A Functional Retro-Fitting Robotic Smart Lock Manipulator

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***Abstract*—This paper presents an optimized design for a robotic smart lock actuator and its implementation in an integrated device named SimSim. The smart device is installed on top of an existing deadbolt lock and responds to secure wireless commands from a smartphone. It is optimized for ease of installation, various deadbolt thumbturn geometries, and simplicity of design (which reduces cost and quantity of failure points). It leverages several unconventional designs to implement various features without significantly increasing complexity, including a retreating clutch to prevent backdriving, a sliding gripper that takes advantage of common lock geometry, and a rotating body to simplify mechatronic design. SimSim is manufactured using FDM 3D printing techniques and houses a custom PCB and firmware. It is controlled over Bluetooth Low Energy using a smartphone.**

***Index Terms*—smart locks, robotic actuators, robotic manipulators, design for manufacturing, mechatronics, internet of things**

I. Introduction

The advancement of the Internet of Things has pushed the automation of many personal home devices such as lighting, HVAC, and home security. Smart locks facilitate access control by allowing a user to lock and unlock their front door using either a smartphone or over the internet. In addition to removing the need for a physical key, they also enable additional features such as making it easier for disabled people to unlock doors, being able to give and revoke access to other people, or alert owners when a door is accessed [1] [2]. These devices are often installed by users instead of trained professionals, so ease of installation is emphasized. Furthermore, as consumer-grade products, there is a tight budget restriction. [3] Normally, cost constraints and additional features required for user-friendliness reduce reliability, but this tradeoff cannot be made in the case of smart-locks, where the security of the home is at stake. [4]

It is in this environment in which retro-fitting an existing deadbolt lock becomes an attractive solution. Instead of conventional smart locks that replace the existing lock system, it is installed on top of the existing deadbolt, gripping and rotating the thumbturn as if it were a robotic hand. Thus, it leverages the existing mechanical reliability of a traditional deadbolt system while simplifying installation as the user does not need to disassemble the existing deadbolt (Fig. 1) [5].

Note that these are not true "smart-locks" (as the term "lock" would refer to the existing deadbolt system) but rather "robotic lock actuators".

Figure 1. The retro-fitting smart devices install on top of existing deadbolts.

Retro-fitting smart devices have several design challenges [6]:

They must allow users to operate the lock manually should they not wish to use their phone, particularly in the case of electronic malfunction or a dead battery. The more technical interpretation is that the motor should not be backdriven when the user attempts to operate the lock manually. Further, the device must be able to detect when and how the user has operated the lock manually.

1. They must fit on top of existing deadbolt thumbturns, which are of varying shapes; in particular, the axis of rotation of the lock may not necessarily line up with the axis of the thumbturn (Fig. 2).

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Figure 2. User-friendly installation requirements results in uncertain placement relative to the thumbturn's axis of rotation.

2. The device must be cheap yet reliable, but also compact, meaning that additional functionality must correspond with minimal additional complexity. [7]

3. Since the deadbolt it is installed over may be older and difficult to operate, the device must have sufficient torque to overcome additional resistance due to factors such as rust.

II. Overall Architecture

A typical retro-fitting smart lock system consists of supporting electronics, and a series of transducers (Fig. 3) (Fig. 4).

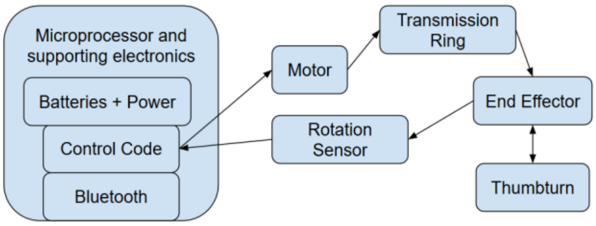

Figure 3. Overall architecture of a retro-fitting smart-device

A. Supporting Electronics

The center of the architecture is the "supporting electronics" package, which includes a microprocessor, batteries, power electronics, and radio. All these items must all be low-power to minimize the frequency at which batteries need to be replaced.

The at328p microprocessor, while not computationally powerful, consumes little power and can also be put to sleep (and also woken up by the position sensor or commands from the radio). It houses the control code and interfaces with all the various components of the device. It also contains non-volatile EEPROM memory that is used to record the parameters concerning the lock, as well as password hashes for authentication.

Because the lock is put to sleep most of the time, the majority of power is consumed while sleeping, so it is more important that the regulator has low quiescent current than use a traditionally "efficient" switching architecture. This made the MCP1702 linear regulator the optimal choice. The relative simplicity of linear regulators also improves reliability and decreases footprint and material cost. A pair of CR123A lithium-ion batteries were selected for their form factor, high power density, and availability.

The BLE113 radio provides encrypted communications over Bluetooth Low Energy (BLE). BLE was used because of its low power consumption and integration in modern smartphones. This module can be controlled by either a smartphone app from its built-in Bluetooth radio or from an internet server though a nearby Wifi-to-Bluetooth translator.

Finally, there is an RGB LED that shines through the translucent plastic and a piezoelectric speaker. These alert the user to the state of the lock and facilitate development.

B. Transducers

The Pololu Micro-Metal gearmotor was chosen for its power-to-size ratio. It also includes an internal gearbox that provides a significant 298:1 gear ratio, that aids in the ability to control aged locks that may require additional torque. These gearmotors control a gripper to actuate the existing deadbolt thumbturn. The details concerning the force transfer from the motor to the gripper will be covered in greater detail later in this paper.

A position sensor is required to know how far to turn the motor. There are several possible implementations for this, but an analog position sensor is required because of the variance of thumbturn actuation angles. An ADXL345 accelerometer is used to measure the direction of gravity and from there deduce the orientation of the lock in the world. Since an accelerometer used in this way only needs to be mounted on the gripper, it both cheap and simple to integrate compared to other sensors such as limit switches or encoders that need more specific mechanical interactions. This will be covered in greater detail later.

A manual lever is built into the body of the lock that allows users to manually control the lock.

C. Installation

Finally, the device must be mounted to the door or existing deadbolt in some way. A convenient option is the use of command-tape, a unique double-sided tape is extremely strong, but can be removed without damaging the furnishings by pulling on a special tab. However, this further exacerbates the problem of a misaligned axis of rotation between the actuator and thumbturn as there are no mechanical guides to assist in installation positioning.

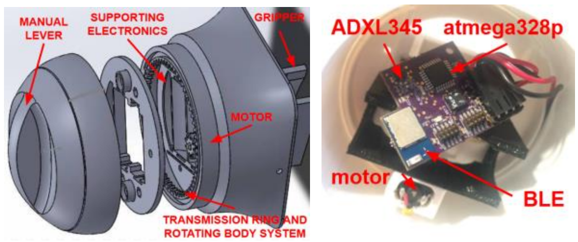

Figure 4. (Left) An exploded view of the lock. Many of the unusual mechatronic details will be explained in the next few sections. (Right) Supporting electronics (with integrated accelerometer). Batteries not shown.

III. Retreating Transmission Design

The retreating transmission design addresses the issue of allowing users to operate the lock manually, either internally using a lever on the device, or externally using the key. Directly connecting the gripper to the motor gear-system would result in the user being forced to back-drive the motor when operating the lock manually, which is both undesirable from a reliability standpoint, but also inconvenient and confusing for the user, as it would seem like they are damaging the lock (which they are). Traditional solutions would require a clutch of some kind, but this would result in an additional actuator, which introduces an extra failure point while increasing the cost.

Thus, a "retreating transmission design" is required in which the motor pushes against a ring with stoppers. The motor (Fig. 5, green) can push the ring (Fig. 5, blue) such that the lock moves, but afterward retreats so that the motor is not backdriven when operating the lock manually (Fig. 6) (Fig. 7). Since this approach does not require additional actuators, it does not increase the number of likely failure points.

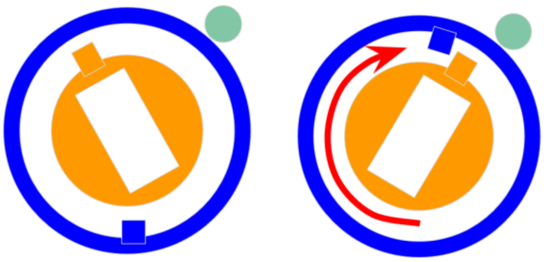

Figure 5. (Left) Original unlocked position, with the retreating transmission ring (blue) in the idle position. (Right) The motor (green) moves the transmission ring to push the thumbturn gripper (orange) into its locked position.

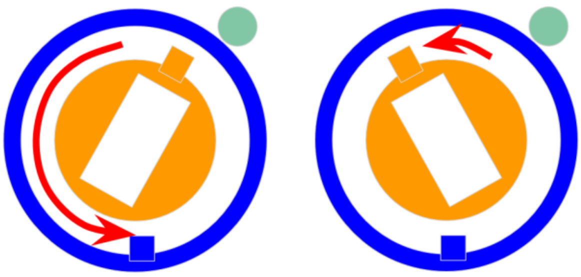

Figure 6. (Left) The motor "retreats" the transmission ring into the idle position where it will not get in the way. (Right) The user manually unlocks the lock with no interference from the motor and transmission ring.

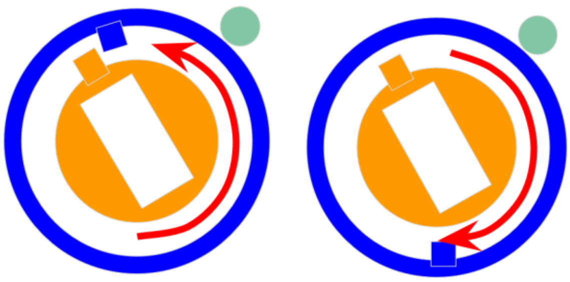

Figure 7. (Left) Alternatively, the motor moves the transmission ring to push the lock back into its unlocked position. (Right) The motor then "retreats" the transmission ring back into the idle position, so that the user will not experience resistance when manually locking the ring.

The accelerometer should be located on the end effector of the actuator (Fig. 8). This allows it to keep track of the location of the thumbturn no matter the position of the retreating lock, even if manually actuated. The caveat is that the accelerometer cannot measure the angle of the transmission ring when the transmission ring is not in contact with the end effector. Therefore, the retreating action does not benefit from accelerometer feedback, and so relies on a timer. This is acceptable as there is a large range of values that allows the transmission ring to stay out of the way of the manual rotation, so accuracy is not needed.

Figure 8. The accelerometer (red) should be on the end effector to keep track of the position of the thumbturn. The position of the transmission ring is not tracked directly, but its position can be deduced based on the history of motor commands and accelerometer values.

This results in the control algorithms in Fig. 9, which allows both manual and commanded operations of the lock without backdriving the motor.

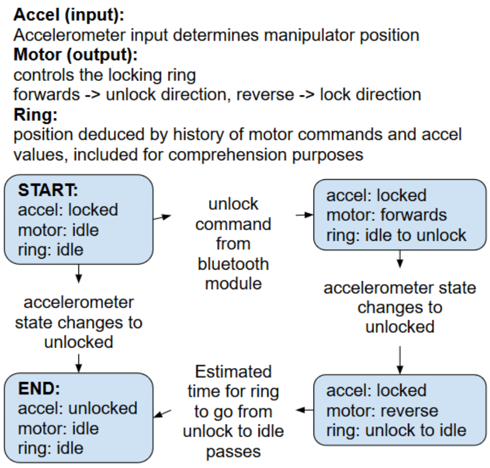

Figure 9. The state diagram governing the locking process. The "left" path shows a manual unlocking, and the "right" path shows a commanded unlocking. Note that this is only one half of the overall state diagram; the unlocking state half of the state diagram is identical, with reversed commands.

IV. Sliding Gripper Design

The sliding gripper design addresses the issue of a misaligned axis of rotation. This issue is a potential result of user error, which is unavoidable if the lock is installed without mechanical guides (such as SimSim, which is installed using command-tape). It is further exacerbated if the axis of rotation of the deadbolt thumbturn does not align with the rest of its body (Fig. 10). This is not only confusing from a user-installation perspective, but the faceplate outline of the deadbolt may even prevent alignment of the axis of rotations between the device and the deadbolt thumbturn during installation.

Figure 10. Some deadbolt thumbturns do not align with the deadbolt faceplate, which results in a counterintuitive identification of axis of rotation, and exacerbation of the problem of misaligned axis of rotations. [8]

The obvious approach is to solve this by implementing a sliding gripper to allow three degrees of freedom in the X-Y-Z direction, while maintaining rotational control, but this would greatly increase complexity. In this case the complexity is mostly mechanical so the primary issue is that it would result in enlargement of the system to accommodate the additional mechanisms and degrees of freedom.

Removing the Z-axis (normal to the door) is relatively simple given that the axis misalignment is only the X-Y axis, so simply adding an optional spacer suffices. (Fig. 11)

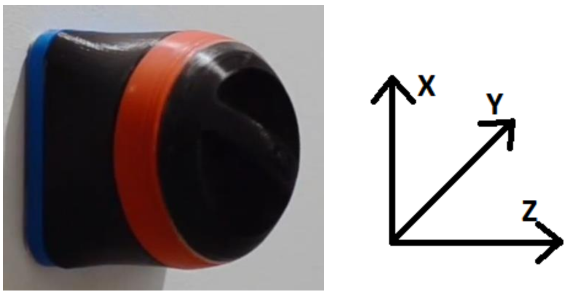

Figure 11. The spacer (blue) allows adjustment in Z-axis

However, taking into consideration that the vast majority of thumbturns have an elongated shape, this allows sliding in one of the X-Y axis (the exact axis cannot be specified as it is in a moving frame of reference). Thus, only one degree of freedom needs to be implemented by the slider (Fig. 12).

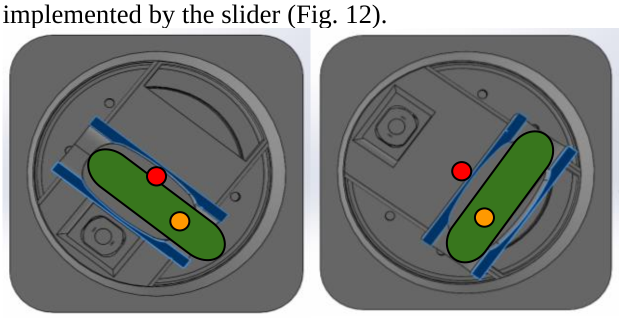

Figure 12. A sliding gripper (blue) can still rotate a thumbturn (green) despite its axis of rotation (red) being misaligned to the thumbturn's axis of rotation (orange). Note how the gripper moves sideways towards and away from the motor, and that the elongated thumbturn slides up and down in the gripper. Additionally, note that the motor interferes with the range of motion of the gripper in one direction.

By allowing the gripper to slide orthogonally to the direction of elongation of the deadbolt thumbturn, misalignments in axis of rotations between the manipulator and the thumbturn can be accounted for in both remaining degrees of freedom.

One disadvantage of allowing the gripper to slide is that the sliding motion consumes much of the available internal space in the lock. This is particularly true if the rotating body design is used, which will be explained in the next section.

Also, the friction from these sliding motions, especially the sliding motion from the uncontrolled geometries of the deadbolt thumbturn, reduce the amount of torque that can be transferred to the deadbolt mechanism. Further, there is theoretically the risk that the resistance may cause the sliding mechanism to seize up, although this scenario has never been encountered while developing SimSim. These issues can be overcome by extra-careful placement to minimize the axis misalignment for particularly difficult locks.

V. Rotating Body Design

Most robots house the bulk of their electronics in one location, to simplify design and manufacturing cost. Even decentralized systems generally attempt to reduce the total number of electronics "groupings" as much as reasonable. Usually, stationary robots such as smart locks keep this majority of supporting electronics stationary, while moving the actuator. However, this would be disadvantageous for the smart lock: for instance, the accelerometer must be placed on the moving part of the lock. Thus we introduce the rotating body design (Fig. 13), which houses all the electronics as part of the actuator.

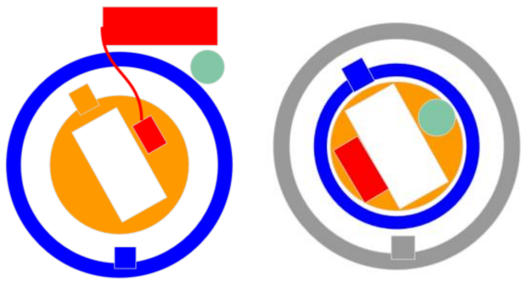

Figure 13. The exterior design (left) requires the separation of electronics into two different areas, as well as an awkward cable to connect them (red). Additionally, since these two bodies are moving relative to one another, the cable's bending in response to this motion must be controlled to prevent entanglement. The rotating body design (right) houses all the electronics together, and the accelerometer can be integrated with the rest of the electronics. The stationary element (grey) has no electronic components.

By using a rotating body design, all the electronics can be housed together, including the accelerometer. This reduces cost, design complexity, and quantity of potential failure points.

The rotating body design also enables the housing of electronics and motor within the empty space of the actuator. Without the rotating body design, all these electronics would be housed outside the rotating body, increasing the overall profile of the lock.

Further, it has the additional effect of creating a significant mechanical advantage by the inherently large gear ratio (15:1 in the case of SimSim) from the internal gearing system used to implement this motion (Fig. 14). Thus, the rotating body design also includes a solution to the issue of rusted locks being more difficult to manipulate. Note that the additional mass from moving more components is negligible considering the potential resisting force of the lock.

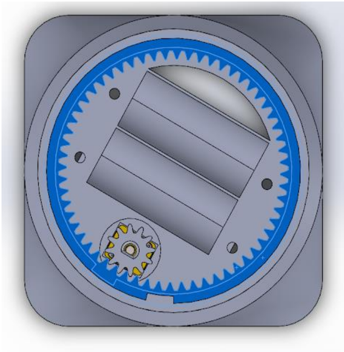

Figure 14. Transmission ring (highlighted in blue) and rotating body implemented in the actual design. The motor is located directly under the smaller gear, and the supporting electronics are housed in the empty space on the upper-right.

The result of implementing this design can be shown by comparing the overall sizes of locks that use this design against locks that do not (Fig. 15) (Fig. 16).

Figure 15. August (left) implements these designs and Friday (center) which does not [9] [10]. Neither of these designs are “retro-fitting” smart locks [11]. SimSim (right), a retro-fitting smart lock, is the same size as August, despite needing to house the additional gripper feature and reside on top of the existing deadbolt thumbturn. Note that the circumference and depth of all these designs are roughly the same.

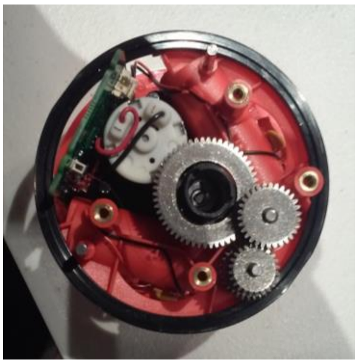

Figure 16. August has a complicated system of gears while requiring clearance for the accelerometer cable (hidden below other components), which results in its unusually large size compared to other smart locks.

VI. Conclusion

This paper proposes empirically proven and practical solutions to various smart-lock design challenges that have relatively small complexity tradeoffs. The sliding gripper allows control despite a misaligned axis of rotation with minimal increase to complexity. The retreating transmission ring allows manual manipulation of the deadbolt, again, with minimal increase to complexity. Finally, the rotating body design further reduces the complexity of the device with a more intuitive integration of the accelerometer.

Exploration of these designs in conventional smart locks, including smart locks that use linear solenoid actuators, would potentially facilitate application of these designs across a broader range of smart locks.

These designs will reduce cost and size while improving reliability of future smart locks if implemented.

Conflict of Interest

All authors (Andrew Zhang, Raghavendra Venkata Prasad Palipi Kandubai, and Stowe Hammarberg) have partial ownership of the SimSim design and company, upon which this paper is based.

Author Contributions

Andrew Zhang developed the electromechanical design and preliminary firmware for SimSim, and conceived of the designs outlined in this paper. Raghavendra Venkata Prasad Palipi Kandubai conceived of the idea and application, and contributed to the firmware. Stowe Hammarberg modified the design for ease of manufacture. All authors had approved the final version.

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