Finding a Master Lock® Combination through System Identification

G. Zak, B. Peters, and D. Erb

***Abstract*—The aim of this project is to find the combination of an unknown Master Lock® padlock through mechanical system identification. System characterization is performed by displacement feedback on the lock shackle using force perturbation. By taking displacement measurements through three rotations of the lock dial, two of the combinations numbers are found. As such, the combination can be solved in at most ten attempts, as opposed to approximately one hundred through alternative numeric algorithms.**

***Index Terms*—System identification, mechanical feedback, combination locks, Master Lock®, padlock, lock cracker**

I. Introduction

OVER the course of many decades, Master Locks® have become the "go-to" product for securing relatively low cost items in public places. From high school lockers to bicycles to tool sheds, the three number combination allows the owner to access his or her items while keeping everyday passers-by or potential thieves at bay.

A problem can arise when the combination becomes lost and even the owner cannot open it. When this occurs, the owner may choose to try all 64,000 combinations, or the lock must be cut and thrown away. Obviously, it is impractical to numerically attempt all the combinations (by design) and so the lock is inevitably discarded.

This paper aims to reveal a third option. The proposed method will allow a Master Lock® owner to recover a lost combination and bring a second useful life to the lock, thereby reducing waste. The process follows a particular algorithm, mechanically perturbing the lock shackle while rotating the dial and measuring the resulting displacement response. Finally, the method for processing the data collected through this algorithm and deciphering the combination will be discussed.

Other sources [1-3] have aimed to solve this problem and have narrowed the 64,000 possible combinations down to ~100. Although this is impressive, it still leaves ~30 minutes of brute force combination entering. The process described in this report narrows the list down to ~10 possible combinations, and brings the brute force time down to ~4 minutes.

In order to learn more about the inside of the lock without harming it, an external perturbation and response technique has been implemented using a custom built apparatus. This machine can both pull and push on the lock shackle while simultaneously turning the lock dial and measuring the resulting displacement. Displacement sensing was chosen over other feedback options because of the manner in which the combination is physically encoded into the lock. The lock derives its combination from a series of three notched wheels, shown in Figure 1. A correct combination is found when all three notches are aligned with the shackle lever, which subsequently allows the shackle to move upwards and unlock the lock. The proposed method observes the relative location of the notches in the wheels by capitalizing on the fact that the maximum displacement of the shackle is correlated to the location of the wheel features. Other methods, such as torque sensing of the dial, could be implemented to gather more information, however, in the interest of simplicity, this method uses only displacement data.

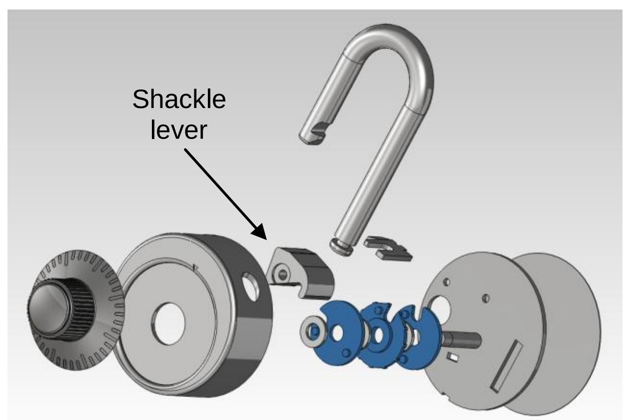

Figure 1: Exploded view of a Master Lock®; notched combination dials highlighted in blue

II. Apparatus Design

A. System Level Overview

For mechanical actuation of the Master Lock®, it is necessary to repeatedly rotate the dial to precise positions, both clockwise (CW) and counter-clockwise (CCW). Also, independent linear actuation of the shackle outwards and inwards is necessary. Although many designs could successfully achieve these desired movements, it was found that a stepper motor to turn the dial and a linear voice coil to pull the shackle are sufficient. The position feedback of the linear actuator is determined by a coupled linear potentiometer, while the stepper motor requires no electronic feedback. See appendix for full schematic.

B. *Shackle Actuation System*

A linear voice coil actuator (LVCA) was chosen to manipulate the shackle. A main performance criterion for the lock cracking is speed; a voice coil is advantageous since it can almost directly follow the frequency of its input current. Other actuator alternatives, e.g., screw actuators or servomotors, do not compare in terms of speed. Further, a voice coil can also have relatively high forces for a rather small number of coil turns.

The voice coil is sized based on the maximum force needed to bind the lock by pulling on the shackle. This force is estimated to be 9N, which was measured by pulling the lock with a known force until the dial could not be turned. Another consideration is the necessary stroke length, which corresponds to the total length needed to pull the shackle from a solved lock, i.e., about 1.5 cm based on lock measurements. The MotiCont LVCM-032-038-02 linear voice coil [4] was chosen as the best fit given design and budget constraints.

C. *Dial Rotation System*

For the rotation system, the required capabilities are at least 120 RPM, 1 N-m of holding torque, and resolution of at least 200 steps per revolution. The speed and torque requirements were determined as high level approximations with a factor of safety, considering the need for quick actuation. The stepper resolution was determined by the requirement to step between dial numbers, i.e., the absolute minimum requirement is 40 steps per revolution since there are 40 numbers on the dial. Several motor types were considered, but a stepper motor was determined to be the most suitable option because it would allow the rig to quickly move to discrete measurement points. To fulfill these requirements, the Lin Engineering 5718L-12E-01 was chosen with a holding torque of 1.48 N-m at 2 amps and a resolution of 200 steps per revolution [5].

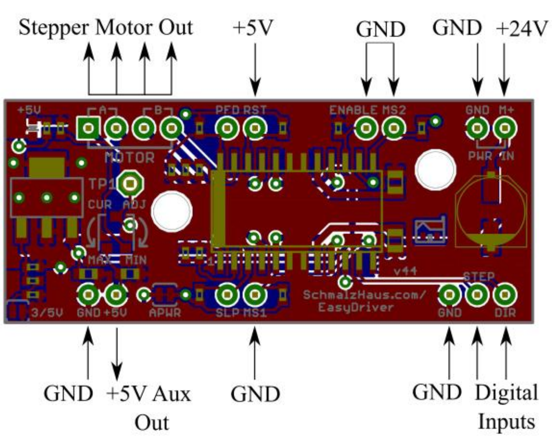

Figure 2: Easydriver 4.4 circuit schematic

In order to drive the stepper motor, an Easydriver 4.4 was selected as a quick and effective solution. The Easydriver utilizes the Allegro A3967 stepper motor controller and has the added functionality of current limiting and an auxiliary 5V voltage supply [6]. The electrical inputs and outputs of the Easydriver 4.4 are shown Figure 2. The "MS1" and "MS2" are grounded in this work, which indicate no stepper motor micro-stepping. Since the Easydriver 4.4 was utilized, no other advanced circuitry was needed herein, i.e., electrical connections for shackle actuation and feedback were directly wired.

D. *Shackle Position Feedback*

A linear potentiometer with low internal friction was selected to supply position feedback to the linear actuator. The positioning resolution was sufficient for the system and the low cost of this device made it an optimal choice.

E. *Test Rig Layout*

After several iterations of the mechanical assembly, it was determined that the following requirements were necessary for the rig: a visible dial/stepper motor coupling, a rigid connection of the linear actuator and linear potentiometer and for the entire rig to be easy to disassemble. Because there is no feedback on the stepper motor and dial positions, it is important that the coupling is translucent to allow for visual confirmation of position and to check for slippage. In an early iteration, the coupling to the linear actuator was slightly compliant and the positioning of the linear actuator was inconsistent over time--this was solved by more directly

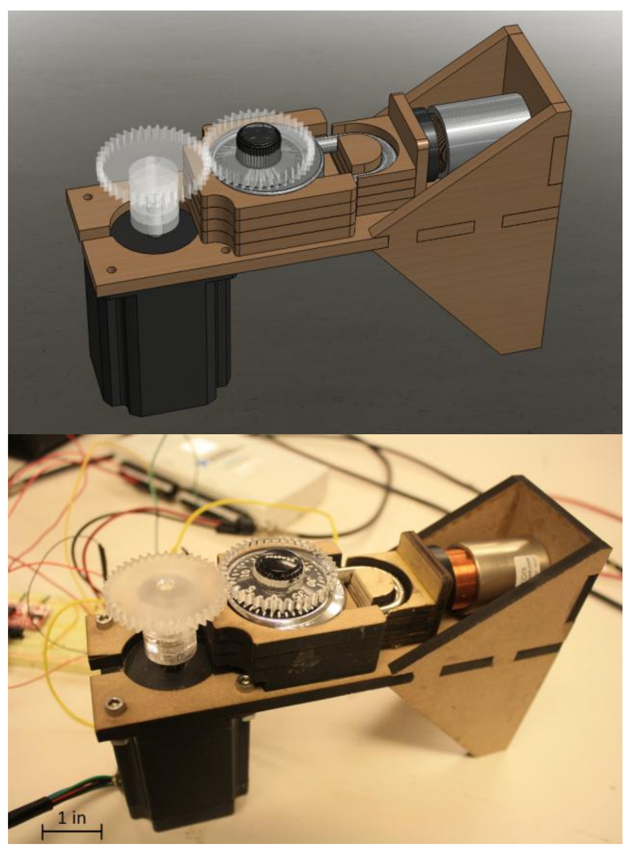

Figure 3: CAD model versus implementation. From left to right: stepper motor, gear coupling, Master Lock®, shackle coupling and voice coil actuator.

coupling the potentiometer and actuator with a phase changing adhesive. Due to the experimental nature of this rig, it was also important to maintain easy disassembly and utilize rapid prototyping techniques to facilitate small changes to part geometry and part compliance.

The overall orientation of the lock is lying flat with the dial facing upwards. With this orientation, the dial is visible and all rotating and sliding components are orthogonal to earth's gravitational force, allowing gravity's effect on the mechanism to be disregarded. The stepper motor was placed on the side and below the lock so as not to visually interfere with the turning dial. A simple 1:1 gear coupling is attached to the stepper motor and the dial to reliably orient the dial with respect to the rotational position of the motor. Other gear ratios are possible to further optimize the turning speed/resolution of the dial. The linear actuator is coupled to the shackle by several pieces of laser cut wood to allow for repeatable shackle insertion and removal. The linear potentiometer is adhered to the bottom of the coupling mechanism to aid the actuator in uniaxial alignment and ensure rigid coupling. Figure 3 shows both the CAD model and the implemented rig.

F. *Control Interface*

Control of the stepper motor and LVCA and sensing of the potentiometer voltage was accomplished by the NI USB-6215 [7] data acquisition system and linking to NI LabVIEW graphical development environment. The NI USB-6215 is capable of analog and digital inputs and outputs. As shown in Figure 4, the LVCA speed and force are controlled via voltage output, and the potentiometer signal is read via a voltage input port. The output voltage signal to control the LVCA is amplified by a gain of 4 by a power amplifier. The power amplifier is a Techron 8803 [8]. Digital pulse ports control the motor step and direction.

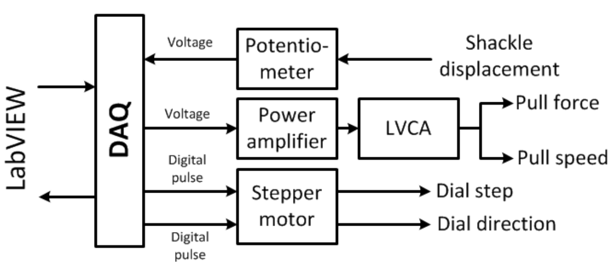

Figure 4: System flow

III. Experimental Methods

After fully disassembling a Master Lock®, and milling viewing ports into a functioning Master Lock® to learn how they are solved, an algorithm was devised that allows for the combination of the lock to be determined simply through externally perturbing the lock and measuring the response. Three rotations are taken in the characterization because for the first rotation, only the wheel with the third combination is rotating. In the second rotation, both the first and second wheels are rotating, and so on. Therefore, in each rotation, more information is added to the system.

The following steps are taken in order to characterize the lock:

1. The lock must be reset by rotating the dial three times in the counterclockwise (CCW) direction.
2. The lock is stepped once (1.8 degrees) clockwise (CW).
3. The shackle is pulled with approximately 9 N of force.
4. The position of the shackle is recorded and the shackle is returned to the home position.
5. Steps 2-3 are repeated 599 times (3 rotations total).
6. Steps 2-5 are repeated with CW replaced with CCW.

Once the lock characterization is complete, the signal is broken up into three signals corresponding to each rotation executed in the characterization. The second and third numbers of the combination can be found from the characterization data. The second number can be seen in the second rotation data and corresponds to the lowest "valley" of the data; most likely two of these valleys will be observed and if the data was taken in the CW direction, then center of the first valley corresponds to the second combination number.

The third number can be seen in any of the three rotations, but the first rotation gives the clearest view. This number once again manifests itself as the center of a valley, but this time all the valleys have the same amplitude, so more processing must be done before the correct number becomes obvious. First, the center of each valley on the first rotation is calculated. Once this is done, a pattern starts to appear. The centers can be sorted into four different groups. The first two groups are made up of 4 numbers, each separated by multiples of 10. The third group is made up of 3 numbers each separated by multiples of 10. The final group contains the only remaining number, which corresponds to the third number in the combination sequence. For example, if the centers are calculated as {3, 6.3, 9.6, 13, 16.3, 20, 23, 26.3, 29.6, 33, 36.3, 39.6}, this yields the following groups: {3, 13, 23, 33}, {6.3, 16.3, 26.3, 26.3}, {9.6, 29.6, 39.6}, and {20}. In this case, 20 would be the correct combination number.

The lock characterization algorithm is coded in LabVIEW using DAQmx VI blocks. The solving algorithm is implemented by three code blocks in a "SEQUENCE" structure which are embedded in a "FOR" loop. The first sequence block commands the stepper motor to move one step in the desired direction via DAQmx digital pulse virtual channels. Second, the shackle is actuated and the displacement is simultaneously read via DAQmx analog output/input signals.

Signal post-processing is executed for each signal read in the iteration. First, the potentiometer signal is filtered via a second order Butterworth filter. Next, triggering and signal extraction blocks are utilized in order to keep only the part of the potentiometer signal which corresponds to the maximum shackle displacement. Refer to the Appendix for a diagram of the implemented LabVIEW code developed for lock characterization.

IV. Results

By finding two out of the three combination numbers, the potential number of combinations is narrowed from 64,000 to 40. However, these remaining 40 can be further narrowed to ten possible numbers by using the methods outlined in [1-3]. Therefore, the proposed method can solve the lock in 10 tries.

Before the algorithm described in the previous section was discovered, the authors attempted to extract the combination by resetting the lock in the CCW direction, and then measuring over a full CW rotation. The result of this analysis is shown in Figure 5. Note that lower values of the potentiometer output correspond to greater displacement of the shackle during perturbation, and that the relative displacement is important, while the absolute value has little significance. After accounting for the offsets shown in Table 1, no clear pattern emerges for extracting the combination numbers. Despite failing to illuminate the proper numbers, this figure does highlight the need to isolate each wheel for separate analysis.

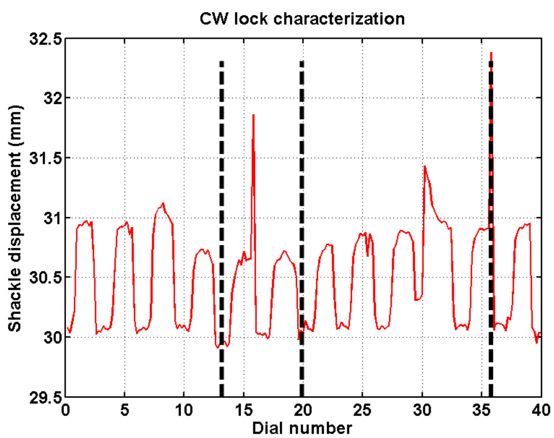

Figure 5: Data gathered from first method; the lines represent the combination numbers for the tested lock.

Table 1: Combination number offset versus direction

Combo	*CW*	*CCW*
1	0	-7
2	-3.5	0
3	0	0

Isolation of the first wheel for measurement is the main advantage of this methodology. Following the algorithm outlined in Section III, the plot shown in Figure 6 was obtained for a lock with combination 36-10-20. It is interesting to note that the third rotation in this method yields the same information as the method shown in Figure 5.

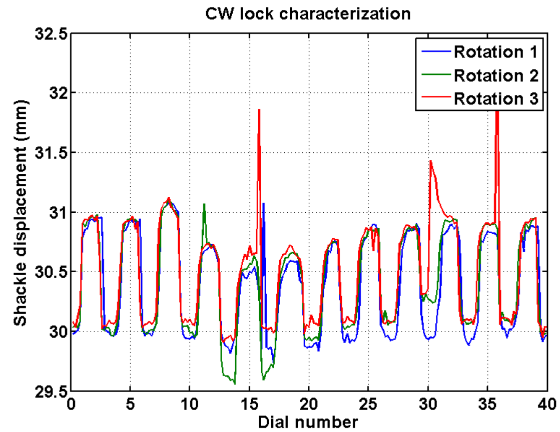

Figure 6: Displacement data of lock characterization

By examining rotation 1 of Figure 6 by itself, the process for determining the third combination number can be illustrated as shown in Figure 7. Red lines depict the center points of each valley as calculated in Section III. Visually one can see that the third number in the combination lies between a peak of large pulse width followed by a peak of small pulse width with respect to the average (or vise versa).

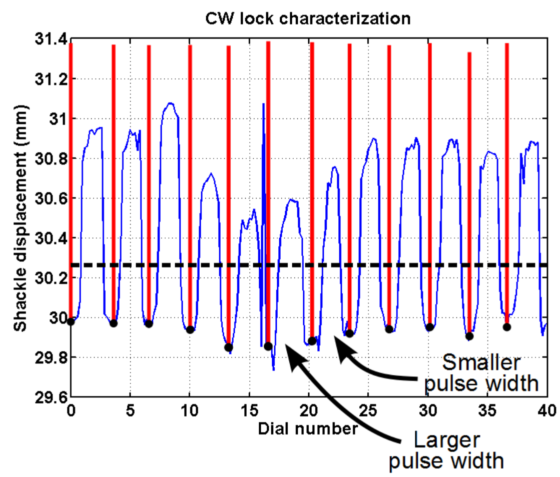

Figure 7: Data gathered from first rotation

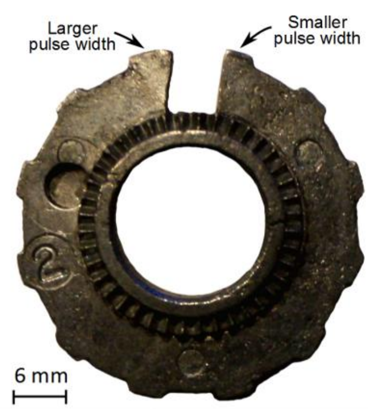

Figure 8: Third combination number wheel

Figure 9: Polar plot of gathered data

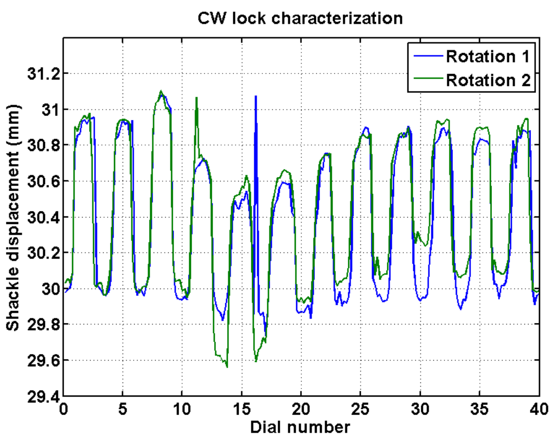

Figure 10: Displacement data from rotations 1 and 2; observing the deepest valley on Rotation 2 (13.5) and shifting by -3.5 due to the offset in CW rotation direction yields the second number (10).

The physical reasoning for this phenomenon can be seen in Figure 8. It is simply a result of the geometry of the third wheel, and this can be seen clearly because only the third wheel is rotating during rotation 1 of the algorithm. To further illustrate this point, a polar version of Figure 7 is overlaid on a lock in Figure 9.

During the second rotation, both the third and second wheels are turning. In order to find the second combination number, the second wheel must be isolated. This can be accomplished by subtracting rotation 1 from rotation 2, thereby removing the effects of the third wheel. Visually, this is as simple as overlaying the two plots and observing where the second rotation deviates from the first. This visualization is depicted in Figure 10. The lowest deviation from rotation 1 reveals the location of the second combination number. In this case, the lowest lies at 13.5. Compensating direction of rotation according to Table 1 yields the second combination number of 10.

From the analysis completed in this work, the first number was unable to be reliably located. The first number is difficult to determine because by the 3rd rotation of the characterization, all combination wheels are turning in unison, which makes information corresponding to the first number difficult to isolate. In future work, the first number could most likely be detected with further signal processing. In present work, with two out of three numbers known, the first number can be numerically iterated. By utilizing the numeric algorithm from literature [1-3], the lock can be solved in approximately 10 iterations, which the rig can complete in a matter of a few minutes.

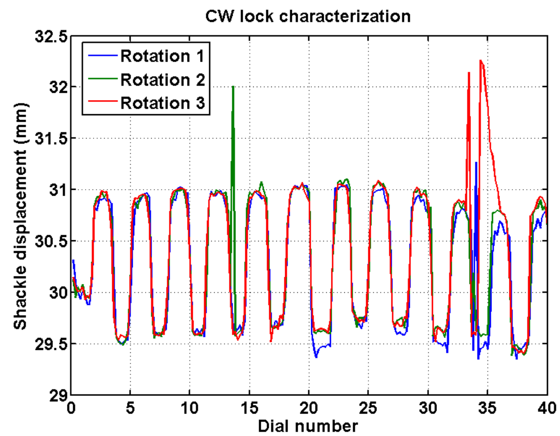

Figure 11: Data when a combination number is near zero

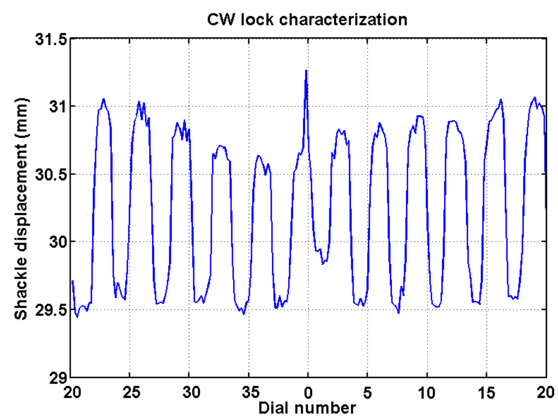

Figure 12: Data from 20 number offset

Although the algorithm works well in most cases, an issue can arise when one of the numbers in the combination is near zero. The main problem is that the isolation of the third wheel is no longer complete and unexpected patterns emerge as shown in Figure 11. To remedy this, a starting offset, i.e., starting at dial position "20" as opposed to "0", can be added as in Figure 12. Future versions of the algorithm will account for this case, and possibly use it to more quickly determine the combination of the lock in question.

V. Measurement Sensitivity and Repeatability

The order of magnitude for voltages which are sensed by the potentiometer are in the 0.01V to 0.1V range. The variation in the voltage input signal without filtering creates variability within 0.05V. With the second order filter, the variability in maximum displacement is reduced to 0.01V. After filtering, the steady-state value of the signal is taken as a single point for each combination step. Therefore, the input voltage noise is reduced through signal post-processing.

The accuracy of mechanical actuation is dependent on several factors. It was found that the alignment of the LVCA with the shackle pull direction and the alignment of the potentiometer with the LVCA create potential inaccuracies in measurement. These sensitivities were minimized through rig tuning and alignment. A second identified mechanical sensitivity was the over- or under-stepping of the stepper motor. This inaccuracy was dependent on the stepping speed of the motor, especially upon characterization start-up. This effect was minimized by reducing the speed of the motor.

The repeatability of a characterization is determined by the relative amplitude changes in the potentiometer signal and the amount of phase shift of 'peaks' and 'valleys' between two characterizations. The phase shift is dependent on the starting point of the characterization, i.e., variability of dial starting point from the number zero. Given this variability and assuming the dial is set by hand, the phase shift is at most one dial number between runs. The relative amplitude of the potentiometer signal has some degree of randomness associated with it, e.g., in the 0.01V range or 0.1mm displacement. This randomness is due to combination dials being able to slip slightly on the dial shaft during each actuation. This effect cannot be minimized since only external perturbation is utilized; therefore, this effect is the greatest obstacle in repeatable displacement measurements during characterization. However, for a given lock, the combination numbers can most often be determined from one characterization, and in some cases the characterization may need to be attempted more than once.

VI. Conclusion

In the attempt to reduce the waste of "disposable" Master Locks® a mechanical system that reduces the number of possible combinations for a given lock by mechanical perturbation and system characterization has been developed. By incrementally rotating the dial and pulling on the shackle, a characterization (from the displacement of the shackle) for two out of the three numbers used in the lock's combination can be found. With these two numbers, the number of combinations possible is reduced to 10, making the solving time of the lock roughly four minutes. With this device, hardware stores could easily determine the combination of an unknown lock that a customer brings in and restore the lock to working order, reducing waste.

Although the proposed method greatly improves on existing algorithms for acquiring lost combinations, it is not optimal. The authors believe that further work along these lines could reveal a method for obtaining the first number of the combination by processing the data in rotation 3 and comparing it to rotation 3 of the opposite direction. Observing the features that are shifted by 7 between these two plots could provide the necessary information to find the third number, and therefore find the combination without any numerical iteration.

Acknowledgments

We would like to thank Professor Ian Hunter, Bryan Ruddy, and Adam Wahab for thoughtful discussions regarding the implementation of this project, and use of the equipment and materials in the Bioinstrumentation Lab.

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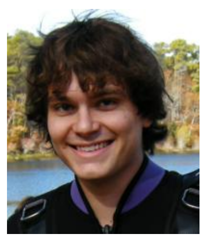

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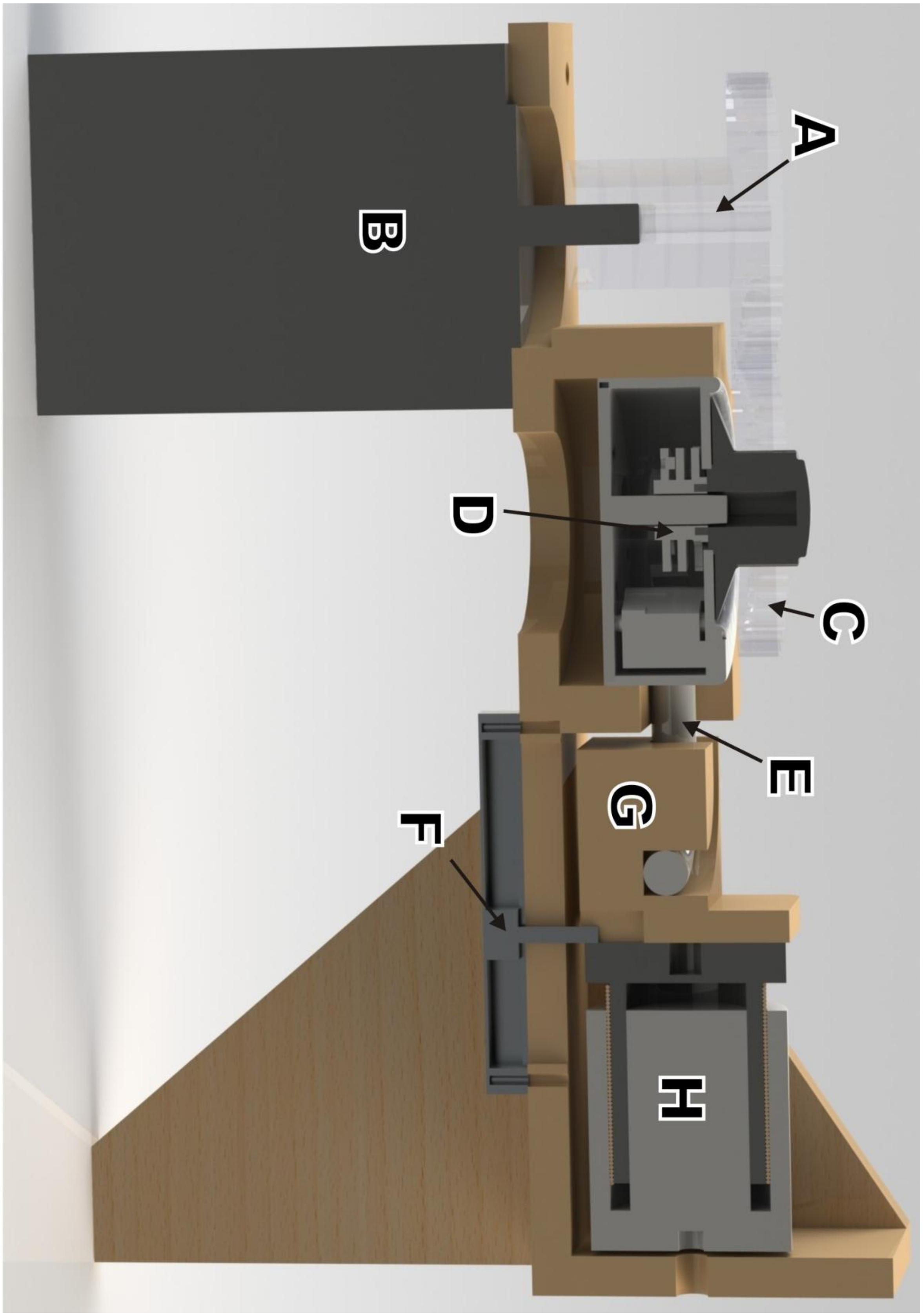
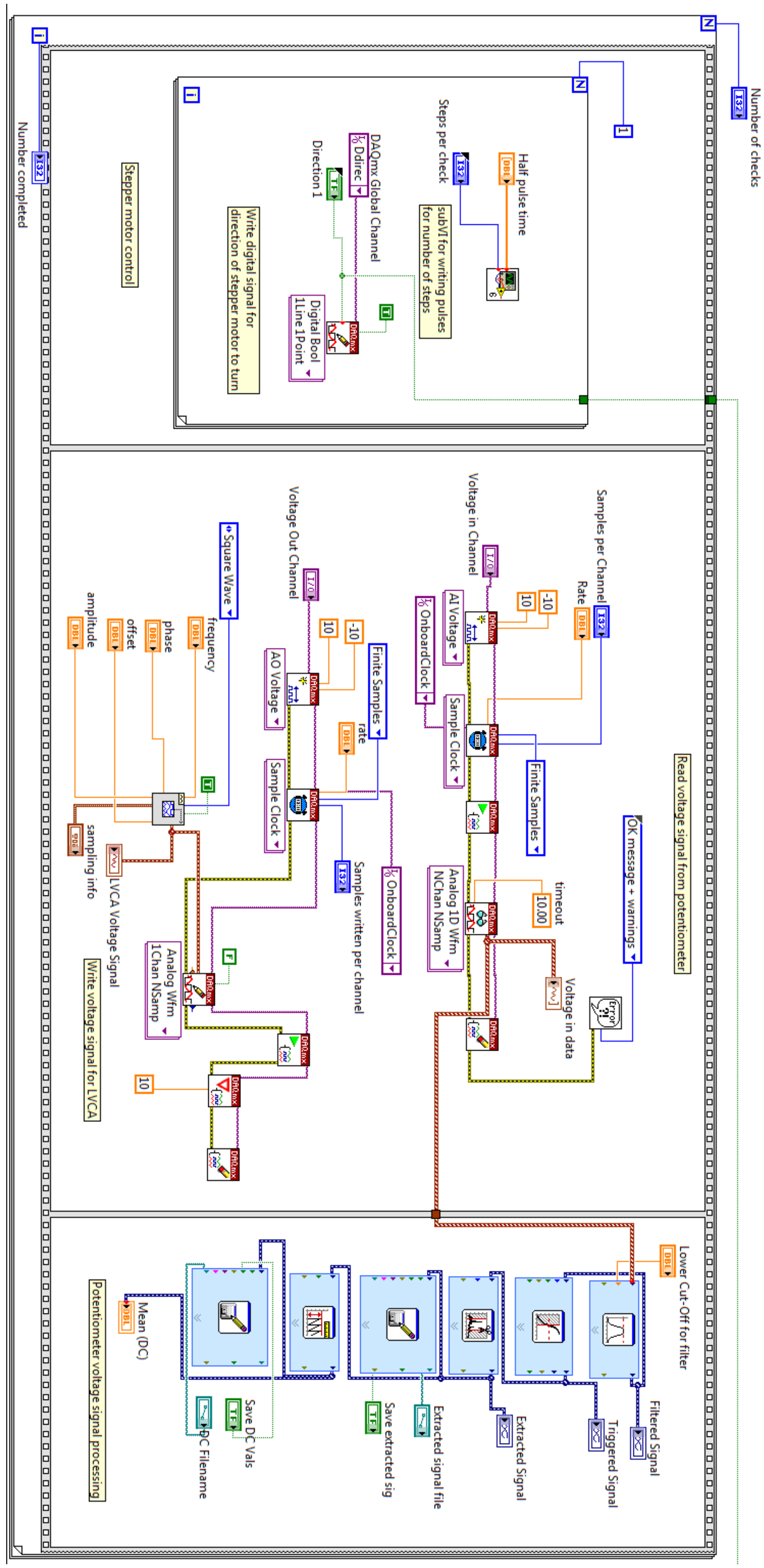
APPENDIX:



A: Stepper motor output gear, **B:** Stepper motor, **C:** MasterLock dial coupling gear, **D:** MasterLock internals, **E:** Shackle, **F:** Linear potentiometer, **G:** Shackle/linear motor/sensor coupling, **H:** Voice coil actuator



LabVIEW code of control algorithm for lock characterization