Exploring the Use of Electromagnets to Influence Key Targeting on Physical Keyboards

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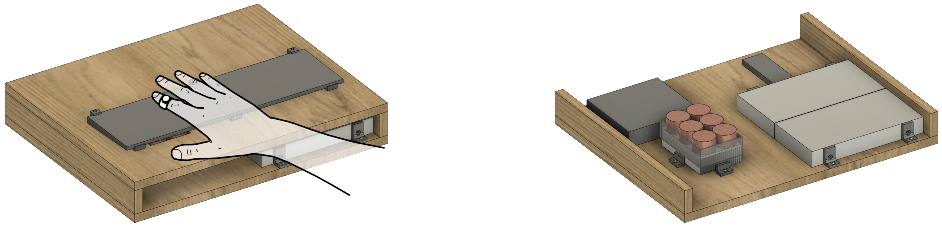

Figure 1: We present a prototype to explore if and how users' key targeting on keyboards can be influenced. This is achieved using a magnetic strip on the user's finger (left) that is actuated with electromagnets below the keyboard (right).

ABSTRACT

In this work, we explore the use of force induced through electromagnets to influence finger movement while using a keyboard. To achieve this we generate a magnetic field below a keyboard and place a permanent magnet on the user's finger as a minimally invasive approach to dynamically induce variable force. Contrary to other approaches our setup can thus generate forces even at a distance from the keyboard. We explore this concept by building a prototype and analyzing different configurations of electromagnets (i.e., attraction and repulsion) and placements of a permanent magnet on the user's fingers in a preliminary study (N=4). Our force measurements show that we can induce 3.56 N at a distance of 10 mm. Placing the magnet on the index finger allowed for influencing key press times and was perceived as comfortable. Finally, we discuss implications and potential application areas like mid-air feedback and guidance.

*Both authors contributed equally to this research.

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CCS CONCEPTS

• **Human-centered computing** → **Keyboards**; • **Hardware** → **Sensors and actuators**.

KEYWORDS

keyboards, typing, output, electromagnets

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1 INTRODUCTION

Keyboards are one of the most widely used input devices for entering text and controlling computers. While the keyboard primarily remains a means to enter text, researchers also looked into how interaction with keyboards can be extended and enhanced. Examples include modifications to the resistance [2, 8, 18] and sensation when touching a key [3, 13, 14], or lights and vibration to provide feedback [5]. With our work, we aim to extend interaction by not only augmenting touch or providing passive feedback but actively exerting force before, while, and after a key is touched. To the best of our knowledge, there are no other systems in the related literature that are capable of doing this. Our system could be used to provide feedback, feed-forward (e.g., warnings), or subtle guidance during keyboard interactions.

To achieve this, we propose an array of electromagnets below a keyboard to exert forces on a permanent magnet placed on the user's finger and consequently on the finger itself. In this paper, we prototypically implement this approach and provide an initial technical evaluation and preliminary study with 4 users to understand how the exerted force is perceived and if it can be used to modify key targeting. We show that we can exert noticeable forces of 3.56 N at a distance of 10 mm. We observe an impact on key press times and errors made as well as a trade-off with the pinkie being easiest to actuate but also liked least. Actuating the index finger allowed for modifying key press times while also being perceived as comfortable. Our work is complemented by a discussion of application opportunities and implications of the introduced approach.

2 RELATED WORK

There are different approaches to augment or influence typing. One option is the use of visual and auditory cues [5] or haptic feedback like vibration [10]. Tactile cues [6, 7, 14] can be used to alter touch sensation, e.g., through ultrasonic waves. Other approaches had great success by changing the structure of a touched surface, e.g., through modifying the stiffness of a hydrogel [13] or using stretched fabric [7]. Another approach is to change the resistance when pressing a key through servos [2] or solenoids [8]. Savioz et al. [17, 18] used electromagnets and permanent magnets under the keys (instead of being attached to the users' finger as in our approach) to control key press resistance. While influencing users was not always the goal in the named approaches some demonstrated such abilities. Hoffmann et al. [8] could reduce typing errors with their approach and participants in the experiment by Bell et al. [2] took more breaks. That said, most approaches are limited in that they require touching a surface (e.g., to feel the resistance or vibration) or are passive (e.g., lights [5]). Our aim is to be able to actively influence users' movements also before and after touch. The best option we see for this are magnetic fields which have also been shown effective in the context of physical keyboards [8, 17, 18].

The use of magnetism to influence users has been researched in the past with both electromagnets (EMs) and permanent magnets. Yamaoka and Kakehi [20] moved a permanent magnet under a table through motorised actuators to control the motion path of a pen and guide users (e.g., to replicate or scale drawings). Zarate et al. [21] developed a sphere with three orthogonally oriented EMs, which exerted forces on a ring-shaped neodymium magnet attached to a pen. Mignonneau and Sommerer [12] created an artefact that simulates atomic forces. It contains arrays of large electromagnets that actuated permanent magnets attached to the user's hand at distances of up to 15cm. Similarly, Weiss et al. [19] used an array of EMs and a permanent magnet attached to a finger to guide users' fingers on tabletops. They created an attraction force right below two touch buttons visualised on the screen and repulsing forces around them. This resulted in reduced cumulative drifting in comparison with their baseline without a force field. In our work we follow a similar technical approach in a different context (keyboards) and with a stronger focus on the impact of design choices (e.g., the placement of the magnet).

3 PROTOTYPE TO INFLUENCE KEY TARGETING

Related work has shown that electromagnets can be used to exert noticeable forces and induce changes in user behaviour. With our work we extend this research to the context of keyboards. The particular challenge is to exert *sufficiently strong* forces also in *mid-air* while using a *minimally invasive* setup (magnetic strip). At the same time the electromagnets (EMs) need to be as small as possible to fit below the keyboard and have to be placed densely to allow for precisely exerting force. In this section, we describe the design and implementation of a first prototype for achieving those goals.

3.1 Electromagnets

While smaller EMs provide a higher density of points that can create attraction or repulsion they also produce a weaker magnetic field.

As a trade-off, we chose a diameter of 40 mm and a height of 25 mm. For our prototype, we created a matrix of six such EMs to cover the left half (as we only actuate one hand) of the keyboard (see Figure 2c). All EMs were built with a self made winding machine[1]. We used self-bonding magnet wire (diameter: 0.58mm, resistance: $0.0871\,\Omega \cdot m^{-1}$) to create stable coils. Such coils also have better cooling capabilities as no additional casing is needed to prevent unwinding. We inserted an iron core into the coils to finish the EMs. Due to minor imperfections in the process, diameters ranged from 35.8 mm to 40 mm and resistance from 7.3Ω to 7.7Ω (measured at 23.7°C). When applying 40 V, we measured currents between 4.2 A and 5.3 A. To achieve a similar force for all EMs we set the maximum current to 4.2 A. We used pulse width modulation (PWM) to dynamically control the force created by the EMs. We used a frequency of 17.5 kHz for the PWM as it is slightly below the maximal audible frequency (20 kHz) and thus hardly noticeable.

3.2 Electronics

Each EM consumes a maximum of 168 W ($4.2A \cdot 40V$). We design for a maximum of three simultaneously powered EMs (504 W) and thus use two 360 W *power supply units (PSU)* that we adjusted to provide 40 V each (9 A); leaving a 216 W margin for current peaks. Each EM has one *current sensor* with a measurement resolution of $0.2V/A$. This allowed us to monitor the consumed current, which is crucial as it is directly related to the created force and can be affected by variations in the coil resistance due to temperature changes. We further included an *envelope detector* to smoothen the current sensor's output signal and filter possible peaks. Next, we sample the data using an analog to digital converter (ADC)[2]. We specifically chose an ADC with a high sampling rate to measure the current signal, since it is influenced by the 17.5 kHz PWM signals. To control our setup we used an ESP32 *micro controller (μC)*, which generates 12 independent PWM signals (i.e., two 17.5 kHz signals per driver with a 10-bit resolution). We isolated the μC to protect it from high currents and to allow for a modular circuit design. We used two *drivers*[3] suited for a current of 3.6 A in parallel for each

[1]https://github.com/bonafid3/CoilWinder, *last accessed March 6, 2023*
[2]MCP3008, ADC with 8-Channel, SPI capable with a max. sample rate of 200 kilo samples per second and 10-bit resolution
[3]DRV8871 motor driver breakout boards,https://www.adafruit.com/product/3190, *last accessed March 6, 2023*

(a) The matrix of electromagnets is on the left and the power supply units are on the right side. The microcontroller is situated behind the power supply units.

(b) Top view of our finished prototype. The keyboard is fixed with 3D-printed clamps and an emergency button is placed in the right corner.

(c) Dimensions and placement of the electromagnets under the keyboard.

Figure 2: Overview of our final prototype consisting of a wooden box a) housing the EMs and the electronics, b) the keyboard mounted on top. Figure c) shows how the magnets are placed under the keyboard

EM. Both drivers in parallel can handle a current of a maximum 7.2 A – enough for the required 4.2 A and potential current peaks. Please refer to Appendix A for detailed schematics of the circuit.

3.3 Assembly

We built a portable wood box that contained the EMs and attached the keyboard on top (see Figures 2a and 2b). A cut-out on the top panel of the box exposes the EMs. We used a generic wireless keyboard[4] with a QWERTZ layout. The keyboard contained a steel sheet, that we cut to accommodate the EM matrix, remove all magnetic elements between keys and EMs, as well as to minimize the distance to the top to 5.84 mm, leading to more exerted force. We used an aluminium cooling block and thermal pads to cool the EMs. To exert forces on the users' fingers we built a magnetic strip that is attached to a finger and actuated by the magnetic field. We sewed a cylindrical N52 neodymium magnet (10×8.5 mm) to a velcro strap (see Figure 3). It is reusable, adjustable to different finger sizes, and sufficiently rigid to avoid the rotation of the magnet.

4 EVALUATION

The aim of this paper is to evaluate if our prototype can generate sufficient forces to influence a user's finger movement and could thus in a next step be used to influence typing. To this end we 1) measure the forces exerted on the magnetic strip and 2) conduct a preliminary user test to determine the best electromagnet configurations (strength and direction of the force) and positioning of the magnetic strip to induce noticeable changes.

4.1 Force Measurements

We measured the force exerted to a cylindrical N52 10×8.5 mm neodymium magnet (as used in the magnetic strip) with a force gauge (Sauter FK10) while applying constant currents to the EMs.

4.1.1 Maximum Force. To determine the maximum force we measured repulsion exerted by the EM to a permanent magnet centered above the core while changing currents and distances. Figure 4a illustrates the exponential decrease of force with respect to distance (e.g., 0.90 N for 4 A at 25 mm vs 3.56 N at 10mm). We measured a maximum force of 3.56 N for a distance of 10 mm at 4A. For 3 A, 2 A and 1 A we measured 2.91 N, 2.01 N and 1.04 N respectively.

4.1.2 Force Distribution. To understand the interaction between EMs we also performed measurements at 2 A in 5 mm steps in the orthogonal and parallel planes with two EMs side by side. Figures 4b (side) and 4c (top) show, that the measured force in points between the two EMs is greater than the force in points that are situated on the outer sides. For example, we measured a force of 0.48 N (between) in comparison to 0.3 N (outside). This implies that we can exert more consistent forces within the EM matrix, while the field rapidly decays when reaching the outer border.

4.2 User Study

To find the best configuration for influencing finger movement we conducted a pilot study, exploring both the choice of finger and positioning of the strip thereon under varying exerted forces.

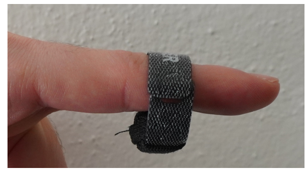
4.2.1 Conditions & Measurements. We used a within-subject design with 3 independent variables: We vary magnetic CONFIGURATIONS between *50%* and *75%* of the maximum current (2.1 A and 3.15 A respectively) for both, *attraction* and *repulsion* as well as an additional *off*-condition. We decided against stronger currents to avoid potential overheating. We explored placing the magnetic strip on all FINGERS but the thumb as it is not commonly used for typing letters. We further placed the strip at the top and bottom POSITION of each phalanx of the fingers[5] (see Figure 3). We excluded the bottom of the distal phalanx because of the resulting inability to press a key and the top of the proximal phalanx due to the large distance to the EM. To assess the best position we captured typing-related measures like key press duration, flight time, and error rate as well as subjective feedback on the comfort and noticeability of the force.

[4]https://www.amazon.de/gp/product/B089FF153B/, *last accessed March 6, 2023*

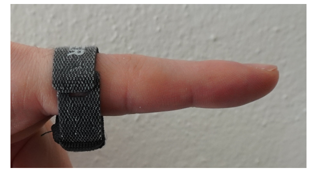
[5]*Phalanges* are the bones forming the fingers. From fingertip to palm they are called *distal phalanx*, *intermediate phalanx*, and *proximal phalanx*.

(a) Pos. 1: distal (top)

(b) Pos. 2: intermediate (top)

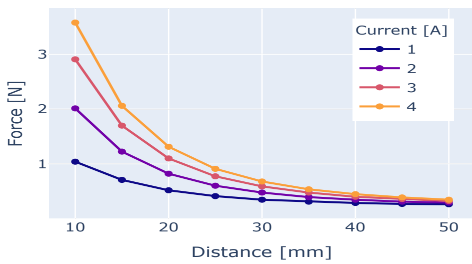


(c) Pos. 3: intermediate (below)

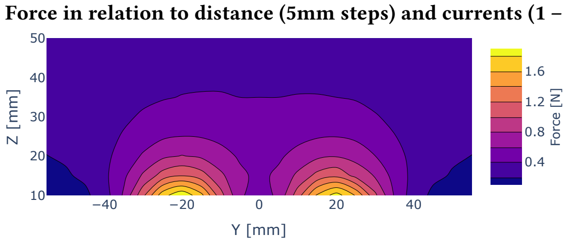


(d) Pos. 4: proximal (below)

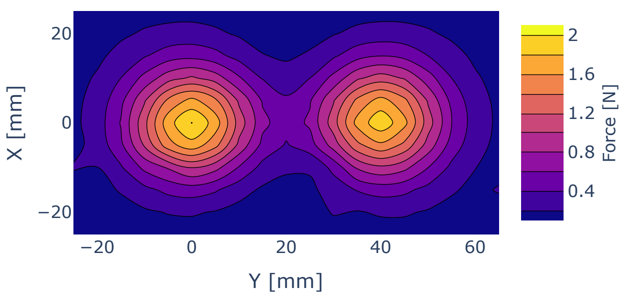
Figure 3: Positions of the magnetic strip in our study.



(a) Force in relation to distance (5mm steps) and currents (1 – 4A).



(b) Side view of the force field of two EMs at a current of 2A.



(c) Top view of the force field of two EMs at a current of 2A (measured 10mm above the EMs).

Figure 4: Results of force measurements in a regular 5mm grid: a) We measure a maximum force of 3.56N for 4A and a distance of 10 mm that decreases exponentially with distance. When combining two EMs their magnetic fields merge (b, c).

4.2.2 Procedure. Participants answered a demographic questionnaire before the magnetic strip was placed on the first position. Subsequently, they entered a specific two-key-sequence five times. Each repetition included pressing Ctrl and then one of the keys *y*, *s*, or *w*. The target key varied depending on the *position* of the magnetic strip and was chosen so that the strip was always situated over the bottom left EM (see Figure 2c) when typing the key. Note, that for this preliminary test, only this EM was active and we did not evaluate interaction effects of multiple EMs. All participants first repeated the task for all EM configurations at the first position (top of distal phalanx) of the first finger (index finger). This procedure was repeated for all positions on the first finger before changing to the next finger. The force configurations followed the order: 1) both attraction configurations, 2) off, 3) both repulsion configurations. After each configuration participants filled in a questionnaire. Placing the off-level between the attraction and repulsion allowed the EMs to cool down before being turned on again. The order of force magnitudes (50% and 75%) was balanced between tasks. At the end of the study, participants filled out a final questionnaire with questions on the study experience. Overall participants completed 80 tasks (5 configurations, 4 fingers, 4 positions) and filled out 50 questionnaires (48 task questionnaires, demographics, and final questionnaire). The study took about 105 minutes per participant.

4.2.3 Participants. We recruited 4 participants (ages 26–64, two male, two female). They all type more than two hours per day. *Note*: this evaluation is intended as an initial test of possible prototype configurations so we chose a small sample. We intend to investigate actual typing in a larger study with more participants next.

4.3 Influence on Key Targeting

To account for learning effects we discarded the first repetition of each task. Given the small sample size, we do not conduct statistical tests but report general tendencies. We found that the overall mean key press duration was 0.111s ($\sigma = 0.037s$) and the mean flight time was 0.398s ($\sigma = 0.107s$). Participants made a total of 34 errors (i.e. hit a wrong key) but 306 of the 320 conducted tasks (80 tasks per participant) did not include errors. Results are shown in Figure 5.

We observed mostly comparable results across *fingers*. However, both flight time and key press duration were longer when using the pinkie. Similarly, 30 of the 34 errors were made when using this finger. Regarding the *position* of the magnetic strip we saw no clear impact on the flight time but longer hold times in the first and third positions. This effect particularly shows for the pinkie and index finger (only for the first position). Most errors (30) occurred in the third position. The *configuration* had no clear impact on flight time but impacted key press times with time increasing for attraction compared to repulsion. This is most prominent in the first position. Most errors (30) were made in the attraction conditions. In *summary*, errors mainly occurred for the combination of pinkie, third position, and attraction. Effects were generally more pronounced for the pinkie. While flight time was mostly unaffected we observed longer key press times in the first and partially also third positions that increased with stronger attraction.

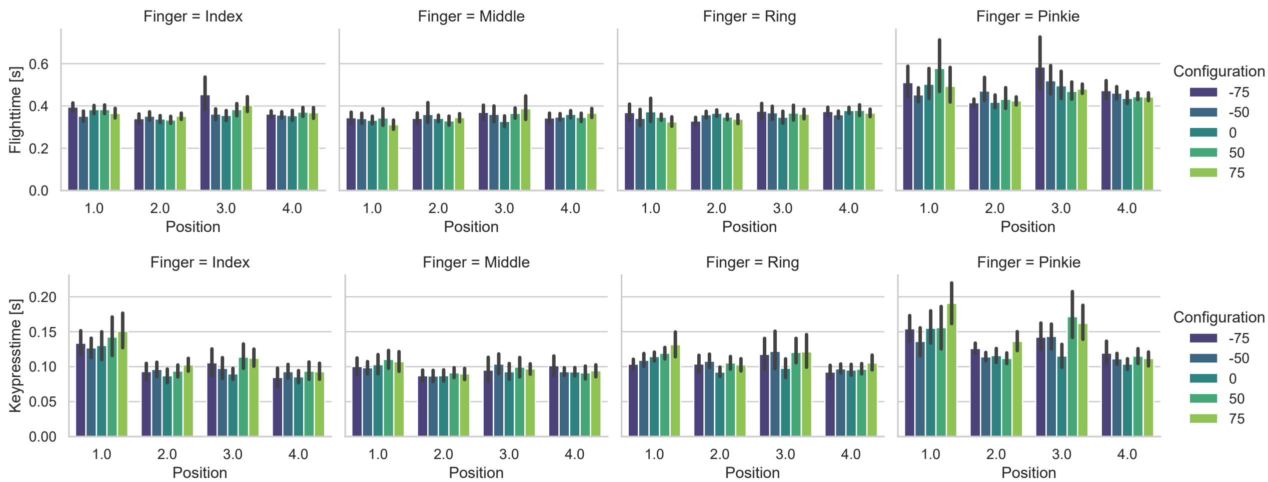


Figure 5: Flight time and key press time depending on *finger* used, magnetic *configuration* applied (negative values denote repulsion) and the *position* of the magnetic strip. Errors mainly occurred for the pinkie in the third position under attraction.

Table 1: Median participant response to the Likert items presented after the tasks from 1 (totally disagree) to 5 (totally agree).

	Finger				Position				Configuration		
Statement	*Index*	*Middle*	*Ring*	*Pinkie*	*1*	*2*	*3*	*4*	*Repulsion*	*Off*	*Attraction*
Force was noticeable	2	2	2	2	2	2	2	2	2	1	3
Typing was comfortable	4	4	3	2	3.5	3.5	3	3	3	3	3
Typing was influenced	1	2	2	3	2.5	2	2.5	2	2	1.5	2.5

4.4 User Perception

Participants were asked to rate Likert statements from 1 (totally disagree) to 5 (totally agree) after each task block. The results are shown in Table 1. Participants generally rather disagreed to *noticing* the force except for the attraction configuration which was rated neutral. *Comfort* was rated best for the index and middle finger (Mdn=4) and decreased towards the pinkie (Mdn=2). Both position and configuration were rated as neutral (3<Mdn<3.5). Conversely to the comfort, the participants' feeling of being *influenced* increased from the index (Mdn=1) to the pinkie (Mdn=3). Participants felt slightly more influenced in the first and third positions (Mdn=2.5) as well as under the attraction configuration (Mdn=2.5) compared to repulsion and the other positions (Mdn=2).

In the final questionnaire, participants rated the force for positions three (under the middle phalanx) and four (under the proximal phalanx) as the most noticeable. They felt the strongest force for the ring finger and pinkie. Participants liked the off-condition best, followed by attraction at 50% and repulsion at 50%. The least preferred options were both 75% configurations. For a direct comparison, 3 of our 4 participants generally perceived the attraction as stronger than the repulsion. Two participants rated attraction to be more comfortable, while the others found both conditions to be equal.

4.5 Limitations

Reflecting the preliminary nature of our study our sample was quite small so results may not generalize to the general public. We also simplified the interaction for the study and used only a single EM at a time. Hence, we have no insights into the interaction effects of multiple EMs (as can be seen in Figure 4). Furthermore, we limited the supply current to avoid potential overheating. A more effective cooling mechanism could reduce this for future applications.

5 DISCUSSION AND NEXT STEPS

5.1 How to Influence Users' Key Targeting?

We found, that exerting forces on the pinkie was most effective in influencing users' key targeting. It led to more errors, longer key presses, and flight times. It was also perceived by participants as the most influencing. Furthermore, our results show that the exertion of forces on the various fingers affects the key-targeting less the closer the finger is to the thumb. Hence, participants rated the index and middle finger as comfortable but participants felt less influenced. We assume that this is connected to the strength of the fingers and their frequency of use in daily life. However, it also implies, that there is a trade-off: Placing the strip on one of the weaker fingers opens more opportunities for manipulation but was rated less desirable. With regard to the positioning we observed that placing the strip at the fingertip (first position) lead to a longer key press duration that increased when moving from repulsive to attracting configurations. This makes sense, as placing the strip at the fingertip means the force is applied right at the touch-point (and with a longer lever). Overall, placing the strip on top of the fingertip of the index finger may be the best option, as it combines the perceived comfort of the index finger and the observed (but not perceived) possibility for targeted key press time manipulations through different electromagnet configurations.

5.2 Applications

To use our prototype in a running system, further tests, adaptations, and extensions will be needed. Nonetheless, we would like to outline some application examples and describe how our approach could either enable or improve them.

The addition of feedback is beneficial in most areas of human-computer interaction (HCI). However, feedback (e.g., vibration feedback to confirm a button press) can only be given *after* an action. By inducing repulsion or attraction we can instead provide *mid-air feed-forward information*. A user can thus *anticipate* the consequences of an action before it is executed (e.g., induced resistance on the enter key could indicate missing information in a form).

Our approach also has potential for *learning applications*. Pangaro et al. [15] showed, that with additional tracking an array of electromagnets could be used to precisely guide a permanent magnet in a 2D plane. This could be transferred to guiding a user's fingers, e.g., for learning to type with 10 fingers. For learning timing tasks (e.g., playing music or gaming) no tracking is required: users could be guided by targeted attraction and repulsion alone.

Beyond text production, the unique way a user types can also be used to identify them [1, 9] using so-called keystroke dynamics. While this comes with benefits like seamless and continuous authentication it can also happen unwanted or unnoticed (e.g., a website recognizing users without cookies). Mecke et al. [11] showed that this can be mitigated through intentional behavior change. Our approach enables a low-effort alternative. Through random attraction and repulsion a user's unique *typing patterns could be veiled*, making identification harder or potentially even impossible.

5.3 Next Steps

In our work, we only influenced a single finger. While this may be enough for many applications (e.g., mid-air feedback or teaching one finger at a time), other approaches may require being able to influence multiple fingers. One way could be the use of multiple magnetic strips per hand (e.g., to influence the pinkie and thumb which are commonly responsible for using the space bar and enter key), though the magnets could interact and lead to unwanted effects. The question of how to address this remains up for exploration, but one solution may be using gloves with small, embedded electromagnets that can be activated on demand. An additional requirement for many applications is tracking. Park et al. [16] made use of a magnetic ring and the smartwatch magnetometer to identify the finger used for interaction. Our prototype could achieve this by measuring the induced current of the magnetic strip on the electromagnet matrix to determine the finger used. Alternatively, Dai et al. [4] have shown, that using magnetic sensors (below the keyboard in our case) it is possible to track the position and orientation of a permanent magnet.

For our prototype, we made specific decisions with regard to the size and placement of the electromagnets as well as the magnetic strip to generate sufficient force to exert noticeable effects on a user's finger. As a next step, we plan to build smaller magnets to be able to more precisely target keys. This may be achieved by choosing thinner wire to enable more windings or experimenting with stronger permanent magnets. Note, that requirements also strongly depend on the application (see Section 5.2) (e.g., guiding a user's finger may require a better resolution but could be subtle and thus use less force). Moreover, while we used a regular keyboard, alternatives such as ergonomic keyboards could also be interesting for future research. We look forward to discussing future applications and improvements with attendees at CHI.

6 CONCLUSION

In this paper, we presented the design and implementation of a prototype to exert forces on a user's finger with the goal of influencing key targeting. To achieve this, we generate a magnetic field using a matrix of electromagnets under the keyboard. A permanent magnet on the user's finger serves to transmit the force. We describe the design and implementation and suggest areas, where the ability to induce force without requiring touch can be leveraged to enable new applications or improve existing ones.

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A SCHEMATICS OF THE ELECTRONICS

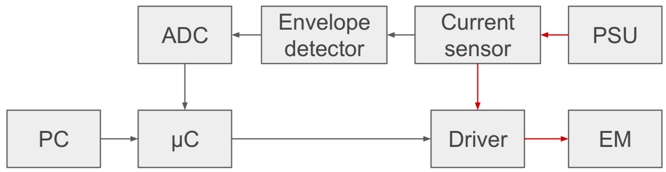

Figure 6: Overview of the components of our prototype and their interactions. Red lines indicate a high current. The power provided by the power supply unit (PSU) is monitored by the current sensor. Hence, the current sensor measures the current that drivers and electromagnet (EM) are consuming and sends the measured signal to the envelope detector. The signal's envelope continues to the analog-to-digital converter (ADC). The digital data is then processed by the microcontroller (μC), which communicates with the motor drivers to control the EM.

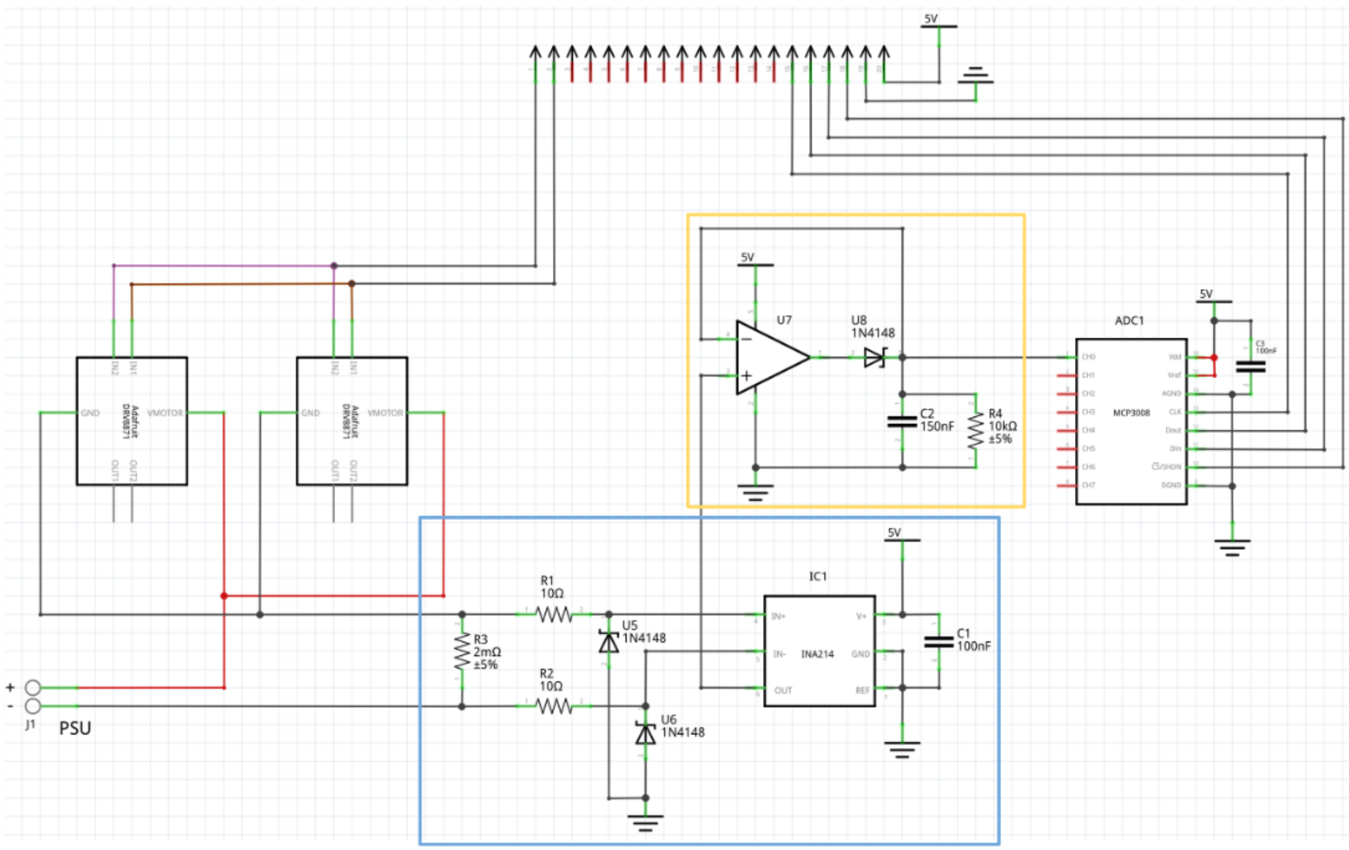

Figure 7: Schematic of our circuit except for the microcontroller. The current sensor is marked blue, and the envelope detector yellow. The ADC is shared between EMs.