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Lock Picking Simulation Using Visual and Bimanual Haptic Display

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ABSTRACT

As locks become more and more complex and numerous, locksmiths have less opportunity to practice on and find design flaws with each type of lock. As in other fields, such as dentistry, haptic simulations can provide an alternative form of practice. Lock picking is inherently suited to haptic simulation, as feedback during lock picking is limited to the sense of touch, and the inner workings of locks are intentionally hidden to prevent easy inspection. The technique used to bypass a simple pin-tumbler lock relies on haptic feedback experienced through both hands, with one hand managing a tension wrench and the other hand manipulating a pick. A visual-haptic simulation of pin-tumbler locks that mimics the sensations of lock picking was developed and tested. Experimental results show that haptic training with our simulation enables participants to more quickly pick their first tumbler lock and provides better preparation to pick more difficult locks. Our visual-haptic simulation could be used to provide practice on increasingly difficult locks, and if generalized, could be used to model any number of complex locks on the market, enabling locksmiths and lock-designers to test the security of various locks, or to train apprentices.

KEYWORDS: Haptic, visual, virtual, bimanual, multi-display, simulation, lock, key, wrench, pick, feedback, locksmith, design, touch.

INDEX TERMS: Haptic interfaces, Force feedback, Human-robot interaction, Graphical models, Emulation, Computer aided instruction, Educational robots.

1 INTRODUCTION

We rely on locks to protect our homes and belongings. Pin-tumbler locks, commonly found in deadbolts and doorknobs, can be found throughout the world. However, an experienced lock-picker could potentially bypass one of these locks in less than sixty seconds [1]. Anyone who has locked themselves out of their home knows that it is invaluable to have a locksmith around with experience opening these locks.

As locks become increasingly complex and expensive it may become impractical for locksmiths to own every lock available on the market. Additionally, in practicing for their trade, locksmiths may also find it useful to see the moving parts inside new locks while they interact with them. To this end, we developed a haptic program that simulates the complex dynamics inside a pin-tumbler lock. A simple feasibility study was then done to investigate the ability of such a program to assist in the learning and understanding of these locks.

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Lock picking simulation holds a myriad of benefits. Locksmiths could have a stable platform to practice on a wide variety of lock models. Then, when necessary, the locksmiths would be prepared to bypass the actual locks, with less risk of damaging the soft-metal parts of the actual lock. The simulation would also provide lock manufacturers with the ability to test the security of new lock designs within an interactive environment, immediately (and cheaply) finding obvious design flaws before mass-producing actual parts and locks.

An obvious alternative to haptic simulation is to create transparent physical models of each lock to practice on. While these models would provide realistic interaction, a different model would need to be produced for each design, which would take time and money. Haptic simulation provides a much more flexible platform to interact with and develop a variety of different locks.

The haptic cues presented by our lock picking simulation program match those from our own experiences and those described in books written by the master locksmith Steven Hampton [1], [2]. In his works he describes specific haptic cues that are present when picking various locks. He also provides images to help conceptually bypass various locks, patterns for picking tools, and caution against illegal use of his techniques. Many books and sources are available for learning how to bypass various simple locks, but few refer to these techniques as belonging to the field of haptics (e.g., see [1]–[3]).

2 THEORY

2.1 Pin-tumbler Locks

To understand the theory of lock picking it is necessary to understand the internal workings of the lock and the tools used to pick locks. Figure 1 shows a cross-sectional view of a pin-tumbler lock, and will be referred to throughout this paper. A typical pin-tumbler lock consists of three primary parts: the housing, cylinder, and five or six sets of pins and springs.

The housing is secured to a door along with a latch (possibly a deadbolt). It provides the structure for the lock, holding each

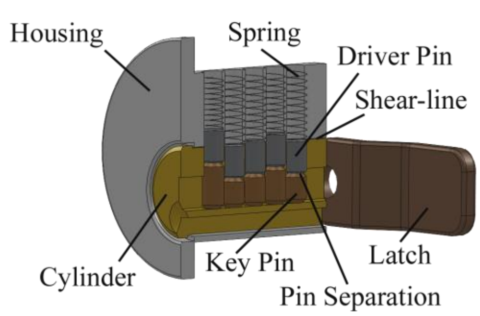

Figure 1. Cross-sectional view of a pin-tumbler lock with latch.

component aligned and contained, and may provide mounting holes for the system.

The cylinder fits snugly within the housing such that it is able to freely rotate but not shift axially. It is held in the housing by a lip on the front and a removable nut on the back. Typically, this nut and the cylinder are attached to the latch which engages and disengages as the cylinder is turned.

A hole for each set of pins is vertically bored into the top of both the housing and the cylinder. Each pin set consists of a spring, driver pin, and any number of key pins (depending on the number of different keys designed to work with the lock). The spring causes the pins to push inward and against the key when it is inserted. All driver pins within the lock are the same length, and are positioned between the spring and key pin(s). The lengths of the key pins vary to match the displacement grooves of the key. When the proper key is inserted, as shown in Figure 2, the tops of the key pins align with the shear-line separating the housing from the cylinder. In the case of locks that accept master keys (such as are common within apartment complexes), multiple key pins are used in a set, allowing more than one key to align the key pins with the shear-line. Consequently locks that accept multiple keys are inherently easier to pick because more opportunities exist to properly align the key pins. If an incorrect key is used, all the pins will not align with the shear-line, thus preventing the cylinder from rotating and the lock from opening.

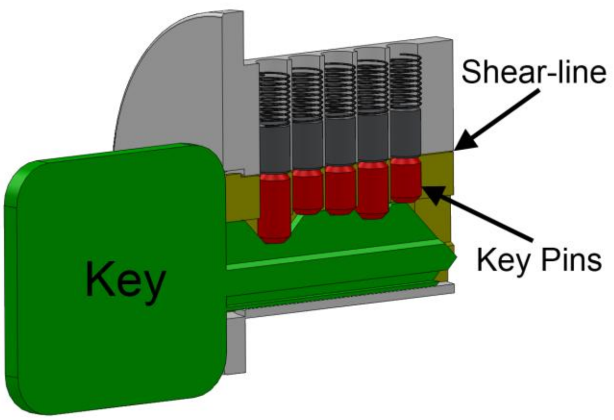

Figure 2. Key-pins align with the shear-line when the proper key is inserted.

2.2 Picking a Pin-tumbler Lock

The picking of a pin-tumbler lock can be accomplished using two instruments such as those shown in Figure 3. The first (A) acts as the pick (fashioned in this case from a bent safety pin), and the second (B) acts as a tension wrench (based on a pattern suggested by [1]). The tension wrench is inserted into the base of the key entryway and used to apply a torque to the cylinder. This torque creates enough friction force on the pins to hold them in position against the spring and gravitational forces. The amount of pressure applied to the wrench is a delicate balance. Too much pressure and the pins may jam or the lock may be damaged. Too little pressure and the pins will not stay in place as they are individually pushed upward to match the shear-line.

While the friction from the tension wrench holds the pins in place, the pick is inserted into the key entryway and used to lever the pins to the proper position with respect to the shear-line. As the pin separation of each pin set reaches the shear-line, the cylinder moves slightly, creating a vibration that can be felt by the lock picker through both picking instruments (as is also rendered

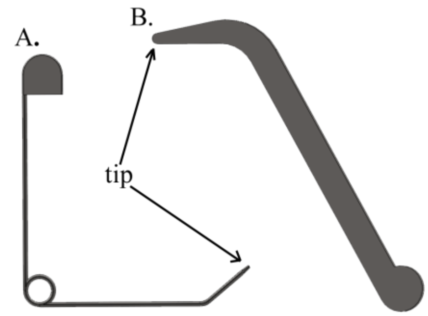

Figure 3. Simple lock picking instruments. (A) Pick made from safety pin and (B) tension wrench.

in our simulation).

Some locks provide additional measures of protection against picking. One such measure includes replacing the cylindrical driver pins with mushroom pins (see Figure 4A) whose midsections are a reduced diameter. As the midsection of the mushroom pin reaches the shear-line the cylinder moves slightly, providing the lock-picker with a false sensation of bypassing the pin along with hindering any further motion of the pin. Another security measure taken may include spring-loaded cylinders. These locks make it difficult to apply the proper friction force needed to hold the pins with the wrench. Mushroom pins are not included in our simulation program, but spring-loaded cylinders are.

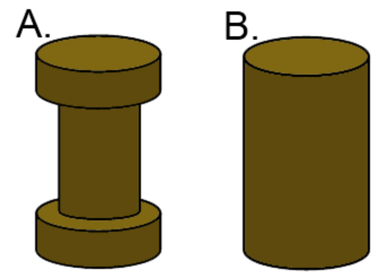

Figure 4. (A) Mushroom and (B) cylinder style driver pins.

3 The Lock Picking Simulation

The lock picking simulation program was written in C++, using OpenGL for graphics and CHAI3D [4] for quick prototyping and model interaction. The program was designed to mimic the internal mechanism and dynamics of a pin-tumbler lock. Models used in the simulation for each component of the lock were created in SolidWorks and exactly match the size and scale of their real world counterparts used in the experiment in Section 4. Each pin's position was dynamically updated based on friction, gravity, and spring forces as well as forces from the pick provided by the user (see Figure 5). Simple constraints were placed on the models to ensure the dynamics were computed properly and efficiently. For example, the pins were assigned a mass and only allowed to move axially along their holes, and coulomb friction was computed as a function of wrench and spring-loaded cylinder forces (where the wrench force minus the force contributed from the spring-loaded cylinder is the normal force in the friction model). The pins' dynamic motions were determined through numerical integration techniques based on the computed friction forces, pin mass, spring stiffness, and gravitational forces.

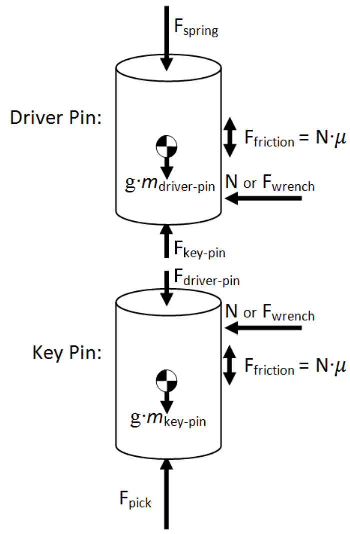

Figure 5. Forces used in the dynamic simulation acting on the key-pin and driver-pin.

Additional haptic cues, such as the transients triggered when compromising a pin, were implemented separately and added to the other interaction forces.

Haptic interactions are displayed using two separate devices to roughly match the two tools used to pick locks (see Figure 3). When a tension wrench tool is used properly it is constrained to a single axis of rotation (i.e., that of the cylinder's axis of rotation) and thus can be adequately represented by a one degree-of-freedom device. A Utah haptic paddle [5] (similar to the Rice University design [6]) is used to display the wrench forces, directly computed from the cylinder and pin positions, based on a simple spring model to represent the cantilever bending of the tension wrench as force is applied to it. The Utah haptic paddle uses a single Maxon RE35 DC motor with encoder through a capstan pulley system to provide rotational forces to the handle.

In order to more closely mimic the actual motion of a tension wrench for the purposes of this simulation, it is undesirable to have the user manipulate the handle at the top of the haptic paddle. Therefore, a lock picking wrench attachment was rapid prototyped via Fuse Deposition Modeling (FDM) and added to the handle of the haptic paddle. This allows the haptic paddle to present forces to the user in the same manner and orientation as the tension wrench. This attachment can be seen in Figure 6.

The pick needs to move with six degrees-of-freedom when interacting with the elements of the lock. These interactions were rendered using a PHANToM Omni [7], because it was readily available and could sense all six degrees-of-freedom. No modifications were made to the Omni since it could already be manipulated in a manner similar to the lock pick. However, while Omnis sense with six degrees-of-freedom, they can only provide forces and not torques, and thus are considered a partial-force feedback system for our application [8], [9]. Instead, the authors chose to limit the simulation to partial feedback because most forces in actual lock picking occur within a small space and thus these forces are more significant than corresponding torques during lock picking. This partial-force feedback system provides a more economical approach to simulating this environment than a full-force feedback device such as a PHANToM Premium 6 DOF [10] or a custom designed device for lock picking. Since only forces could be rendered, the virtual pick was haptically represented by a spherical proxy at its tip, and all computed forces are spatial. That is, we did not represent the reaction torques that would occur due to lateral confinement of the length of the pick within the keyway. While both of the haptic devices are larger than their physical counterparts, the scale difference between the haptic devices and actual tools, along with the additional hand separation, did not appear to significantly alter the perception of the haptic cues provided to our users (see Section 4).

Both the haptic paddle and Omni were placed at the edge of the table in front of the monitor in locations analogous to the simulated wrench and pick, as can be seen in Figure 6. Forces generated through the haptic interactions were calibrated to closely mimic the same magnitudes felt when picking similar real locks such as those used in the study we present in Section 4.

In addition to providing proper haptic cues, a graphical display of the virtual lock could be rotated and cut away to show the internal workings while the user interacted with the pins (see Figure 6 and Figure 7). Although the graphical display appeared as a scaled-up version of the workspace, it did not impact the computations used to determine the dynamics of the pins or interactions.

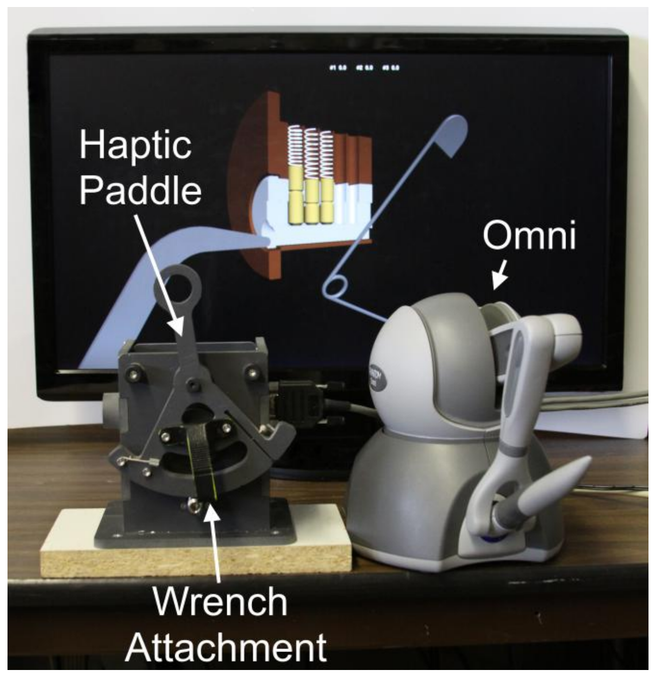

Figure 6. Image of lock picking simulation setup, computer monitor display, haptic paddle (left), and PHANToM Omni (right).

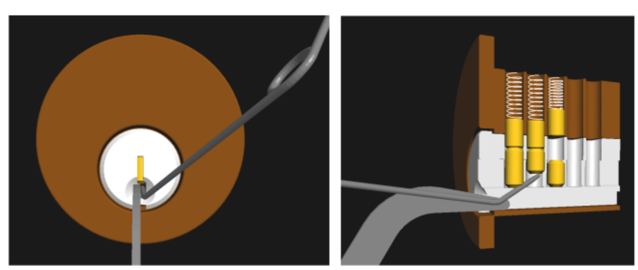

Figure 7. User modified views of the lock assembly: front view (left) and cross-sectional view (right). Users could toggle between these views during haptic training.

4 User Evaluation

4.1 Design and Procedure

A study was performed to evaluate the potential of our lock picking program to assist in learning about the internal mechanics of typical pin-tumbler locks while picking a lock. The study consisted of teaching untrained participants to pick a lock followed by picking three actual locks. After a break, we asked the participants to pick the physical locks a second time to test for learning retention. We simplified both the simulated and actual lock picking tasks by removing all but 2 or 3 pin sets from each lock, which allowed untrained participants to pick the locks more easily (and kept the experiment duration tractable).

Pre-test lock picking training took the form of either visually explaining how these locks work, or through both visual and haptic training. During the visual portion of the training the proctor explained and demonstrated how to pick a lock on our developed simulation as the participant watched, similar to how the authors learned to pick locks. All participants received visual training. Half of the participants also received haptic training.

The participants who received visual-only training were immediately asked to pick the real locks after training was complete. The second group, who received both visual and haptic training, was allowed to haptically interact with the lock picking simulation program after receiving the visual training. They were allowed to change the visual representation from a solid to cut-away view, as well as rotate the display as they desired (see Figure 7). Once these participants felt comfortable with the workings and feel of the internal mechanism they were required to pick the virtual lock three times while the mechanism was hidden to show competency before picking the real locks. The haptic training took an average of 6 minutes to complete with each final pick attempt requiring an average of 12.24 seconds to complete. When a participant was ready to pick the real locks both the haptic paddle and Omni were pushed aside and the board containing the real locks was put in their place and clamped to the desk (see Figure 6 and Figure 8).

Participants were given a maximum of 6 minutes to pick each lock, after which they were stopped and the time was recorded as a failure (a 6 minute completion time was recorded for analysis purposes). A 2-5 minute break was required before picking the next lock to allow the participant's hand muscles to rest before the next lock was attempted. Participants were asked to pick each of the three locks again, in the same order, after waiting at least 15 minutes. Several participants could not finish immediately and returned a day or two later to finish testing. However, despite the longer break, their results follow the same trends as the remainder of the participants and their data are included in our analysis.

The real locks were Ace Hardware brand locks for residential door deadbolts, with each lock mounted 200 mm apart onto a vertical board at an appropriate height to simulate picking a door lock. The three locks were picked from the left to the right and increased in difficulty with each one (see Figure 8). Initial testing indicated that locks with 3 pins were too difficult for participants who received visual-only (non-haptic) training to begin with. Thus the first lock contained only 2 pins to allow each participant to more easily succeed on their first lock – both to avoid frustration and to provide positive feedback that their methods were a result of their lock picking understanding, rather than just luck. The remaining two locks contained 3 pins each; with the third lock possessing a more challenging pin configuration.

Figure 8. Physical locks: 2 pin (far left) and 3 pin (right).

Twenty-six participants between the ages of 20 and 39 (4 females) were evaluated, and took an average of one hour to complete the experiment. Half of the test participants completed the experiment in each condition. In contrast to typical testing practices with haptic devices white noise was not played during the training or during picking of the physical locks, as professional locksmiths also use the sounds from the locks as cues during picking.

4.2 Results and Discussion

All participants were able to pick Lock 1 (simple 2 pin) on their first attempt. However, not every participant was able to pick Locks 2 and 3 (3 pins) within 6 minutes each. Figure 9 shows the total number of failed pick attempts for each lock attempt for all participants combined.

Over 50% of visual-only trained participants failed to pick Lock 3 during both the first and second attempts. As expected, participants who received haptic training were more capable of successfully picking each lock. Thus individuals trained on this system would be more likely to bypass an actual lock with less risk of damaging the soft-metal parts inside the lock. Participants performed better on their second attempts at Locks 2 and 3, as shown by the reduced number of failed attempts.

A t-test indicated that in addition to being more successful at picking the locks, the participants who received haptic training were significantly faster at picking their first lock [$t(12) = 3.452$, $p = 0.005$]. However, no other lock picking attempts were

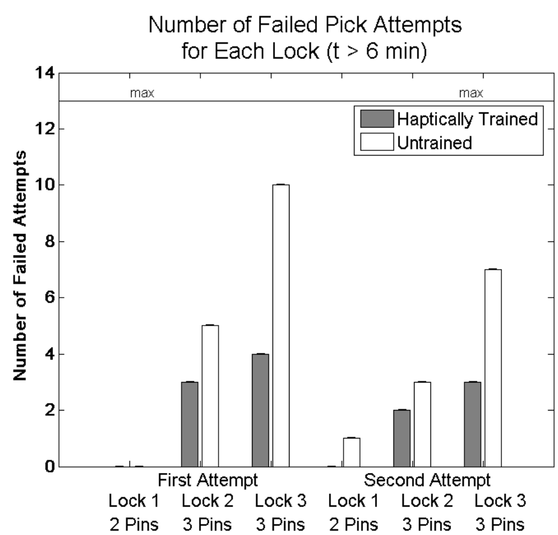

Figure 9. The total number of failed pick attempts, for each lock attempt, for all participants combined. Participants were stopped after 6 minutes and a failure was recorded for that attempt.

significantly different in completion time between haptically trained and visually trained participants. Figure 10 shows the means and confidence intervals of the time taken for each lock attempt. Failed attempts were recorded as 6 minutes and are included in the statistics of this plot.

As can be seen in Figure 10, the time to complete more difficult locks increases, though not significantly. While neither of the following two trends are significant, a larger population of participants would likely show significance. Initial power estimations indicated a sample size of 24 participants would be sufficient to show significance. Our revised power estimations, however, indicate the sample size needed to show significance would require a little over 100 participants, which is beyond the scope intended for this simple demonstration study. The use of a custom device for the pick and wrench could potentially reduce the necessary number of participants needed to show significance. Nonetheless, in each case the haptically trained participants were able to pick the locks more quickly than visually trained participants. It is also clear that all participants were able to more quickly pick the locks on their second attempts, with decreasing improvement with more difficult locks.

When the first and second attempts are combined for each lock, the difference between trained and untrained participants grows larger. Both Lock 1 [$t(25) = 2.6305$, $p = 0.0144$] and Lock 3 [$t(25) = 2.1890$, $p = 0.0381$] show a significant difference in picking times between the trained and untrained participants. Lock 2 also appears to be approaching significance [$t(25) = 1.3921$, $p = 0.1762$]. This shows that in addition to having fewer failures the trained participants are also faster than those without training.

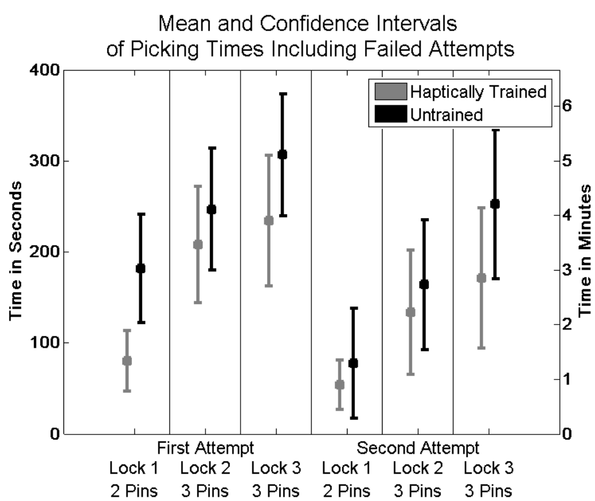

Figure 10. Means and confidence intervals for each of the attempts on the locks. Failed attempts are included in the statistics as 6 minutes or 360 seconds.

5 Conclusion

We have designed and implemented a lock picking simulation using a haptic paddle, PHANToM Omni, visual display, and libraries from CHAI3D and OpenGL. In the simulation the user experiences force feedback similar to actually picking a lock, as well as the sensations that occur when each pin is bypassed. Realistic pin dynamic behavior is implemented within the simulation. The pins respond to ever-present spring and gravitational forces, frictional forces that are modified by the application of wrench forces through the haptic paddle, and forces applied to the pins using a PHANToM Omni.

We have shown the potential for haptic simulations to be utilized in the field of lock design and picking. Our lock picking simulation portrays the lock picking experience with enough fidelity to assist participants in learning the feel of locks and lock picking methods. Training with our simulation increases participants' lock picking success rates and has the potential to reduce the required completion time.

To make further improvements to the lock picking simulation, it can be expanded to include multi-point collision detection and utilize a custom haptic device that better mimics the lock picking experience, including more realistic tool sizing and full 6 DOF force feedback on the pick. The haptic rendering program itself could then be expanded to allow multiple pins to be in contact with the pick as is commonly the case when picking locks. This program could be generalized to allow any kind of lock thus allowing locksmiths to practice their trade on any number of locks and lock designers to investigate the potential problems with their designs before production. A training program could also be written to provide lock pin-set compositions that incrementally increase the difficulty of the lock, including lock-picking problems imposed by mushroom pins. Guiding forces could also be added to the program to provide initial help to the user when they are first learning the spacing and internal positioning of the lock. The realism of the simulation could also be improved through rendering high-frequency tactile feedback for both the wrench and the pick displays, as well as audible clicking, when each pin set is compromised.

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