$ as in the first trial of NAD. Subject completed reading in 30 s, and the reading speed $s_{avg}$ is calculated as 42 wpm.

**NAD - Third trial:** Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been
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Table 6.14: Reading accuracy and reversal analysis of NAD-experiment (second trial) for subject 3

Previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

Table 6.15: Reading accuracy and reversal analysis of NAD-experiment (third trial) for subject 3

Upon subject’s wish, NAD is repeated for the third time, in which \( w_{bl} \) is reduced to \( w_{bl} = 0.35 \) rad/s. Subject completed reading in 97 s, and his reading speed is found to be 54.4 wpm.

AD-2: Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with cosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.
In AD-2, parameters $w_{bl}$, $w_r$, $init_{ramp}$, and $m_{ramp}$ are selected the same as in AD. Values for $\bar{w}$, $w_{CW}$, and $w_{CCW}$ are found as 0.29 rad/s, 0.46 rad/s, and -0.39 rad/s, respectively. Subject has completed reading in 121 s, and subject’s reading speed $s_{avg}$ is found as 48 wpm. Time intervals, during which subject read faster than the measured $s_{avg}$ are given below:

23 words/20 sec = 69 wpm:
Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial

24 words/20 sec = 72 wpm:
diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported

18 words/20 sec = 54 wpm:
carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated

17 words/20 sec = 51 wpm
overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.
Subject 4

The average Braille reading speed $v_{P_{avg}}$ of the subject is calculated as 45.5 wpm in the pre-training session. The angular speed of the rotating wheel $w_{RW_{avg}}$ corresponding to $v_{P_{avg}}$ is found to be 0.27 rad/s. At the start of the training session, the angular speed is set to 0.135 rad/s, and slowly increased up to $w_{RW_{avg}}$. Upon subject’s request, $w_{RW_{avg}}$ is increased further to 0.45 rad/s, which is used as the baseline speed $w_{bl}$ in all experimental conditions (except second trial of NAD). Tunable parameters of the switching FMA controller are customized according to subject’s comfort in reading, which are selected as follows: $w_r = -0.35 \text{ rad/s}$, $init_{ramp} = 0.2$, and $m_{ramp} = 0.5$.

AD - First trial: A 56-year old man presented to the hospital with weakness, fatigue, body aches and an elevated serum creatinine level (1.2 mg per deciliter). Review of his recuperative record implied erstwhile creatinine level of 4.5 mg per deciliter. He had no proteinuria or hematuria. The urine segment was remarkable for the poise of abundant calcium oxalate crystals. He did not have a peculiar history of kidney stones or any family history of kidney disease. He conveyed not consuming ethylene glycol. He had no malabsorptive symptoms or history of gastric surgery. Worsening renal failure with uremic symptoms necessitated the initiation of dialysis.

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TABLE 6.17: Reading accuracy and reversal analysis of AD-experiment (first trial) for subject 4

In AD, $\bar{w}$, $w_{CW}$, and $w_{CCW}$ are calculated as 0.31 rad/s, 0.46 rad/s, and -0.34 rad/s, respectively. Subject has completed reading in 182 s, and subject’s reading speed is found as 33 wpm. Time intervals, during which subject read faster than the measured $s_{avg}$ are given below:
Chapter 6. Evaluation of FMA Controller through Human Subjects Experiments with Blind Volunteers

20 words/20 sec = 60 wpm:

He did not have a peculiar history of kidney stones or any family history of kidney disease. He conveyed not

14 words/20 sec = 42 wpm:

ethylene glycol. He had no malabsorptive symptoms or history of gastric surgery. Worsening renal

AD - Second trial: A 56-year old man presented to the hospital with weakness, fatigue, body aches and an elevated serum creatinine level (1.2 mg per deciliter). Review of his recuperative record implied erstwhile creatinine level of 4.5 mg per deciliter. He had no proteinuria or hematuria. The urine segment was remarkable for the poise of abundant calcium oxalate crystals. He did not have a peculiar history of kidney stones or any family history of kidney disease. He conveyed not consuming ethylene glycol. He had no malabsorptive symptoms or history of gastric surgery. Worsening renal failure with uremic symptoms necessitated the initiation of dialysis.

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Table 6.18: Reading accuracy and reversal analysis of AD-experiment (second trial) for subject 4

Upon subject’s wish, AD-experiment is repeated. In the second trial of AD, parameters $w_d$, $w_r$, $init_{ramp}$, and $m_{ramp}$ are selected the same as in the first trial of AD. Subject has completed reading in 112 s, and subject’s reading speed $s_{avg}$ is found as 53.6 wpm. Time intervals, during which subject read faster than the measured $s_{avg}$ are given below:

19 words/20 sec = 57 wpm:

The urine segment was remarkable for the poise of abundant calcium oxalate crystals. He did not have a peculiar
history of kidney stones or any family history of kidney disease. He conveyed not consuming ethylene glycol. He had no malabsorptive symptoms

**NAD - First trial:** Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraigments of arcane seizure a thorough dietary history should be attained.

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Table 6.19: Reading accuracy and reversal analysis of NAD-experiment (first trial) for subject 4

In NAD (first trial), the baseline wheel speed $w_{bl}$ is set to 0.45 rad/s. Subject has completed reading in 25 s leading to a reading speed of 55.2 wpm.

**NAD - Second trial:** Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning.
acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

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Table 6.20: Reading accuracy and reversal analysis of NAD-experiment (second trial) for subject 4

Upon subject’s wish, NAD is repeated with a reduced wheel baseline speed of 0.35 rad/s. Subject has completed reading in 102 s leading to a reading speed \( s_{\text{avg}} \) of 45.3 wpm.

**AD-2:** Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with *Averrhoa carambola*, *bilimbi* (cucumber tree), *rhubarb*, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

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Table 6.21: Reading accuracy and reversal analysis of AD-2-experiment for subject 4

In AD-2, parameters \( w_{\text{bl}} \), \( w_{r} \), \( \text{init}_{\text{ramp}} \), and \( m_{\text{ramp}} \) are selected the same as in AD. Values for \( \bar{w} \), \( w_{\text{CW}} \), and \( w_{\text{CCW}} \) are found as 0.23 rad/s, 0.45 rad/s, and -0.34 rad/s. Subject
has completed reading in 152 s, and subject’s reading speed is found as 36.7 wpm. Time intervals, during which subject read faster than the measured $s_{avg}$ are given below:

25 words/ 20 sec = 75 wpm:

Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with

19 words/ 20 sec = 57 wpm:

The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola

15 words/ 20 sec = 45 wpm:

Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as

Subject 5

The average Braille reading speed $v_{P_{avg}}$ of the subject is calculated as 72.8 wpm in the pre-training session. The angular speed of the rotating wheel $w_{RW_{avg}}$ corresponding to $v_{P_{avg}}$ is found to be 0.43 rad/s. At the start of the training session, the angular speed is set to 0.215 rad/s, and slowly increased up to $w_{RW_{avg}} = 0.43$ rad/s. This value is used as the baseline speed $w_{bd}$ in all experimental conditions (except second trial of NAD). Tunable parameters of the switching FMA controller are customized according to subject’s comfort in reading, which are selected as follows: $w_r = -0.4$ rad/s, $init_{ramp} = 0.1$, and $m_{ramp} = 0.3$.

AD: A 56-year old man presented to the hospital with weakness, fatigue, body aches and an elevated serum creatinine level (1.2 mg per deciliter). Review of his recuperative record implied erstwhile creatinine level of 4.5 mg per deciliter. He had no proteinuria or hematuria. The urine segment was remarkable for the poise of abundant calcium oxalate crystals. He did not have a peculiar history of kidney stones or any family history of
kidney disease. He conveyed not consuming ethylene glycol. He had no malabsorptive symptoms or history of gastric surgery. Worsening renal failure with uremic symptoms necessitated the initiation of dialysis.

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Table 6.22: Reading accuracy and reversal analysis of AD-experiment for subject 5

In AD, $\bar{w}$, $w_{CW}$, and $w_{CCW}$ are calculated as 0.35 rad/s, 0.44 rad/s, and -0.39 rad/s, respectively. Subject has completed reading in 97 s, and subject’s reading speed $s_{avg}$ is found as 61.9 wpm. Time intervals, during which subject read faster than the measured $s_{avg}$ are given below:

28 words/ 20 sec = 84 wpm:
A 56-year old man presented to the hospital with weakness, fatigue, body aches and an elevated serum creatinine level (1.2 mg per deciliter). Review of his recuperative record

25 words/ 20 sec = 75 wpm:
The urine segment was remarkable for the poise of abundant calcium oxalate crystals. He did not have a peculiar history of kidney stones or any

24 words/ 20 sec = 72 wpm:
He conveyed not consuming ethylene glycol. He had no malabsorptive symptoms or history of gastric surgery. Worsening renal failure with uremic symptoms necessitated the

**NAD - First trial:** Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at
99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

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Table 6.23: Reading accuracy and reversal analysis of NAD-experiment (first trial) for subject 5

In NAD (first trial), the wheel baseline speed $w_{bl}$ is set to 0.43 rad/s. Subject has completed reading in 102 s leading to a reading speed $s_{avg}$ of 43.1 wpm.

**NAD - Second trial:** Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

Upon subject’s wish, NAD is repeated with the reduced wheel baseline speed of 0.3 rad/s. Subject has completed reading in 114 s leading to a reading speed $s_{avg}$ of 45.7 wpm.

**AD-2:** Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which showed interstitial inflammation with eosinophils, and interstitial edema consistent with a diagnosis of nephropathy. The oxalate defecation was intensified. The excretion was hoisted, at 99 mg in
Chapter 6. Evaluation of FMA Controller through Human Subjects Experiments with Blind Volunteers

Table 6.24: Reading accuracy and reversal analysis of NAD-experiment (second trial) for subject 5

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24 hours. Some of the cases are reported with *Averrhoa carambola*, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arraignments of arcane seizure a thorough dietary history should be attained.

Table 6.25: Reading accuracy and reversal analysis of AD-2-experiment for subject 5

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In AD-2, parameters $w_{ld}$, $w_{r}$, $init_{ramp}$, and $m_{ramp}$ are selected the same as in AD. Values for $\bar{w}$, $w_{CW}$, and $w_{CCW}$ are found as 0.29 rad/s, 0.43 rad/s, and -0.39 rad/s, respectively. Subject has completed reading in 97 s, and subject’s reading speed is found as 49.8 wpm. Time intervals, during which subject read faster than the measured $s_{avg}$ are given below:

21 words/ 20 sec = 63 wpm:
Owing to the rapidly progressive nature of the patient’s failure yet habitual kidney size on ultrasonography, a biopsy was performed, which

27 words/ 20 sec = 81 wpm:
The excretion was hoisted, at 99 mg in 24 hours. Some of the cases are reported with
Averrhoa carambola, bilimbi (cucumber tree), rhubarb, and peanuts. Patient had none of the factors that have been previously amalgamated with hyperoxaluria, such as overingestion of ascorbic acid poisoning. In arrangements of

6.3.2 Comparison between Experimental Conditions

Subjects’ performances on reading accuracy in AD, NAD and AD-2 are presented on Table 6.26. Reading accuracy is calculated as a percentage by dividing the number of accurately read words by the total number of the words given in the text in each experimental condition. While the wheel baseline speed $w_{bl}$ is the same in all conditions, the percentages shown in red on Table 6.26 reflect trials, in which $w_{bl}$ is reduced upon subject’s wish. Results indicate that subjects were able to achieve higher reading accuracy in AD and AD-2 when compared to NAD. Reducing $w_{bl}$ in repeated trials in NAD helped subjects achieve higher reading accuracy, however subjects’ scores in these trials did not reach the high scores in AD and AD-2. Reading accuracy percentages and task completion rates in first trials of each condition are plotted in Figures 6.2 and 6.3, respectively.

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<td>88</td>
<td>95</td>
<td>37</td>
<td>44</td>
<td>-</td>
<td>93</td>
</tr>
<tr>
<td>S3</td>
<td>98</td>
<td>-</td>
<td>25</td>
<td>22</td>
<td>91</td>
<td>97</td>
</tr>
<tr>
<td>S4</td>
<td>99</td>
<td>99</td>
<td>24</td>
<td>80</td>
<td>-</td>
<td>96</td>
</tr>
<tr>
<td>S5</td>
<td>99</td>
<td>-</td>
<td>63</td>
<td>90</td>
<td>-</td>
<td>96</td>
</tr>
</tbody>
</table>

Table 6.26: Reading accuracy in different experimental conditions. Percentages colored in red reflect trials with reduced wheel baseline speed.
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Figure 6.2: Reading accuracy in different experimental conditions (first trials)

Figure 6.3: Task completion rates in different experimental conditions (first trials)

Detailed analysis of reversals are given on Table 6.27, where the number of accurately read, inaccurately read and skipped words after a reversal are colored in green, red and
gray, respectively. In Figure 6.4, the number of accurate reversals is plotted against reading accuracy percentage. This plot indicates that subjects were able to do as many reversals as they wanted to achieve high reading accuracy rates when the finger gestures were available to them in AD and AD-2. In the absence of FMA controller in NAD, all subjects, except only one, avoided reversals and performed lower in reading accuracy when compared to AD and AD-2.

### Table 6.27: Number of reversals in different experimental conditions.

<table>
<thead>
<tr>
<th>Subject #</th>
<th>AD (1.trial)</th>
<th>AD (2.trial)</th>
<th>NAD (1.trial)</th>
<th>NAD (2.trial)</th>
<th>NAD (3.trial)</th>
<th>AD-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>17-1-0</td>
<td>-</td>
<td>4-0-5</td>
<td>1-2-1</td>
<td>-</td>
<td>19-0-0</td>
</tr>
<tr>
<td>S2</td>
<td>21-1-0</td>
<td>15-1-2</td>
<td>0-0-2</td>
<td>1-0-4</td>
<td>-</td>
<td>22-1-3</td>
</tr>
<tr>
<td>S3</td>
<td>13-0-1</td>
<td>-</td>
<td>0-0-0</td>
<td>0-0-0</td>
<td>1-0-0</td>
<td>10-0-0</td>
</tr>
<tr>
<td>S4</td>
<td>20-1-0</td>
<td>11-1-0</td>
<td>0-0-0</td>
<td>1-0-0</td>
<td>-</td>
<td>14-0-0</td>
</tr>
<tr>
<td>S5</td>
<td>7-0-0</td>
<td>-</td>
<td>0-0-0</td>
<td>0-0-0</td>
<td>-</td>
<td>11-1-0</td>
</tr>
</tbody>
</table>

This table shows the number of reversals in different experimental conditions. On the table, number of reversals are shown in the following order and color: accurately read reversals in green - inaccurately read reversals in red - skipped reversals in gray.

![Figure 6.4: Reading accuracy rates (first trials) vs. number of reversals.](image-url)
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Figure 6.5 shows subjects’ reading speeds in first trials of all conditions. Analysis of reading speeds in some time intervals of 20 s for conditions AD and AD-2 are presented in Figures 6.6 and 6.7, respectively. These plots indicate that subjects read faster in those time intervals in AD and AD-2.

![Figure 6.5: Reading speed in first trials of all experimental conditions](image)

Figure 6.8 compares the number of total reversals with reversals that are made on low-frequency words. This comparison shows that 84% of the reversals are made on low-frequency words.

6.3.3 Survey Results

Prior to experiments, subjects are asked whether they feel comfortable reading Braille out loud with their single finger of their dominant hand. All subjects answered positively. Subjects are also asked to evaluate their general comfort, fatigue, arm pain and hand pain before and after the experiments by choosing one the following: none/ slight/- moderate/severe. Before the experiments, all the subjects reported that they had none
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Figure 6.6: Reading speed analysis of AD in time intervals of 20 s, in which reading speed is larger than the average reading speed.

Figure 6.7: Reading speed analysis of AD-2 in time intervals of 20 s, in which reading speed is larger than the average reading speed.

of the aforementioned symptoms. After the experiments, one subject reported no symptoms; two subjects reported slight arm pain; one subject reported moderate general
discomfort and slight fatigue; one subject reported moderate fatigue and moderate arm pain, and one subject reported slight general discomfort and slight arm pain.

After the completion of experiments, subjects are asked to evaluate the efficacy of FMA controller by choosing a score from 1 to 10, 1 being the most undesirable, and 10 being very satisfactory. Subjects assessments on the efficacy of the FMA controller were as follows. While subject 1 and 2’s scores were 3 and 5 in pilot testing, their scores after the experiments increased to 8 and 9, respectively. Remaining subjects 3 to 5 gave scores of 8, 7, and 6, respectively.

Subjects shared their feedback about the rotating wheel design and FMA controller. All the subjects indicated that holding the hand at an angled position is not the ideal configuration for reading and rotating wheel system should be positioned horizontally on the table such that it enables subjects to read by holding their hands parallel to the table as they read with conventional displays or from paper. Subjects mentioned that
they are used to read Braille in contracted form, which enables them to read Braille at higher speeds. Therefore, they recommended that the end product should provide access to both contracted and uncontracted Braille. One of the subjects recommended integrating a button to the rotating wheel in order to manually control the text flow speed. Another recommendation was enhancing the controller for two-handed Braille reading. One subject mentioned that with more training he can benefit more from the FMA controller to read Braille faster. Two subjects, who also had participated in the pilot experiments, compared the redesigned FMA controller to its previous version, and mentioned that the new controller is much more useful, works much better and enables easier use of the available finger gestures. They also added that pressure dependency of the controller reduced significantly when compared to pilot experiments and indicated that using gestures to switch between forward reading and reversals is much easier to execute. Subjects also reported that they liked the tunable features of FMA controller, which are customized according to each subject’s comfort in reading.

6.4 Discussions

Subjects were able to read Braille on the rotating wheel although it was their first time

Prior to experiments, we did not know whether subjects would be able to read Braille on the rotating wheel system, since they had no prior experience with this kind of device, and since there was no study with human subjects testing reported in the literature. However, we know from literature that an integral part of Braille reading is the relative motion between the finger and the Braille cells/letters as discussed in Chapter 1. This motion enables blind people to read Braille on conventional Braille displays, where the tangential friction force emerging due to swiping of finger on the static pins of the display helps users discriminate Braille characters. According to us, a similar phenomena occurs as the user reads Braille from a moving surface. Here, the difference is that subject’s
finger might be steady but since the Braille text is moving, a similar tangential force occurs between the finger and the Braille cells. Our observations from the experiments indicate that while the Braille text was moving underneath subjects’ fingers, even though subjects kept their finger steady, they were able to read Braille. Although the rotating wheel concept was introduced to the subjects for the first time, each subject was able to read Braille as soon as s(he) touched the Braille text and practiced for couple of minutes. During the training sessions, where subjects are presented an easy text to read, they even exceeded their measured average Braille reading speed from paper. Same observations are made for the experimental phase in some time intervals, although the text to be read was containing difficult low-frequency words. We found this result encouraging in terms of showing that this prototype holds promise for further improvement to create a refreshable rotating wheel Braille display.

**Subjects performed better in AD and AD-2**

In NAD, while two subjects gave up reading after completing less than half of the text (see Figure 6.3), remaining subjects read an average of 52% of the given text accurately in their first trial. On the contrary, in AD, subjects’ reading accuracy rates reached an average of 96.6%. Based on these results, when we compare first trials of AD and NAD (see Figure 6.2), where the given texts are introduced to the subjects for the first time, we observe that in AD subjects accomplished the tasks with much higher performance based on the predefined goal. Next, we compare NAD and AD-2 to investigate whether subjects could improve their reading accuracy from NAD to AD-2, where they took the same task as in NAD but with FMA controller being active on the rotating wheel. A peer-to-peer comparison of these two experiments is not possible due to some repeated conditions in AD-2, i.e., in AD-2 subjects are asked to read a text which they partially or completely read before, in NAD. Despite this fact, results from AD-2 experiments caught our attention, in which subjects achieved a very similar performance as in AD in reading accuracy (an average of 96.6% in AD and 96.2% in AD-2) and needed to perform the same average number of reversals as in AD (16.2 reversals in AD and AD-2 based on
Table 6.27) to complete reading. Although the text is difficult to read, we would expect subjects to do less reversals and read the text more fluently since they were exposed to the text at least two times before. However, results show that in order to perform scores above 95% on average in AD-2 subjects needed to take as many reversals as they needed (see Figure 6.4) and FMA control was required, which enabled adaptive text flow adjustments based on the subjects’ needs.

One can argue that subjects’ reading accuracy rates in AD and NAD would be similar if the experiments were carried out with a text which was much easier to read and did not attract as many reversals as it did in this study, but was completed with just a few reversals. The idea behind having a difficult text in the experiments was to reveal any potential differences between AD and NAD with a limited number of words in a limited time. If the used text was easier, reducing the need for reversals, it would be very hard to observe FMA control stepping in to the system and to prove its efficacy on Braille reading. However, we can still discuss whether in NAD subjects would be able to perform as good as in AD even if they read an easier text. If we investigate the experimental results, we observe that although the text flow speed set in NAD represents subject’s comfortable Braille reading speed on the rotating wheel, in the situations where after accurate reading of couple of words subjects came across to a word, which caused them to do a reversal, they either skipped that word or read it inaccurately. This means that independent from the difficulty of the text, subjects would miss a word even the text would attract only a few reversals, which would also cause them to skip the subsequent words. This case can be easily observed in Section 6.3 by looking at the subsequent words colored in gray representing skipped words. Another typical example of this case is observed in NAD results of subjects 2, 3, and 4, who gave up reading as a result of missing words and keeping to miss following words. In summary, in light of the experimental results we can argue that if we used a text which would not attract many reversals, in NAD subjects would not be able to perform as good as in AD in terms of reading accuracy since they would eventually miss words, which in turn would lead them to either give up reading due to frustration or partially complete reading causing
comprehension problems.

**Subjects rarely performed reversals in NAD**

If we investigate the high performances in AD as reported on Table 6.26, we observe that the number of reversals ranged from 7 to 22, whereas 0 to 9 reversals have been performed in NAD. Knowing that both texts used in AD and NAD have the same percentage of low-frequency words, we can argue that the difficulty levels of these texts are similar. Therefore, in order to achieve high reading accuracy, in NAD we would expect to observe a similar number of reversals as in AD. However, since in NAD reading accuracy rates and reversal attempts are much lower when compared to AD, we interpret this as follows: Performing a reversal, while the wheel rotates at a constant speed, has a significant drawback. Subject loses time on reversals and has to compensate for the lost time by traveling/reading faster on the text when s(he) switches back to reading in forward direction.

Results shown on Table 6.27 also supports the above discussion. We observe that subjects performed none or very few reversals in all the trials of NAD. However, this does not mean that they did not need to do reversals. On the contrary, number of reversals in AD-2 shows that they needed to do reversals even if they read the same text for the third or forth time. Although subjects got familiarized with the text before, in AD-2 they took advantage of the FMA control to read the words accurately, which they either skipped or gave up reading in NAD as discussed above.

**Reversals are encouraged with the use of low-frequency words**

One of the aims of this study was to compare subjects’ Braille reading performances in AD and NAD. Since FMA controller has been developed taking into account the finger dynamics during reversals, in order to reveal any differences between AD and NAD, we focused on preparing texts which would encourage subjects to do reversals.
Therefore, we used low-frequency words in both of the texts. However, since subjects participated in the experiments were proficient readers, prior to the experiments we did not know whether the low-frequency words placed in the text would challenge them to do reversals. In order to examine this, for each condition we calculated the number of reversals that have been made on low-frequency words, and then divided this number by the total number of reversal attempts. We found that on average 84% of the reversals are made on low-frequency words (see Figure 6.8), which shows that our attempt of using low-frequency words to create the need for reversals was successful.

**Average reading speed varied among subjects**

As discussed previously, subjects had no issues with reading Braille on the rotating wheel system. Subjects’ reading speeds achieved during training sessions also support this finding. Comparison of subjects’ measured average reading speed $v_{\text{avg}}$ from paper and subjects’ preferred baseline speeds $w_{\text{bl}}$ used in the experiments shows that $w_{\text{bl}}$ is even slightly above $w_{\text{RW}, \text{avg}}$ corresponding to $v_{\text{avg}}$. This means that subjects easily reached their average Braille reading speed on the rotating wheel.

The goal in designing the experiments was to reveal the benefits of FMA control for Braille reading instead of measuring the reading speeds that can be achieved on the rotating wheel. During experiments subjects are asked to focus on reading accuracy, hence Braille reading speeds reported here may not be in accordance with subjects’ regular reading speeds from paper. Investigation of measured average reading speeds $s_{\text{avg}}$ in different experimental conditions varied greatly among subjects (see Figure 6.5). One of the reasons is that measured reading completion times for the given text were different for each condition and each subject (see Figure 6.3). For instance, third subject’s reading speed with $s_{\text{avg}} = 55$ wpm for condition NAD is higher when compared to $s_{\text{avg}} = 33$ wpm and $s_{\text{avg}} = 36.7$ wpm respectively for conditions AD and AD-2. This measure however does not prove that subject is able to reach higher reading speed in NAD, since subject could not complete the reading task and gave up reading after reading 25% of the text.
Another reason for $s_{avg}$ to vary greatly among experimental conditions is due to lost time while using the right gesture to switch from a reversal back to forward reading. When we analyzed the recorded videos, we observed that in some cases applied force while sweeping the finger from left to right was not sufficient to activate the right gesture. Since FMA control depends on a sensorless controller design, it works based on the estimated external disturbance. After a reversal occurs, the controller keeps its current state until this estimated disturbance drops below a predetermined threshold. In some cases when subjects wanted to proceed forward reading right after a reversal, sometimes it took them more than one swipe from left to right to initiate forward reading, which caused spending some extra time without actual reading. After the experiments, subjects mentioned that they could get better at using the available gestures with FMA controller with more training.

We inspected the recorded videos for AD and AD-2 further in order to search for time windows, in which subjects performed efficient use of FMA controller gestures. For this, we selected time frames of 20s, for which we measured the number of accurately read words to find subject’s reading speed as presented in Figures 6.6 and 6.7. Results showed that with successful usage of gestures, subjects’ reading speeds in the selected time frames reached and even exceeded their average reading speed from paper in almost all trials in AD and AD-2 despite the difficulty of the texts and the reversals made during these time frames.

6.5 Conclusion

In this chapter, we introduced the evaluation of the ADRC based switching FMA controller with blind subjects through Braille reading tasks. In order to investigate the effects of having FMA control active or inactive during Braille reading, experiments are designed carefully to reveal any differences in reading accuracy between these conditions. The analysis of experimental results based on the predefined performance metrics showed that subjects completed the Braille reading tasks with higher performance when
they were provided with adaptive speed control of the rotating wheel system. Using the
gestures available with the FMA controller subjects were able to rescan the words, for
which they needed to do reversals. Participants’ subjective assessments on FMA con-
trol was positive in general. Based on the different experimental conditions they took
during testing, they found FMA control helpful in terms of achieving their goals in the
presented tasks.
Chapter 7

Conclusions and Future Work

7.1 Concluding Remarks

Access to digital information in Braille, which serves as the primary reading modality for the blind, plays a crucial role in blind people’s lives in terms of employment opportunities as well as educational and recreational aspects. However, high-costs associated with the existing electronic Braille displays make these devices unaffordable and inaccessible by the blind. Extensive research has been carried out on Braille reading displays with the aim to explore and develop inexpensive alternatives. Nevertheless, limitations of existing Braille displays have not been addressed fully in terms of portability, affordability, efficiency and user-adaptability. In order to overcome these limitations, this dissertation proposed a finger-motion-adaptive algorithm which is employed on a rotating wheel type human-machine interface. The algorithm allows real-time user-adaptive Braille reading by automatically regulating the rotating speed of the wheel, namely the Braille text flow, according to user’s specific hand gestures without using any sensor.

First, a machine-to-machine system is built with the aim to study estimation of external disturbance to machine via disturbance observer based techniques under closed-loop feedback framework. External forces acting on the machine are estimated via the disturbance observer and then used to form an adaptive reference speed with the help of
a feedback controller. System’s stability is analyzed and speed adaptation to external disturbance has been successfully implemented in real-time.

Knowledge gained from machine-to-machine system on disturbance adaptive control is used to develop and implement the finger-motion-adaptive algorithm on a human-machine interface. In order to assess the feasibility of the algorithm, human subject experiments are carried out with sighted people. Braille reading inspired tasks are presented to subjects using a rotating wheel and a touchscreen monitor and evaluated by predefined performance metrics pertaining to task accuracy and task completion. Experimental results showed that subjects were engaged with the presented tasks and their performances significantly increased in the presence of the finger-motion-adaptive algorithm.

Upon successful utilization of the algorithm by the subjects, it is also tested by the target population, namely blind participants. External disturbance estimation and adaptive speed control has been implemented using active disturbance rejection control and a finite state machine. Braille reading accuracy of the subjects are evaluated through Braille reading experiments presented to subjects using a rotating wheel interface. The efficacy of the finger-motion-adaptive algorithm is evaluated through Braille reading experiments performed with blind subjects, whose performances are measured based on reading accuracy. Results showed that finger-motion-adaptive algorithm has been successfully utilized by the subjects to increase their performance in the experiments.

In light of all the results obtained through human subject testing, the finger-motion-adaptive algorithm showed strong promise for creating an affordable user adaptive refreshable Braille reading display.

### 7.2 Future Work

Future research directions include:
• Further investigation on user’s hand motions during Braille reading and extension of the finger-motion-adaptive control to multiple finger Braille reading

• Investigation on mechanical design alternatives for converting the rotating wheel human-machine interface into a refreshable Braille display

• Research on thin compact surface-mountable position sensors such as soft potentiometers which could be coupled with the finger-motion-adaptive controller with the aim the to increase its sensitivity to user’s hand gestures

• Further investigation and classification of finger gestures can help design a controller in more versatile ways to accommodate different user characteristics
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