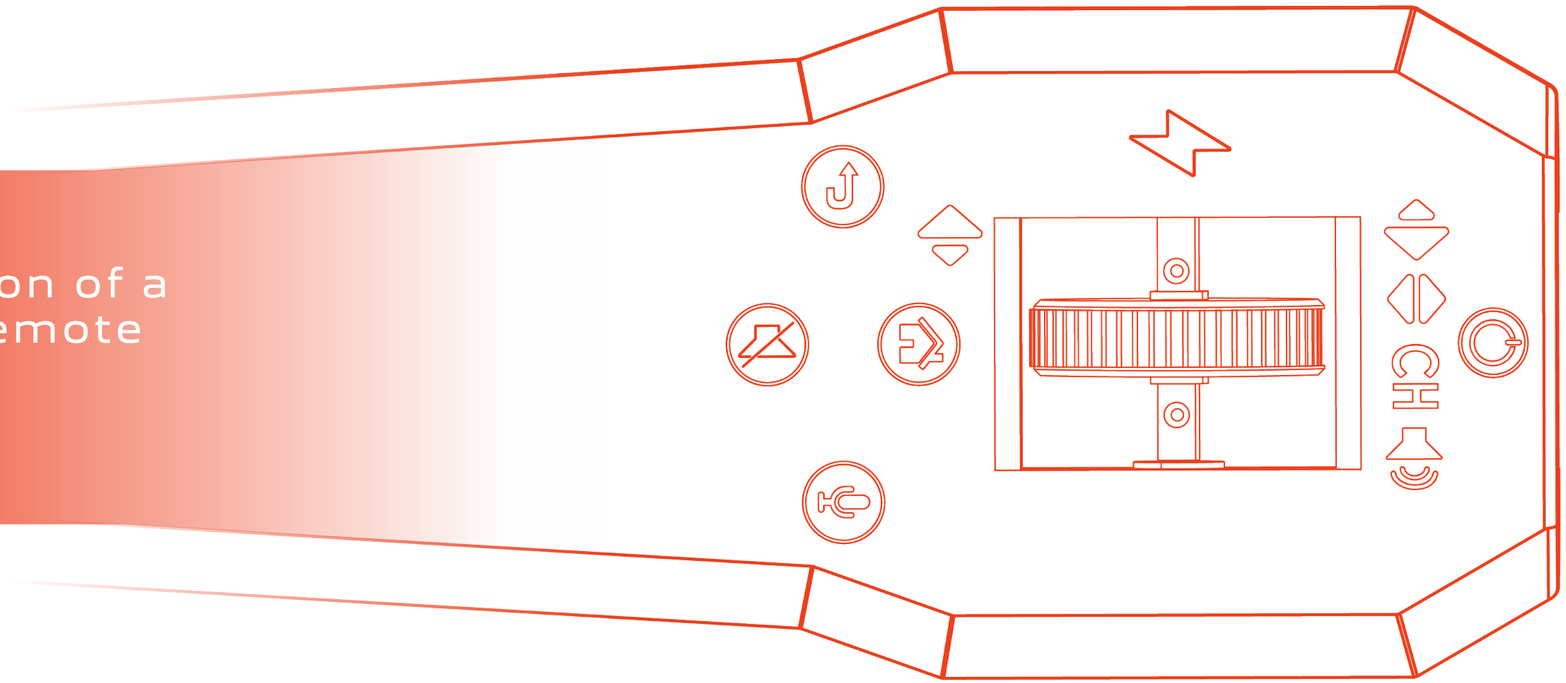
Designing Human-Powered Interaction



Development and Evaluation of a Self-Powered Television Remote

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KINERGIZER
Motion Energy Harvesting

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Summary

This project investigates whether a TV remote can be designed to power itself through the energy generated by its own use. The scroll wheel, the primary input mechanism, drives a DC motor harvester through a bevel gear train. The energy generated by thumb scrolling is rectified and stored in a small rechargeable backup battery, with the goal of making disposable batteries unnecessary. The project was conducted in collaboration with Kinergizer and is aimed primarily at the hospitality sector, where battery replacement across hundreds of guest rooms is a persistent maintenance problem.

The research phase addressed three questions: what ergonomic constraints shape the scroll wheel design, how much energy can the harvester produce and what does TV signalling cost in energy terms. Ergonomic tests with participants established that a single forward-facing scroll wheel positioned 100 mm from the base of the remote, set to an electrical resistance of 25Ω, gives an acceptable balance between mechanical feel and energy output. The harvester produces approximately 6 mJ per scroll at the motor output. After accounting for an estimated 50% rectifier efficiency, approximately 3 mJ per scroll is available to the chip.

On the signalling side, a hybrid IR and BLE architecture is proposed. The power button uses IR to wake the TV from deep sleep, where a BLE connection cannot yet exist. All other commands use BLE via a Silicon Labs EFR32BG22 chip with an interrupt-driven firmware architecture, a connection interval of 250 ms and a peripheral latency of 100, giving an effective connection interval of approximately 25 seconds. An energy model built from measured interaction patterns shows that a one-hour Netflix session consumes 66.66mJ while generating approximately 438 mJ, a surplus of around 371 mJ. Under consistent use the remote sustains itself. A Maxell ML2032 rechargeable coin cell covers worst-case periods of non-use.

Two prototype iterations were built and tested. The first established the core mechanical architecture: a scroll wheel that slides along a square axle to switch between four functions, with position detected by four reed switches responding to embedded magnets. A pilot user test with five participants produced a mean SUS usability score of 76.5, above the above-average threshold of 68. The main issues identified were an unclear select function and unintuitive left/right navigation mapping. The second iteration addressed these points, refined the housing shape based on ergonomic feedback and replaced LED indicators with a screen readout driven by a rotary encoder. Full assembly and a broader user test are planned after greenlight.

The energy model relies on datasheet figures that have not been validated by direct measurement. A measurement of a Samsung SolarCell remote found an idle current of 100 μA, considerably higher than the EFR32BG22 datasheet deep sleep figure, illustrating that finished products do not reach chip-level figures without deliberate firmware and circuit design. The harvester efficiency figure is also an estimate. These limitations are the most important areas for further development.

Glossary & Abbreviations

Abbreviations

BLE	Bluetooth Low Energy
CAD	Computer-Aided Design
CR2032	Non-rechargeable 3V lithium coin cell
DC	Direct Current
FDM	Fused Deposition Modelling
IR	Infrared
MCU	Microcontroller Unit
ML2032	Rechargeable 3V lithium coin cell
NASA-TLX	NASA Task Load Index
NEC	Nippon Electric Company (IR protocol)
PCB	Printed Circuit Board
RPM	Revolutions Per Minute
RX	Receive
SLA	Stereolithography
SoC	System on Chip
SUS	System Usability Scale
TAM	Technology Acceptance Model
TX	Transmit

Technical terms

Connection interval
The time between consecutive connection events at which the TV and remote exchange data packets over BLE. A shorter interval gives faster response times but higher energy consumption.

Deep sleep
The lowest power state of the BLE chip, entered when the remote is not in use and no connection is active. Current draw at this state is a fraction of a microamp.

Extrinsic generation
Energy harvesting that is separate from the primary interaction with a product. The user performs a dedicated action to generate energy, such as winding a hand crank, before or alongside normal use.

Harvester
The energy conversion component in this project. A DC motor driven through a bevel gear train by the scroll wheel. When the wheel is turned the motor acts as a generator, converting mechanical energy into electrical energy.

Interrupt-driven architecture
A firmware design where the chip stays in deep sleep until a hardware event such as a button press triggers a wake-up signal. Eliminates the continuous keypad polling loop used in conventional IR remotes, which keeps the chip in a semi-active state at all times.

Intrinsic generation
Energy harvesting integrated into the primary interaction with a product. The user generates energy as a natural by-product of using the device, with no separate charging action required.

NEC protocol
A widely used IR signalling standard that defines the timing and structure of the pulses carrying a remote command, including address, command data and their logical inverses. Each full transmission takes 67.5 ms plus a final burst.

Peripheral latency
A BLE parameter that allows the remote to skip a set number of consecutive connection events when it has no data to send. Reduces energy consumption without affecting responsiveness, as the remote can still reply immediately when a button is pressed.

Rectifier
A component that converts the alternating current output of the harvester motor into direct current usable by the chip. In this project a bridge rectifier is used, estimated at approximately 50% efficiency at the low voltages involved.

Reed switch
A magnetically activated switch. Four reed switches in the housing detect the position of the scroll wheel by responding to magnets embedded in the wheel, with no current required for sensing.

Components and named systems

EFR32BG22
The Silicon Labs EFR32BG22 is the Bluetooth 5.2 SoC proposed for this project, selected for its low deep sleep current and interrupt-driven wake-up capability.

FreeBie
A BLE system developed by Jasper de Winkel at TU Delft that maintains a Bluetooth connection on purely harvested energy by saving protocol state to non-volatile memory when power is lost, then restoring it when energy becomes available again.

ML2032
The Maxell ML2032 is a rechargeable 3V lithium coin cell with a capacity of 65 mAh, proposed as the backup battery in this project. Unlike a primary CR2032 it can be recharged by the harvester circuit.

Acknowledgements

A graduation project is an individual assignment however it is never undertaken alone, especially in design. Utilising the people around you is critical to a successful design project.

I would like to thank my supervisors Stefan and Erik, for their support and critical assessment during the project. Doing my graduation at Kinergizer provided me with structure and accessible knowledge, thank you for your readiness to help me.

My masters would have looked a lot differently if I hadn't shared the ride with Matthijs and Lenne. Those walks were probably the most important pastime of the whole masters

Thank you to my parents for their unwavering support and interest in my project.

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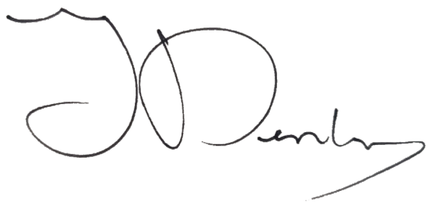

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1. Project introduction

This chapter introduces the problem, the research gap and the approach. It explains why a self-powered TV remote is relevant in a hospitality context and sets out the research questions that structure the project.

1.1 Introduction

Everyday products such as TV remote controls are used frequently but remain dependent on disposable batteries despite their relatively low energy demands. In the hospitality sector this creates a practical problem: batteries fail unpredictably across hundreds of guest rooms, requiring reactive maintenance and creating a consistent source of guest complaints. A remote that generates its own power through normal use would remove this problem.

Human-powered products convert mechanical energy from the user into electrical energy, eliminating the need for an external power source. Examples such as hand-crank radios and the knijpkat demonstrate that human energy can serve as a reliable power source for low-power electronics. Kinergizer has demonstrated the technical feasibility of applying this principle to a scroll wheel mechanism in a computer mouse prototype. While this suggests the concept is achievable, questions remained about how it translates to a TV remote and whether the ergonomics and interaction design can be developed to a level suitable for broad use.

This project investigates how a scroll wheel energy harvester can be integrated into a TV remote, specifically through thumb-based scrolling, without placing additional demands on the user. The aim is to develop a human-powered TV remote that operates without disposable batteries while remaining comfortable and intuitive for first-time users. The hospitality sector is used as the initial context, as it presents the clearest case for removing disposable batteries. The findings are not limited to that setting. For the original project proposal view appendix A.

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1.2 Problem Definition

Kinergizer has demonstrated that a scroll wheel mechanism could generate energy through index finger interaction in a computer mouse prototype. Translating this into a TV remote introduces a new set of challenges. A TV remote is a fundamentally different product from a mouse: it is held in one hand without a surface to rest on and operated primarily by the thumb in a free-held position (Norman, 2016). How the scroll wheel should be integrated into this form factor, in terms of position, orientation and resistance, has not been established.

These factors matter both ergonomically and energetically. The resistance of the harvester directly affects how much energy is generated, but also how comfortable and natural the interaction feels. Getting this balance wrong means either insufficient energy generation or an interaction that users reject. In a hospitality context, where the remote must work immediately for any guest regardless of age or physical ability, this balance is especially critical (Vink, 2004).

Beyond the ergonomics of the wheel itself, it is also unclear whether the typical interaction patterns of TV remote use generate enough energy to power the product. A TV remote is used intermittently, with sessions that may involve only a handful of commands. Whether this is sufficient to sustain the signalling and idle consumption of the remote is an open question that needs to be addressed before the concept can be considered viable.

1.3 Research Gap

Two gaps motivated the research in this project. First, there is no existing research on thumb-driven micro-energy generation through a scroll wheel mechanism. Second, the ergonomic requirements for integrating a scroll wheel into a handheld TV remote have not been studied. Understanding both is necessary to arrive at a design that works reliably across a broad user population.

Main research question

How can a thumb-operated scroll interaction be designed to generate sufficient energy while remaining ergonomic and intuitive for first-time users?

Sub research questions

1. What ergonomic factors, including thumb posture, resistance and placement, influence comfort and fatigue during repeated scroll wheel interaction?
2. How much energy can a thumb generate during scrolling, and what variables influence this most?
3. How is a TV remote typically used in terms of interaction patterns, input frequency and energy demand, and does the harvested energy cover this demand?

1.4 Approach

The project follows a Research through Design (RtD) approach, in which knowledge is generated through the act of designing rather than through purely analytical or theoretical methods. As described by Stappers and Giaccardi (2017), RtD brings a designerly way of working into research, using sketching, prototyping and experimentation as a means of producing insights rather than just solutions. In this project that means initial concepts are developed and tested, the results inform the next iteration, and the research evolves through a continuous cycle of making, testing and reflecting.

This iterative process is structured around the double diamond model as seen in figure 1, which divides the design process into four phases: discover, define, develop and deliver. The first diamond covers the research phase, where the problem space is explored and defined. The second covers the design phase, where solutions are developed and refined (Design Council, n.d.). The end result is a proof of concept prototype that demonstrates the interaction and energy generation of a human-powered TV remote, rather than a production-ready product.

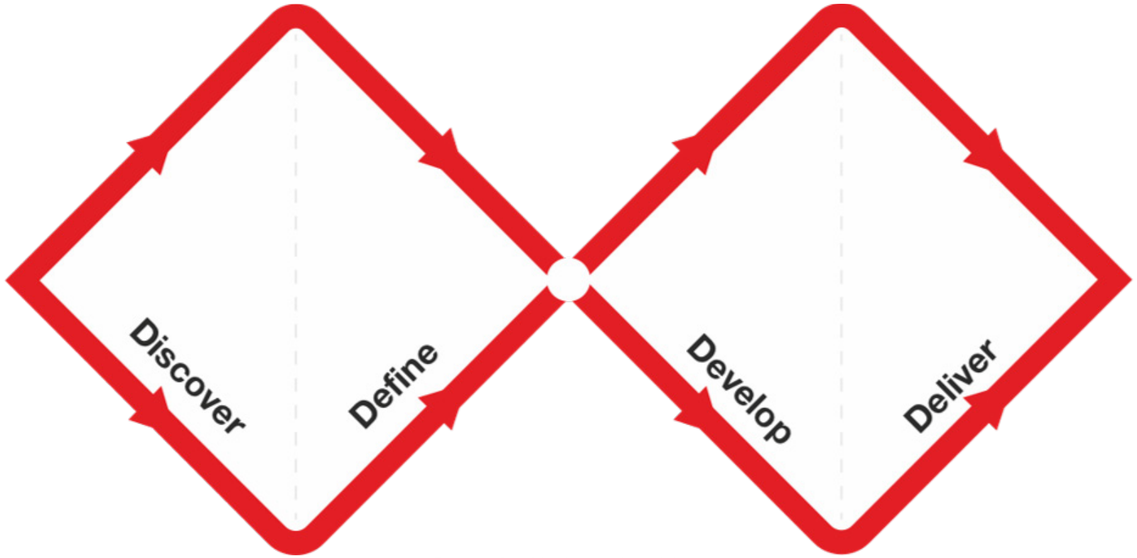


Figure 1 Double diamond model

2. Context Analysis

This chapter looks at what TV remotes currently look like and how they work, covering external design, internal components and the scroll wheel mechanism. It also establishes the constraints of the hospitality context.

2.1 TV Remote External Design

Function

In its half-century of existence the remote control has retained its core features: power, volume and channel selection. The set of additional features has grown considerably over time, but not always in a user-centred way. Remotes tend to evolve from previous versions, adding new features but taking nothing away, with complexity as the result, since each function originally required its own dedicated button. With modern smart TV remotes this has changed: most additional features are now integrated into the on-screen interface of the TV itself, representing a shift from engineering simplicity toward conceptual simplicity (Turbek, 2017). Rather than requiring a button for every feature, functions are progressively disclosed through on-screen menus, reducing the physical remote to what the user needs most (Nielsen, 2006). See figure 2 for visualisation of the switch.

Form

TV remote controls come in many different shapes and sizes, but almost all share one characteristic: they are handheld devices designed to point at the television. There are two main ways to hold a remote. Underhand, where the remote rests in the palm and input comes from the thumb, and overhand, where the remote is gripped from above and input comes from the index finger. The physical and visual ergonomics of a remote can differ considerably, as seen in figure 3.

The three main shape strategies remotes use to improve physical ergonomics, as seen in figure 4, are curves and rounded edges that follow the contour of the palm, sometimes with a thicker base for additional support; indents on the back of the housing to accommodate the index finger in an overhand grip; and a subtle pistol-like curve along the body to make pointing at the TV more natural and less effortful.



Figure 2 Logitec Harmony 650, Right: Apple TV remote and menu



Figure 4 Different ergonomic approaches in TV remote design

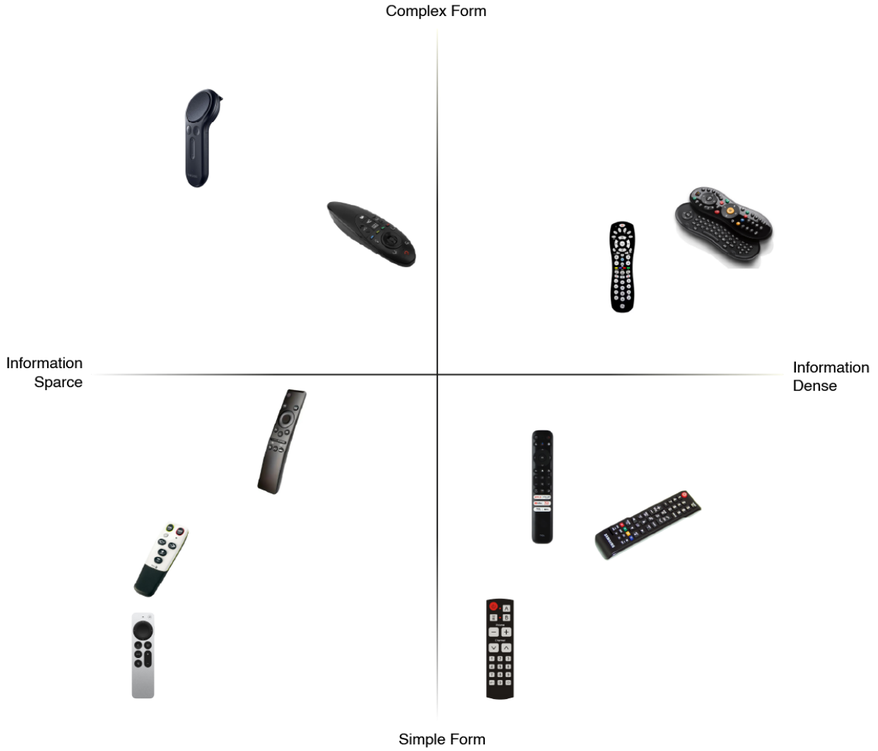


Figure 3 C-box mapping examples of current TV remote design

Layout

Button hierarchy in remote control design is largely determined by use frequency. Buttons can be divided into three groups: used frequently, such as navigation and volume; used occasionally, such as source selection and playback controls; and used rarely, such as settings and information, as seen in figure 5. Every design should make its most important features obvious. On poorly designed remotes the least-used and most-used buttons are the same size and scattered across the surface, creating conflicting visual hierarchies (Turbek, 2017). Norman (2016) frames this in terms of affordances and signifiers: a well-designed layout communicates through its physical arrangement which controls matter most, without requiring the user to read labels or memorise locations. The most frequently used buttons are consistently positioned under the natural resting point of the thumb so they can be reached without shifting grip, with less frequently used buttons clustering around this central zone in line with the proximity principle, related functions grouped spatially to reduce search time (Lidwell et al., 2003). The power button, despite its importance, consistently appears at the top or edge of the remote due to its very low use frequency.



Figure 5 Button hierarchy

All TV remote designs position navigation buttons together with volume and channel control close to or directly next to each other, as these are the most frequently used commands. The exact configuration varies: they are positioned above, next to or integrated into one another, as seen in figure 6. This consistent grouping across all remote types reflects the proximity principle in action: functions that are used together are placed together (Lidwell et al., 2010).

Remote control buttons use shape, colour and additional protrusions as use cues. This is especially apparent on remotes with a large number of buttons, where differing colours and shapes help the user distinguish between functions quickly and without looking.



Volume in corners | *Volume next to navigation* | *Volume above Navigation* | *Volume under Navigation*

Figure 6 Volume and navigation buttons layout

As stated, the most important buttons lie within reach of the thumb without the user having to shift grip, as seen in figure 7. However if the actual range of motion of the thumb is considered, most modern remotes do not use all of it. Gaming controllers are a good example of a device that makes much more complete use of the thumb's range of motion, which points toward an opportunity that conventional remote design has largely left unexplored.



Figure 7 Thumb range of motion

Remote controls are constrained in asymmetric design because they need to be ambidextrous. It is worth noting that asymmetric design does occur: figure 8 shows an example where the button layout follows the natural path of the right thumb together with a gaming controller. For a concept targeting a specific user group this is a consideration worth revisiting.

Besides the button, TV remotes also use rocker switches, D-pads and scroll wheels, though these are less common. The scroll wheel appears most notably in the LG Magic Remote series, where it serves as vertical scrolling input and as the select button. For details see appendix B.



Figure 8 Design for range of motion

2.2 TV Remote & Scroll Wheel Internal Design

TV remote internals

The internals of a standard TV remote control are relatively simple. Inside the injection-moulded casing sits a single piece of silicone rubber where protrusions serve as buttons. Underneath the silicone layer is the PCB, which carries the button inputs directly on its surface. Below the PCB is space for the batteries. The outer housing is held together by straight-arm snap fits, with the PCB and silicone layer constrained within. As seen in figure 9.

Scroll wheel mechanism

To detect the rotation of the scroll wheel a sensing mechanism is needed. There are three main options, each with different implications for energy consumption. Optical encoders use an infrared LED and photodetector to sense interruptions in a patterned disk. They are accurate but require continuous power for the LED. Magnetic encoders rely on a rotating magnet and offer lower power operation, but still require a constant electrical supply for sensing. Mechanical encoders use physical contacts to register discrete steps and do not require active power for position detection, making them the most suitable option for energy-harvesting applications (Smoot, 2019). Based on the energy constraints established in chapter 5, a mechanical encoder is the appropriate choice for this concept. The specific encoder selected is discussed in chapter 7.

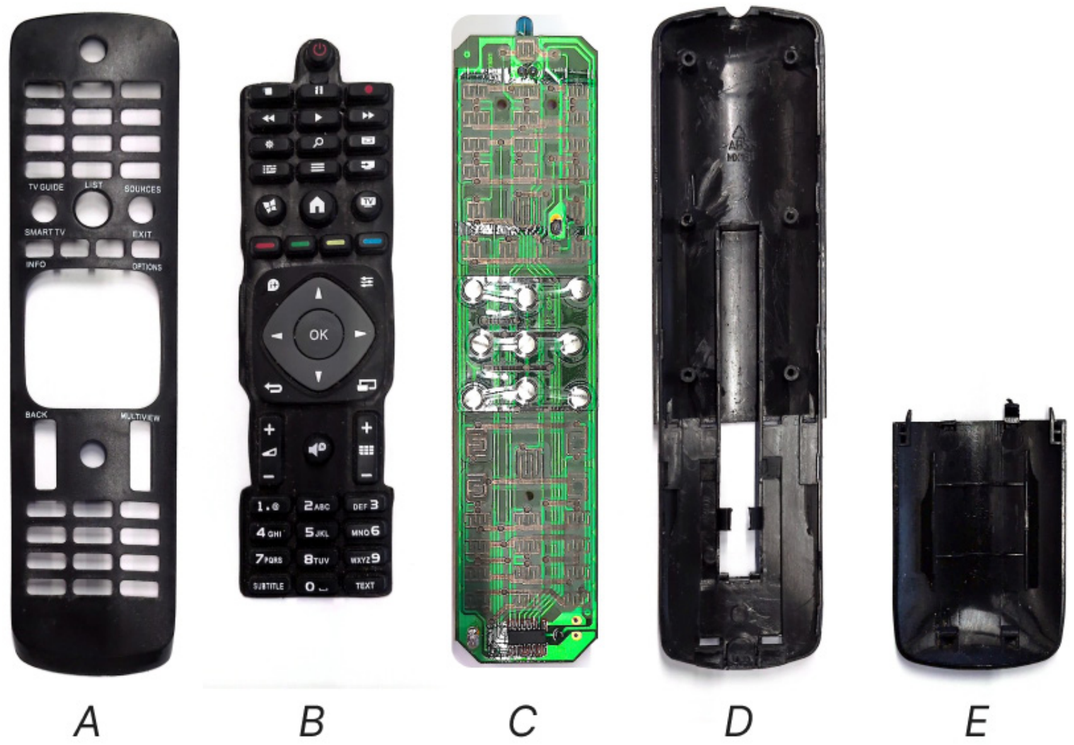


Figure 9 Example of IR TV remote internals

2.3 Hospitality Context

Kinergizer identified the hospitality sector as a primary target market for the TV remote scroll wheel concept. According to them the hospitality market moves more slowly than consumer electronics and works differently commercially: instead of selling to individual consumers through retail, the product can be sold directly to hotels as a procurement decision. This makes it easier to introduce the concept in a controlled environment before any broader rollout.

The pain points on both sides are clear. Hotel guests expect everything in their room to just work. From personal experience in a hotel restaurant context, guests have a very low tolerance for things not meeting their expectations. They will complain quickly and expect immediate resolution, often without wanting to leave the room. Dead batteries in a TV remote are a disproportionately disruptive problem relative to how trivial the fix is. From the hotel side, batteries fail at random across hundreds of rooms, forcing housekeeping to respond reactively rather than on a schedule. A remote that charges itself through normal use removes this unpredictability.

The scale also matters. A single hotel with hundreds of guest rooms eliminates a large number of disposable batteries compared to a single consumer household (Yang et al., 2022).

Main constraints designing for hospitality context

Designing for hospitality introduces constraints that are stricter than for a typical consumer product. Three in particular are relevant here.

The first is that every user is essentially a first-time user. Repeat guests aside, every person who picks up the remote will do so without prior experience, without a manual, and without much motivation to figure it out. The scroll wheel is familiar from a computer mouse but its use in a TV remote will be new, and users will need to adapt without having chosen to (Norman, 2016). Intuitiveness is not a nice-to-have here, it is a minimum requirement.

The second constraint is that the remote needs to work for the full range of people a hotel receives. As discussed in chapter 5, energy generated depends directly on how much physical effort the user applies. A hotel has guests of all ages and physical abilities. Users with limited thumb strength may generate considerably less energy than the tests assume, and may also find the resistance uncomfortable (Vink, 2004). Users will also adapt to the new interaction at different rates, and the concept needs to work for those who do not adapt at all (Fogg, 2009).

The third is that the remote must always work straight away. Hotel guests have paid for comfort and convenience and are not willing to troubleshoot (Pine & Gilmore, 1998). This is discussed further in chapter 4.

Whether the final remote actually meets the hospitality standard needs to be assessed honestly. If it cannot guarantee reliable operation across the full range of users a hotel represents, a different market may be more appropriate, one where users have actively chosen the product and have more motivation to engage with it. This is revisited in the conclusion.



3. Human Powered Devices

This chapter covers what human-powered products are, how they convert human effort into usable energy and where the relevant precedents sit. It introduces the distinction between intrinsic and extrinsic generation and explains why that distinction matters for how the product is designed and how users relate to it.

3.1 Human Power

Human-powered products are devices that use muscular energy as their primary or supplementary power source. Jansen (2011) identifies three eco-design benefits that set them apart from battery or grid-powered alternatives: a material benefit, as they draw no energy from non-renewable sources during use; an immaterial benefit, as power is always available without depending on an external supply; and an emotional benefit, as users feel environmentally active. These properties make human power a relevant alternative to disposable batteries, particularly in contexts where battery failure causes disproportionate inconvenience, as described in chapter 2.

Human power is however not an efficient energy source. Shin et al. (2017) show that the financial savings from Human-powered products are negligible. Powering a television through pedalling yields savings of roughly £0.22 per week, with a cost-recovery period of over twenty years. What human power does offer is independence from an external supply. A device that generates its own power is not constrained by where batteries need to go, how large they need to be, or how often they need replacing. For this project that means eliminating the maintenance burden that battery replacement places on hotel operations.

The scale of energy involved is small. Human-powered products operate in the range of millijoules per interaction. Yang et al. (2022) measured an average of 0.26 J per manual operation across everyday objects including drawers, doors and dials. As the energy requirements of low-power electronics continue to fall, this kind of micro-generation becomes increasingly viable as a supplementary power source.

3.2 Examples of Human Powered Devices

Human-powered devices cover a wide range of interaction types and power outputs. The hand crank is one of the most energy-dense options. Jansen (2011) notes that one-handed cranking can sustain outputs of 30 to 50 W over short periods. It appears in emergency radios and torches, where users are willing to exert effort because the stakes of failure are high. The bicycle dynamo works on the same principle but is driven by the legs, which are already engaged regardless of whether a generator is attached. Both can be viewed in figure 10.

Squeeze mechanisms work differently. The ‘knijpkat’ is a well-known Dutch example, a hand torch powered by repeatedly squeezing a lever, as seen in figure 11. Pierce and Paulos (2012) found that squeezing was rated as more natural and pleasant than cranking, which matters for acceptance in a low-motivation context.

Piezoelectric buttons generate a small voltage spike from crystal deformation when pressed. They are used in self-powered wireless switches and doorbells, where a single press provides enough energy to transmit a signal without any stored power.

Rotary mechanisms, dials, scroll wheels and knobs, sit somewhere in between. Villar and Hodges (2010) present the Peppermill, a self-powered device where turning a knob both generates energy and registers the interaction. Yang et al. (2022) found that rotational everyday objects harvest 0.03 to 0.18 J per operation depending on stroke length and gear ratio. These figures are directly relevant to the scroll wheel mechanism in this project.



Figure 10 Top: Bicycle dynamo, Bottom: Crank radio



Figure 11 “Knijpkat” in hand

3.3 Intrinsic vs Extrinsic Human power

Human-powered products differ in how the act of generating relates to the act of using the product. This has direct consequences for how much additional effort is placed on the user.

With extrinsic generation, energy production is separate from product operation. The user generates first, then uses. The hand-cranked emergency radio is a clear example: cranking charges the device and only once enough charge has built up can it be used. The two activities are sequential, placing a demand on the user that is unrelated to the core function.

With intrinsic generation, energy is harvested from movements the user makes anyway. The bicycle dynamo is the obvious example, the cyclist generates power as a by-product of travelling with no extra effort. Broadhead et al. (2026) describe a related concept they call kinetic coupling, where the harvesting action and the product input are the same thing. Turning the crank in their TURNER console both powers the device and fires a weapon in the game, as seen in figure 12. Yang et al. (2022) apply the same principle to everyday objects, using the manual operation of drawers and doors to generate energy for their automatic operation.

This project is initially focussed on intrinsic generation. Scrolling the wheel is the primary interaction with the remote, and that same motion drives the harvester. No separate charging behaviour is needed. This matters in a hospitality context where users have no motivation to engage with the energy-harvesting side of the product. Which functions should generate and how the scroll wheel should support this is discussed in chapter 9.



Figure 12 TURNER console (Broadhead et al., 2026)

4. Human Factors & Ergonomics

This chapter covers the ergonomic constraints that shape the TV remote and scroll wheel design, including comfort theory, thumb biomechanics, scroll wheel orientation and thumb rpm. It builds on two demands set by the hospitality context in chapter 3: the interaction must require low physical effort to work for the full range of guests (Story et al., 1998), and it must not push past the threshold of what users are willing to engage with (Fogg, 2009).

4.1 (Dis)Comfort and Fatigue

For the acceptance of any product it is important that discomfort is limited. This is especially true when designing for an environment where users expect to be comfortable, i.e. hospitality. Human powered products however are inevitably associated with discomfort. Understanding (dis)comfort is therefore especially important when designing human powered products. (Jansen, 2011)

Vink (2002) states that there are actually three states of comfort as seen in figure 13:

- Comfort: the participant experiences noticeably more comfort than expected and feels comfortable.
- No discomfort: the participant is not aware of the fact that there is no discomfort.
- Discomfort: the participant experiences discomfort because of physical disturbances in the environment.

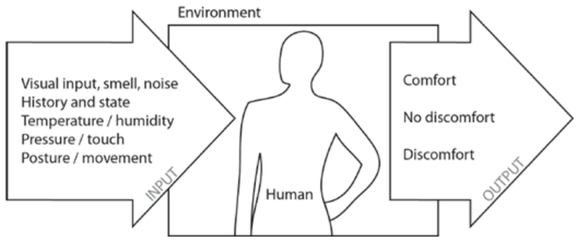


Figure 13 Comfort model by (van Abbema, 2011) after (Vink, 2002)

These are stimulated by external factors (sight, smell, noise, pressure, etc.) and internal factors (history of comfort experience and state).

It is agreed upon that comfort and discomfort are two separate things that do not lie on opposite sides of a single spectrum. The absence of discomfort does not necessarily mean comfort. The different underlying factors for this (applied to sitting on a seat) are showcased in figure 14.

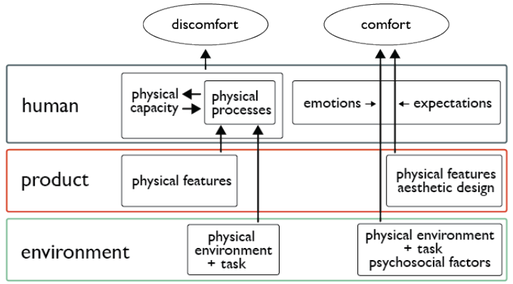


Figure 14 Theoretical model of comfort and discomfort for sitting (de Looze et al., 2003)

Besides being different entities, discomfort and comfort also occur at different awareness levels as illustrated in figure 15. There are three main principles of physical ergonomic design (Vink, 2004):

- More contact area, less peak pressure
- Reduce the moment arm
- Joints in neutral position

Deviation from this neutral posture is perceived joint discomfort (Genaidy & Karwowski, 1993)

Comfort isn't only dependant on physical interaction, as seen in the Vink & Brauer (2011) experience process. Before short and long term comfort are defined, users have an initial expectation and reaction at first sight before physical interaction is happening. In the context of this project this could mean that if the hotel is perceived as uncomfortable by the user it is more likely that he will also experience the human powered TV remote as uncomfortable as that is his expectation.

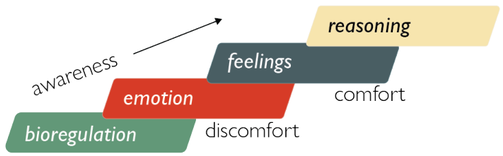


Figure 15 (Dis)Comfort and awareness (Vink, 2004)

Adding discomfort

As stated earlier you can't have a human powered product without some form of short term discomfort, as effort is needed to generate energy. The three main things that influence perceived discomfort are:

- Required power (torque and speed)
- Time
- Design of the user interface.

This added discomfort needs to be accepted by the user which requires motivation. The reasoning model for the acceptance or rejection of discomfort can be seen in figure 16.

In the context of this project the human powered product is a TV remote in a hotel room. One can assume that the users motivation to watch television is relatively low as compared to actions where more is at stake, e.g. powering a torch during a blackout (Jansen, 2011). Furthermore a hotel room is designed to be comfortable so adding discomfort in this context could be quickly noticeable as humans are made to notice differences and not absolute values. Comfort is subjective and is directly influenced by the comfort perceived beforehand (van Veen & Vink, 2016). Lets assume the user watches television on his hotel bed, if the user has been sitting on an uncomfortable hotel room chair beforehand he'll perceive the bed as more comfortable than if he had been sitting on a comfortable chair.

In the context of this product, the primary source of potential discomfort is the thumb operating the scroll wheel. Understanding how the thumb moves and which movements are most comfortable is therefore the starting point for scroll wheel design.

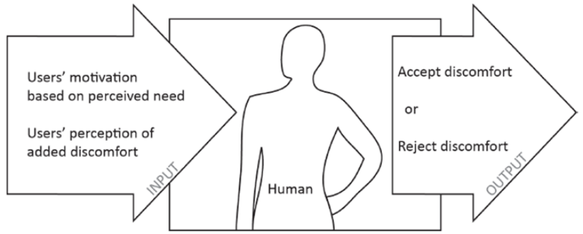


Figure 16 Reasoning model for acceptance of discomfort in human powered products (Jansen, 2011)

Measuring discomfort

Three ways to measure (dis)comfort:

1. Participants to exert a force they deem comfortable with the dependant variable being the exerted force.
2. Force level is predetermined and users are asked to rate the level of discomfort on a scale
3. Measuring spontaneous change of posture and during submaximal force exertion and when it occurs.

The first two ways rely on the participant to be actively aware of their perceived (dis)comfort, which doesn't naturally occur with regular product use. The third method seeks to measure discomfort in a non intrusive way.

As stated earlier context plays a very important role in a users perceived (dis)comfort. What this means is that we can gather all the data we want about a participant's perceived (dis)comfort, but if the context doesn't align enough with the actual use scenario it is meaningless (Jansen, 2011).

4.2 Thumb Biomechanics

There are nine muscles that control the thumb which can be split up into two main groups, the extrinsic muscles located in the forearm, and the intrinsic muscles located on the hand itself. During thumb motions most muscles tend to be active to maintain stability as there are little articular constraints. (Wikipedia contributors, 2026)

The thumb has three main directions in which it can move, as seen in figure 17. Flexion and extension which allows the thumb to curl and uncurl. Abduction and adduction which allow the thumb to move from and to the hand. Finally there is opposition which allows thumb to move across the hand and touch the other finger tips.

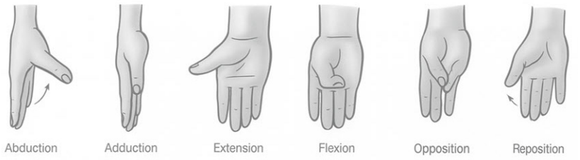


Figure 17 Thumb movements

There isn't any publicly available research on a thumb operating a scroll wheel with resistance, but we can look to the smartphone world to get an idea. In this ergonomic study (Xiong & Muraki, 2014) participants are asked to perform tapping, moving and circling movements on a smartphone. The muscle activity of six thumb muscles where registered together with their perceived exertion and thumb movement speed. The main takeaway from this paper is that the flexion extension movement is slower at maximal speed than the adduction-abduction movement. With fatigue time flexion, extension and abduction adduction have a similar result. See figure 18 for results.

A second smartphone paper tests thumb motor performance in varying directions and movement orientations. Participants are asked to perform tapping tasks on different smartphone shapes. Their main findings concerning this thesis is that adduction-abduction movements score better than flexion extension movements. Their hypothesis for this result was that the adduction-abduction movement has one joint degree of freedom whereas flexion extension has three. This reduced complexity allows the adduction-abduction movement to be faster and more accurate. (Trudeau et al., 2011)

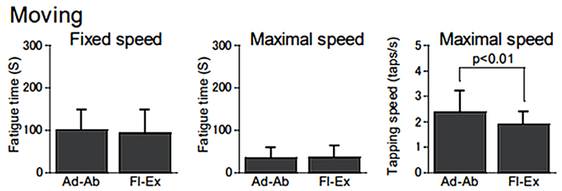


Figure 18 Thumb performance (Xiong & Muraki, 2014)

It is important to note that in both of these papers the thumb isn't performing with any added resistance, which will be the case with the scroll wheel mechanism. One can assume that thumb movement with resistance would favour the adduction-abduction movement due to its lesser complexity.

As stated deviation from neutral joint position is perceived as discomfort. To minimize this it is important to allow the resting position of the thumb, and thus the scroll start position, to be a neutral one. Based on the human hand model described in The measure of man and women (Tilley & Associates, 1993) we can determine basic remote control dimensions. The distance between the grip point of the thumb, scroll wheel contact point, and base of the hand, where the but of the remote rests, is roughly 100mm, as seen in figure 19. To see the full hand dimensions this is based on view appendix C

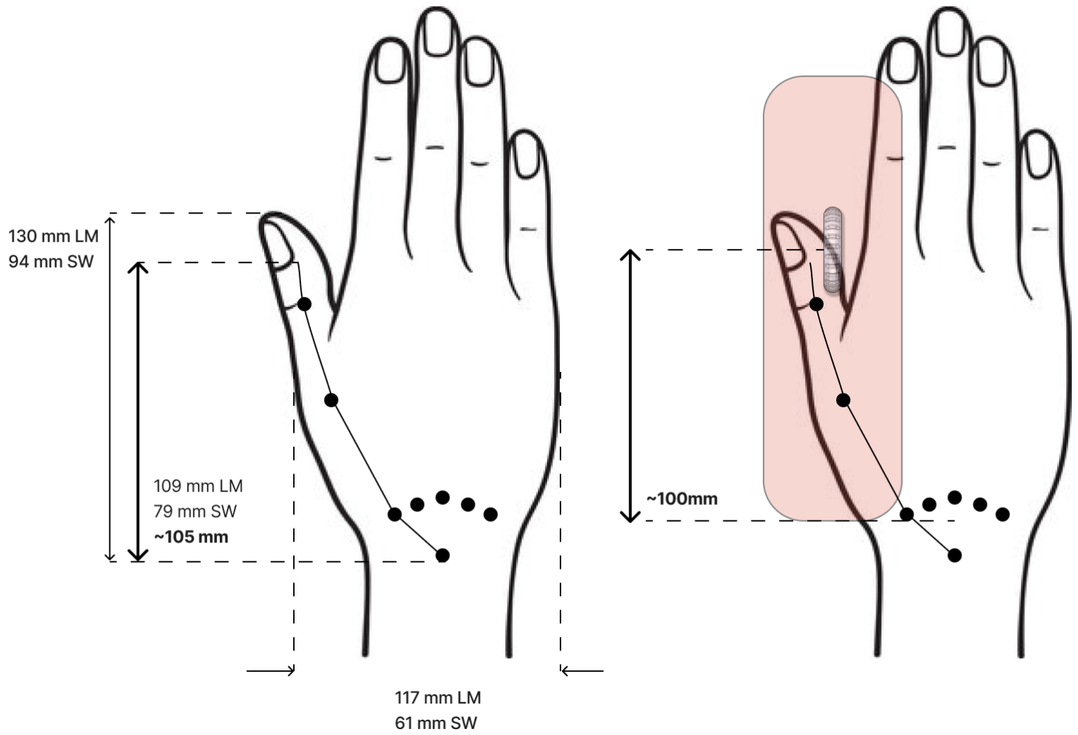


Figure 19 Hand measurements of interest based on (Tilly & Associates, 1993)

4.3 Thumb driven scroll wheel

Having established the multiple movements of the thumb we must now apply these on a scrolling motion in the context of a remote control. For this we are going to assume that the remote is held with the fingers on the bottom and the thumb on top. In this case the scroll wheel is on a horizontal plane. Depending on the orientation of the scroll wheel, a thumb can operate it in multiple ways. It is possible to position the scroll wheel in a way where we can get close to a solely flexion-extension movement, or a adduction-abduction movement. In the first case the scroll wheel would have to be inline with the thumb and in the second case perpendicular, as seen in figure 20. This would require the user to have the exact same grip, thumb and hand dimensions, which will all vary. It is then safe to assume that, although we can determine the main movement of the thumb by the orientation of the scroll wheel, the actual movement of the thumb will have both flexion-extension, adduction-abduction and a bit of opposition.

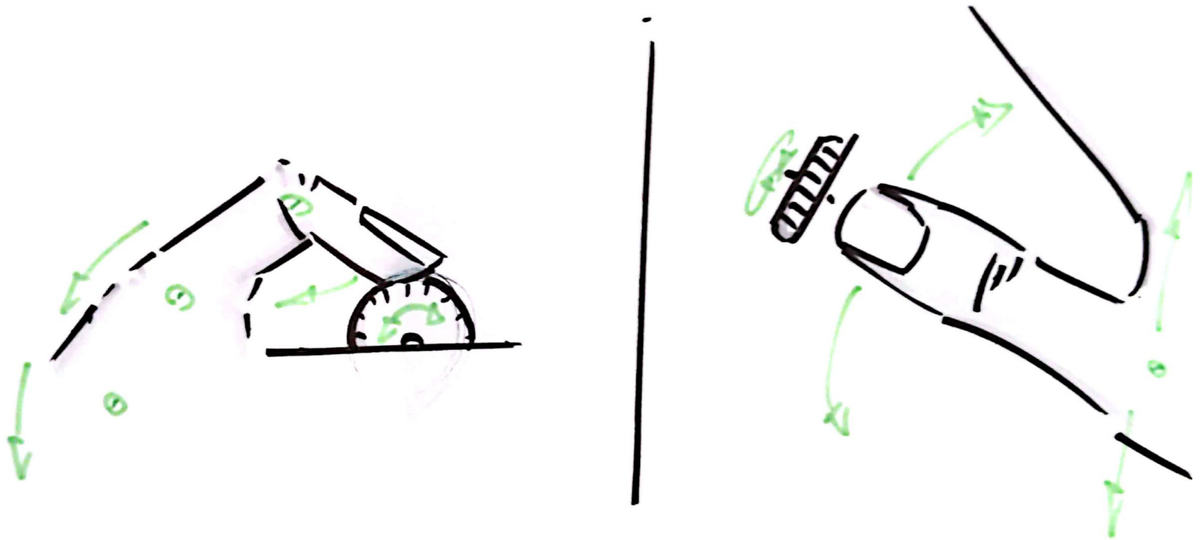


Figure 20 Flexion, extension and adduction, abduction as scrolling movements

4.4 Scroll Wheel Orientation

The following test examines which scroll wheel orientation feels most comfortable in practice. Therefore remote control shapes with varying scroll wheel positions were made, as seen in figure 21. Orientation 1 and 3 require a combination of flexion-extension, whilst 2 will be mostly adduction-abduction movement and 4 mostly flexion-extension, allowing the biomechanics findings above to be tested against user preference.

The prototypes consist of a 3D printed scroll wheel module that is attached to a foam bar. This construction was chosen because it was the fastest way to produce the shapes: with the scroll wheel module sitting on top of the foam, no labour-intensive foam cutting was required.

Initially the test setup was to let users scroll for short and long periods and then rate how comfortable it was on a Likert scale of 1 to 5. It was however quickly determined during testing that it was better to let users experiment themselves and give feedback instead of trying to quantify it. Ten fellow students were asked to handle the prototypes and provide feedback.

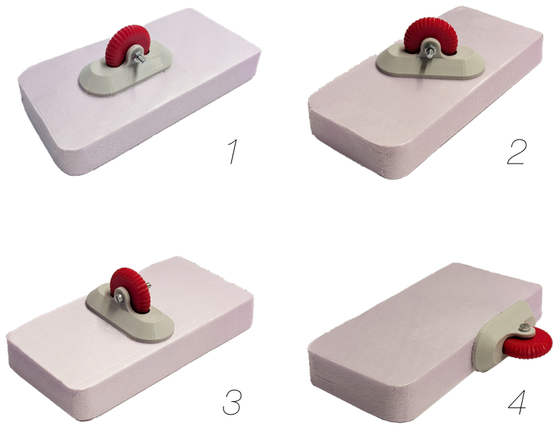


Figure 21 Four different scroll wheel orientations

Results

- 1 was most often rated best for comfort with 2 and 3 having varied reception. 4 was only liked by few.
- 1 felt most conventional, 2 felt like telephone swiping, 3 felt like it could be good for channel swiping.
- The real main takeaway was that comfort is very subjective and based on what participants are accustomed to.
- Because the foam shape was not very defined, participants tended to hold remote 1 in the orientation that gave their thumb a neutral position. Most did this almost unconsciously.
- When their initial grip was not comfortable, participants experimented with different grips and scrolling techniques to find a more comfortable position.
- Participants were inclined to fidget with the remotes and were often already doing so before the test had started.

The preference for orientation 1 over orientation 4 is consistent with the biomechanics literature in the sense that pure flexion-extension, as in orientation 4, was the least preferred. However, orientation 2, which most closely maps to adduction-abduction, did not come out clearly on top either, its varied reception suggests that familiarity and habit play as large a role in comfort as movement type alone.

Discussion

Because the scroll wheel module was mounted on top of the foam rather than integrated into it, there was a large height difference between the foam surface and the top of the scroll wheel. This does not reflect future prototypes, which will have a more integrated wheel. Participants found this uncomfortable as their thumb and palm were not properly supported, which was particularly noticeable with remote 4.

The scroll wheel resistance was caused by friction, adjustable to some extent with a nut and bolt. The resistance level was set intuitively rather than by deliberate specification, as the tolerances had not been properly defined at this stage.

The participants' tendency to fidget should not be generalised to all users, as the sample consisted entirely of design students, who may be more inclined to explore and manipulate objects than the general population.

Although remote 2 was perceived as comfortable by some, it is not ambidextrous and will therefore not be included in future testing.

4.5 Index Finger vs Thumb Scrolling

Having established that a forward-facing scroll wheel is preferred, the next question is how thumb scrolling compares to index finger scrolling, as this is the most established form of finger scrolling.

Index finger scrolling

In 2024 Kinergizer performed a test where they measured rpm at different torques on a index finger operated scroll wheel. Five participants (4m, 1f) from the office where asked to scroll at 6 different torque settings in the manner that they usually would when operating a computer mouse. Each of the participants was asked to indicate at what torque setting the scrolling didn't feel doable any more. See figure 22 for the test setup. A scroll wheel drives a gear train which is attached to a spool. The spool wire has a magnet hanging from it allowing you to change the torque on the scroll wheel by adding weight. The gear train has a rectifying function which turns the bidirectional movement of the scroll wheel into unidirectional rotation for the spool. This means the weight is always pulled up.
The main findings of this test where:

- When torque increased rpm didn't drop.
- The mean rpm speed is around 55-60 rpm.
- Rpm varies per person
- When a torque is "doable" is very subjective

See graph 1 for full results, a graph of the push rpm can be seen in appendix D. To test if a thumb operating the scroll wheel would yield similar results the test setup was modified to accommodate thumb scrolling

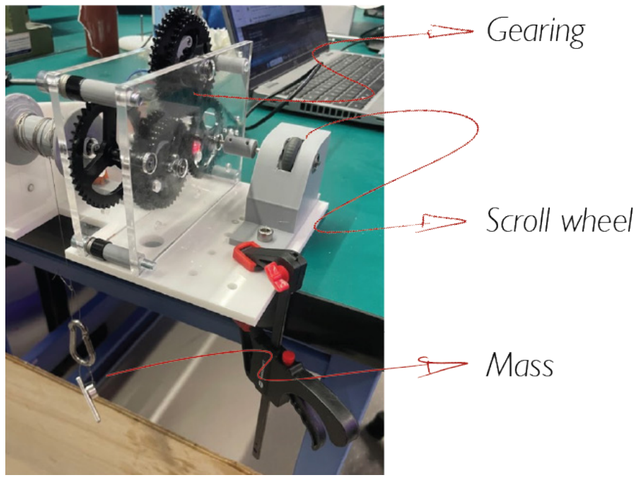
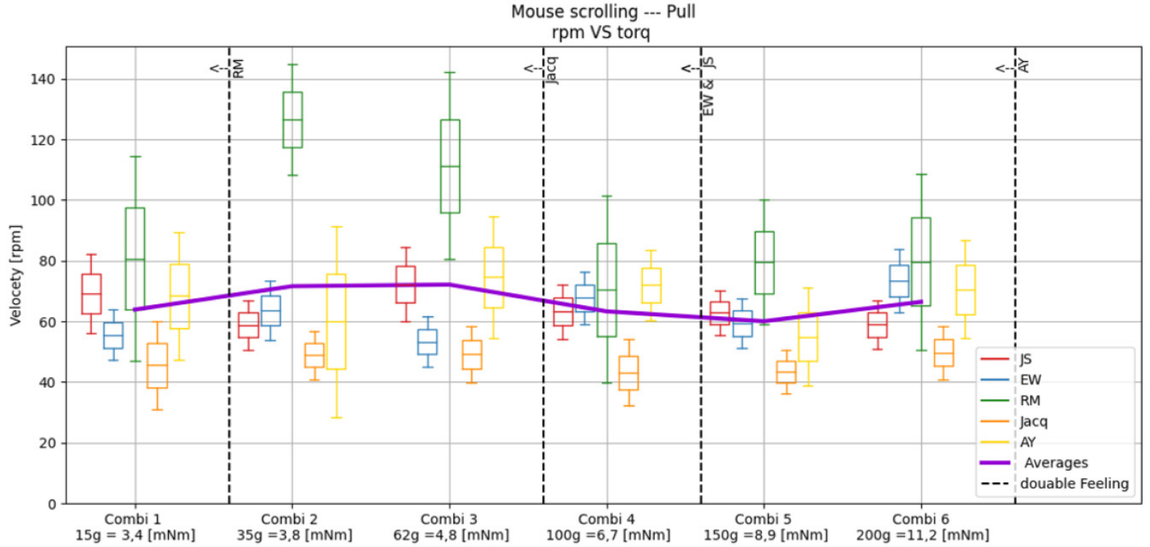


Figure 22 Index finger scroll test setup



Graph 1 Results index finger rpm test

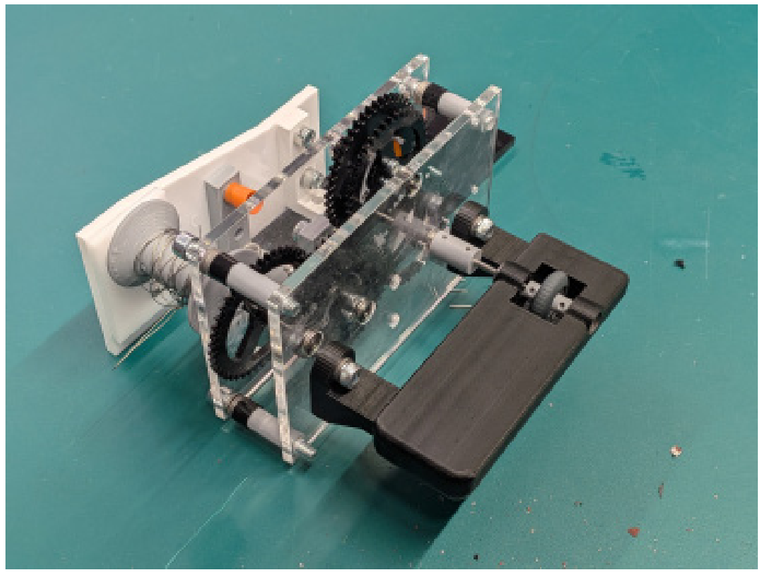
Test setup for thumb scrolling

To adapt the test setup to thumb scrolling a TV remote shape was 3D printed and bolted to the side of the test setup. The rest of the test stayed the same. With this new grip participants are able to grip the remote like they normally would. See figure 23.

Like with the old test setup the scroll wheel axle is attached to a magnet. Using the software Flexlogger the rotation of the magnet is measured in degrees together with the duration of the test. This data is put into a Python script written by a college which export the RPM over time. Once again five participants from the office were asked to intuitively scroll at different torque settings. After the pilot it was decided to add a heavier torque as the participant experienced no difficulty.

Results

The thumb rpm test showed a similar trend as the index finger test: Although torque increased, rpm didn't drop a large amount. The lowest thumb rpm, 100 rpm, was in the same region as the fastest index finger rpm. Overall speeds were more than double the index finger test. There seemed to be a tighter spread in the do ableness rating. Most participants preferred scrolling towards them (pulling) instead of away. The higher the rpm the more it varies. The results of pulling can be seen in graph 2, and the result of pushing can be seen in appendix E. All torque settings didn't introduce real discomfort, the do ableness rating was based on what they would expect from normal handheld product use.



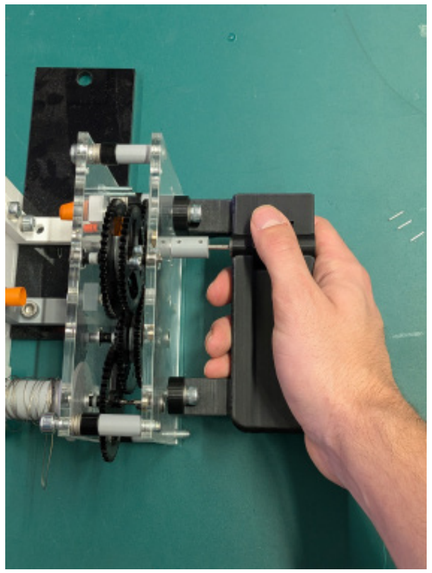
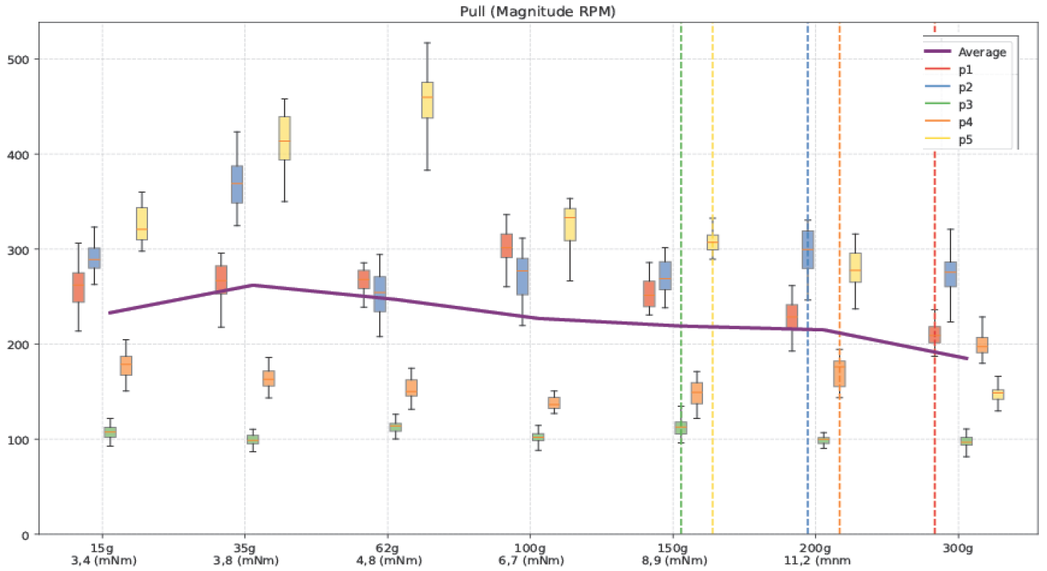


Figure 23 Modified rpm test setup



Graph 2 Result thumb rpm test

Discussion

Although this test tries to replicate the previous index finger scroll test to the best of its abilities, there are of course limitations. The first being that the participants are different than with the index finger test. In general the small sample size means the rpm output can only be used as an order of magnitude and not exact results. Another limitation is that, although there was some documentation of the index finger test, only one person in the office was present during the first test. This means that even though we assume we set up the test and interpreted the results in the same manner, we cannot be a 100% certain. Due to the differing context of this test and real life we cannot assume that users will have the same rpm output at these torque's in a real life setting.

4.6 TV Remote Shapes

The next step in ergonomic experimentation was to combine findings from the first ergonomics test and desk research on remote control shapes. The goal of this iteration was to discover how participants would react to a more integrated scroll wheel in different TV remote shapes. All TV remote prototypes have the same scroll wheel size and depth. The distance from the scroll wheel centres to the bottom of the remotes is 100mm.

Traditional shapes

From research we see that most TV remotes have a rectangular shape with curved edges. This is what shape 1 and 3 are based on, as seen in figure 24. Although side scrolling was not well received in the first test, shape 3 gives it another chance now that the wheel is more integrated into the remote, which is expected to improve the experience. Shape 2 is based on remote controls that widen in the middle to better fit the cup shape of the palm of the hand.

Novel shapes

Shapes 4, 5 and 6 experiment with utilizing the thumbs full range of movement, as seen in figure 25. By widening the area around the neutral resting point we can insert more buttons that the thumb can reach. Shape 5 experiments with an offset scroll wheel to create space for the navigation buttons. Unlike shapes 4 and 5, shape 6 has a more aggressively formed handle.

Results

Once again it was found that comfort is very subjective. Some remote shapes were rated more favourably than others, but participants often contradicted each other: one participant might find a shape comfortable to hold and scroll, while another disliked the same shape.

Shapes 1 and 2 came out best, because the neutral shapes allowed participants to adjust the grip to their liking.

An interesting finding was that both large and small hands encountered difficulties. Both could operate the scroll wheels, but while the larger hand could not always achieve a neutral position, the smaller hand sometimes could not reach the scroll wheel comfortably, as seen in figure 26. This supports the earlier finding that the remote shape should be relatively neutral so that users can adjust their grip to accommodate different hand sizes. Full images and findings can be found in appendix D. As with the scroll orientation test, participants showed a tendency to fidget with the remotes.

Discussion

Although TV remote shape 1 and 2 came out best in the test, shape 3, 4 and 5 shouldn't be excluded from future design directions. The main reason behind the lower scores was not the core concept of utilizing the ROM of the thumb but shortcomings in other parts of the design.

As with the first ergonomic test the results should be seen as indicative and not conclusive. Although TV remote control shapes are based on real TV remote shapes there is not enough reasoning behind them. Some of the specific shapes of the remotes are simply a result of CAD modelling and not a conscious decision that is supported by research.

Although this test was explorative, the methodology should be better defined and structured in future iterations. Participants' hand size should be measured rather than estimated by eye; at minimum, hand length and width should be recorded, for example by placing the hand on a measured sheet of paper and photographing it. Photographs should be taken with each remote from a consistent angle.



Figure 24 Traditionally shaped TV remote shapes

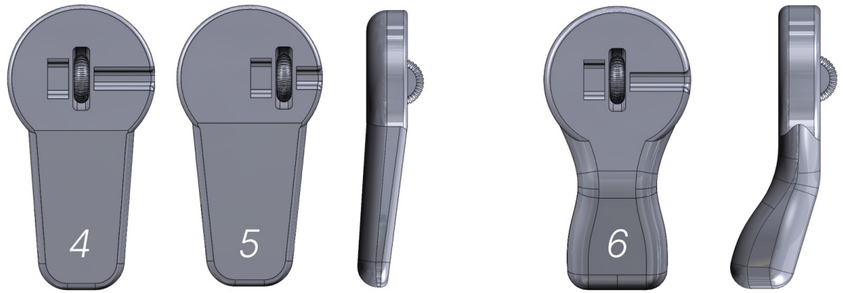


Figure 25 Novel shaped TV remote shapes



Figure 26 Three different hand sizes on same TV remote shape

4.7 Conclusion Human Factors & Ergonomics

The research and tests in this chapter establish the ergonomic parameters for the scroll wheel design and confirm that thumb scrolling is a suitable interaction method for a human-powered TV remote.

The discomfort literature makes clear that in a hospitality context, where users have a high baseline expectation of comfort, the threshold for perceived discomfort is lower than in most other product categories. This places a strict constraint on the harvester: the mechanical resistance must stay within a range that feels natural rather than effortful.

The biomechanics literature points toward adduction-abduction as the more comfortable thumb movement due to its lower complexity. The orientation test offered partial support for this: orientation 4, involving predominantly flexion-extension, was least preferred. Orientation 2, the closest match to adduction-abduction, had varied reception however, suggesting that familiarity plays as large a role as movement type. A forward-facing orientation is recommended as the best balance between the two.

The thumb rpm test confirmed that the thumb produces speeds more than double those of the index finger at the same torque levels, with no resistance setting causing real discomfort, only a subjective sense of what felt appropriate for a handheld product. The limiting factor is user expectation rather than physical capability. What resistance level strikes the right balance between energy generation and user comfort is investigated in chapter 5.

The shape test showed that neutral forms outperform more opinionated shapes because they allow users to adjust their grip to suit their hand size. The 100 mm scroll wheel placement derived from the Tilley hand model is consistent with this finding. Across both tests participants showed a tendency to fidget.
Together these findings establish two design parameters carried forward into the project: a forward-facing scroll wheel orientation and a neutral remote shape with the wheel placed at 100 mm from the base.



5. Energy Generation

This chapter investigates how much energy the scroll wheel harvester can produce and what variables influence that most. It describes a series of tests covering electrical resistance, scrolling speed and the effect of context on user behaviour, and works through the system losses between the harvester output and the chip.

5.1 Main Variables Energy Generation

The amount of energy generated is critical to the feasibility of the concept. The current energy harvester allows the electrical resistance to be set. This has a direct effect on energy generated as seen in the following formula:

Current (A) = Voltage (V) / Electrical resistance (Ω)

The electrical resistance has a direct relation to the mechanical resistance one feels when scrolling the wheel as a higher current means a higher torque (E. Weteringen (Kinergizer) personal communication). As seen in the following formula(Staff, 2025).

Torque (Nm) = Motor constant (Nm/A) x Current (A)

This means, counterintuitively, that a lower electrical resistance means a higher mechanical resistance. This trade-off between electrical resistance and mechanical feel is consistent with findings from Yang et al. (2022), who found in their MiniKers system that a lower resistance in the motor powerline increased harvested energy but also increased the force required to manually operate the object.

To gain a better understanding of the amount of energy generated by the harvester two tests were conducted. To do this a basic TV remote shape was 3D printed to accommodate the harvester and scroll wheel housing. The electrical resistance could be set to the desired value and generated energy was measured using a power analyser, as seen in figure 27.

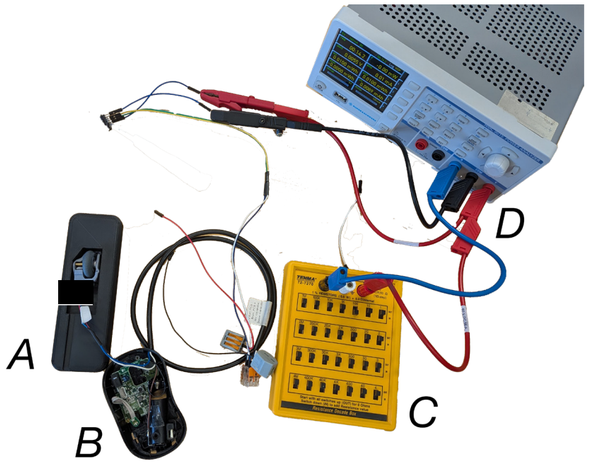
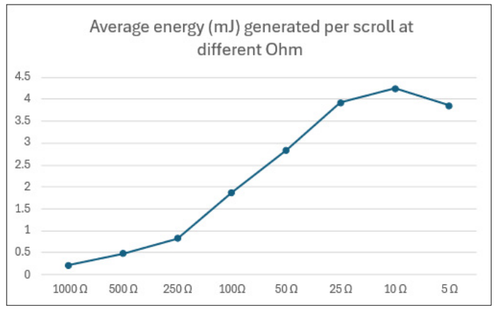


Figure 27 A: Scroll wheel in TV remote shape, B: Old mouse prototype still connected, C: Variable electrical resistance, D: Power analyser

Influence electrical resistance (test 1)

The goal of the first test was to determine the ideal electrical resistance for the best energy generation with thumb scrolling. At 8 different resistances the wheel was scrolled for 10 scrolls (approximately 1/3 rotation) over 10 seconds. Each resistance had 3 runs. The average of these runs can be seen in graph 3.

From graph 3 we can see that the ideal electrical resistance for generating energy is 10 Ω as the scroll RPM starts to drop once the resistance gets too high. This decrease in rpm starts at 25 Ω. It also shows that with a semi relaxed input we can achieve an energy generation of 4mJ per scroll.

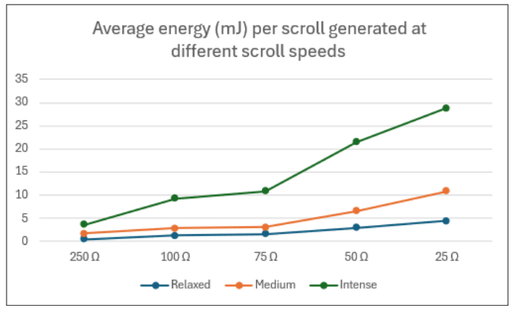


Graph 3 Energy generated at different electrical resistances

Influence scroll speed (test 2)

The second test showcases the effect of different input speeds on energy generation. Three input speeds were tested across five different electrical resistances, each run taking 10 seconds. Because the test setup cannot read the scroll wheel RPM the input has been classified as the effort perceived by the user (relaxed, medium, intense). The results can be viewed in graph 4.

What graph 4 shows is that input speed has a substantial effect on energy generation. It has a larger effect than increasing the electrical resistance.



Graph 4 Energy generated at different electrical resistances and scroll speed

Conclusion (test 1&2)

Even though test 2 shows that there is high potential for energy generation if the wheel is spun fast enough, it cannot be assumed that users will consistently exert that level of effort. A safe assumption is that of test 1 and the relaxed scrolling of test 2, which are both around 4mJ per scroll. The main limitation of these tests is that they were performed by a physically fit, informed participant. It is safe to assume that a user with a weaker thumb will not generate the same amount of energy.

5.2 Comfortable Resistance

The previous section focused on finding the ideal electrical resistance for energy generation. It is also necessary to test whether this resistance aligns with user expectation and comfort. To test this the following setup was used. Five participants (male, aged 24–30) were asked to scroll (2 scrolls forward, 4 back, 2 forward) at five different resistances (250Ω, 100Ω, 50Ω, 25Ω, 10Ω), after which they were asked which resistance felt most comfortable and, if applicable, at what resistance the scrolling became too heavy. Participants were asked to give feedback at every resistance. During each run a power analyser was used to measure the energy generated as secondary data.

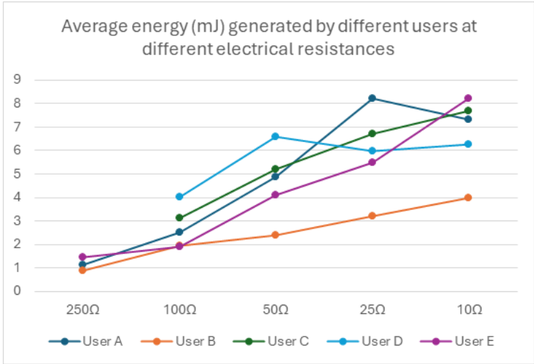
Results (test 3)

The main findings are as follows:

- All participants deemed 10Ω too heavy.
- Participants had difficulty distinguishing in the 100-25Ω range.
- Although participants found the <10Ω resistances acceptable, knowing they were generating energy, the mechanical resistance was higher than they would expect from a handheld product.
- Two participants noted that as the electrical resistance decreased the inertia of the wheel got higher which had a negative effect on the responsiveness of the wheel.

Based on these results an electrical resistance of 25Ω is advised as it has an acceptable resistance without sacrificing too much energy generation. Average energy per scroll at these resistances is 6mJ.

Graph 5 showcases the energy generated by participants at different resistances. Participants A and D show a similar trend as with previous test where a lower electrical resistance leads to a lower RPM and thus less energy generated.



Graph 5 Energy generated at different electrical resistances by different users

Discussion (test 3)

The main limitation of this test is the absence of diversity among the participants. All participants were male, in their twenties, physically fit and aware that they were generating energy. In a realistic context the TV remote would be used by a much wider range of participants. It should be noted that energy generated should be seen as optimistic as participants scrolled quite fast.

5.3 RPM in Relation to Context

Energy generation has two main input variables: electrical resistance and scrolling RPM. The ideal electrical resistance was determined to be 25Ω in the previous section, based on user feedback and energy generated. In contrast to electrical resistance, scrolling RPM varies per user and cannot be predetermined. Because a high scroll RPM is beneficial for energy generation, it is important to understand how this can be influenced. The hypothesis was that if users were informed they were generating energy, they would be motivated to scroll faster and thus generate more energy.

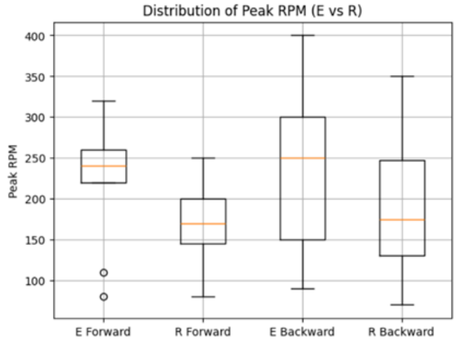
Setup (test 4)

The same test setup was used as with the index finger vs thumb test in chapter 4. Right handed participants, male and female students from the IDE faculty between the ages of 18 and 30, are asked to scroll a wheel with 150g of mass. Half of the participants are told they are using a TV remote and the other half is told that they are using an energy generation TV remote. Participants are asked to grab the remote shape and scroll the wheel for 5 seconds forward and for 5 seconds backwards. They are asked to do so in a manner that feels fitting for the context given to them.

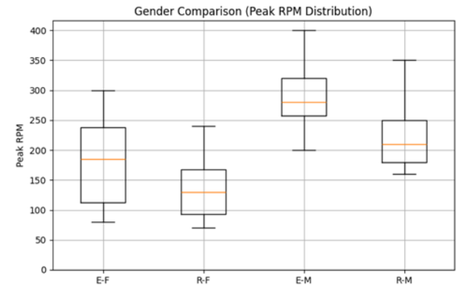
Results (test 4)

There is a substantial difference in RPM output between the energy (E) and remote context (R). +/–30% increase in favour of the energy context as seen in graph 6. What is also interesting is the wider spread of output measured with the energy aware context.

This effect is observed across all participants, with a particularly strong response in male participants while female participants also show a moderate but consistent increase. Male participants achieved peak rotational speeds approximately 20–40% higher than female participants, as seen in graph 7.



Graph 6 Context awareness comparison with scroll direction



Graph 7 Context awareness comparison with gender

Discussion (test 4)

An attempt was made to introduce context into the test setup, and the result was a notable difference in output. It must be noted, however, that the test setup context is still far from a real-life situation. A limitation is that, given the participants were clearly being observed for scrolling output, they may have been more motivated to scroll harder than in normal use. Because the remote shape was bolted to the test setup there was no free range of movement as with normal TV remote use. Participants were asked to scroll for a specific amount of time to obtain comparable results. This does not reflect real-life usage of a TV remote control.

5.4 System Losses

The energy figures measured in this chapter are taken at the output of the harvester circuit using a power analyser. They therefore already include the internal losses of the motor used as a generator, such as resistive losses in the windings and friction in the bearings. What they do not account for are the losses between the harvester output and the chip, most importantly the bridge rectifier, which converts the motor output into usable DC. At the low voltages produced by a thumb-scroll harvester these rectifier losses represent a proportionally large share of the total energy, more so than in higher voltage applications.

Erik Weteringen at Kinergizer measured the harvester's output voltage directly and cross-referenced it against a rectifier manufacturer's efficiency curve, arriving at an estimated rectifier efficiency of approximately 50% (E. Weteringen, personal communication). As this figure was obtained by chart lookup rather than a direct end-to-end measurement of the full harvester-to-chip chain, and the setup it was taken from is explicitly unoptimised, it should be treated as an indicative estimate rather than a precise figure. It is also lower than the efficiency Yang et al. (2022) measured in a comparable motor-based harvesting setup, who found an overall system efficiency of 57%, though their figure includes a DigiPot in the motor powerline which is not present in this system. Because the Kinergizer estimate is specific to this project's actual harvester rather than a comparable published system, it is used as the primary working estimate here, with the Yang et al. figure retained as a supporting reference point. Designing, optimising and precisely determining this system's efficiency was out of scope for this project and would require an electrical engineer.

Applying a 50% rectifier efficiency to the measured 6mJ per scroll at 25Ω gives an estimated 3mJ available to the chip per scroll. For the energy model in chapter 7 a figure of 3mJ per scroll is used. The 6mJ figure remains the measured output of the harvester before rectification.

5.5 Conclusion Energy Generation

The four tests presented in this chapter together establish a working range for the electrical resistance of the harvester and identify the factors that most strongly influence energy generation.

Test 1 identified 10Ω as the resistance that maximises energy generation, with rpm beginning to drop noticeably above 25Ω. Test 3 showed that 10Ω feels too heavy to all participants, while 25Ω was rated acceptable without a significant drop in generation. 25Ω is therefore recommended as the operating point, balancing energy output against user comfort. The energy figures from these two tests differ slightly, 4mJ per scroll under relaxed conditions in test 1 versus 6mJ at 25Ω in test 3, most likely because participants in test 3 scrolled faster.

Across tests 1 and 2, scrolling rpm emerged as the dominant variable in energy generation, with a larger effect than electrical resistance. While resistance can be fixed at the design stage, rpm depends entirely on user behaviour. Test 4 showed that this can nonetheless be influenced: informing users that their interaction generates energy produced an rpm increase of roughly 30%.

Several limitations apply across all four tests. Participants were consistently young, physically fit and in most cases male. The energy figures should therefore be treated as optimistic upper estimates rather than figures representative of average use.
As established in section 5.4, accounting for rectifier losses gives approximately 3mJ available to the chip per scroll, used in the energy model in chapter 7. As per Erik Weteringen at Kinergizer, the harvesting system as tested is not yet optimised, and precisely determining its efficiency was out of scope for this project (E. Weteringen, personal communication). The energy figures in this report should be read as conservative, achievable-today estimates rather than the ceiling of what this harvesting approach can deliver.

6. Interaction Patterns

This chapter analyses how a TV remote is actually used during typical viewing sessions. It builds interaction scenarios based on common TV activities, looking at how often commands are sent, which functions are used most and how long different periods of activity and inactivity last. This is the input to the energy model in chapter 7.

6.1 TV Remote Interaction Patterns

To design a TV remote where user interaction has a direct impact on energy generation, it is important to understand what these interaction patterns look like. It is difficult to obtain reliable data, as there is no public database on the frequency and interval of button presses on a remote control. Alternatively, setting up a quantitative study analysing user interaction frequency across different types of TV use would require a considerable amount of time and effort. There are unlimited interaction patterns, varying from very high to very low interaction, which means simply assuming an average and designing for that is not accurate. The TV remote must work in worst-case scenarios. There are two main forms of media on a TV: streaming and television watching. To examine the effect of different interaction patterns on energy consumption, three interaction scenarios were developed, based on real viewing sessions. These are 1 hour of TV watching (figure 28), 1 hour of series watching on Netflix (figure 29) and 2 hours of movie watching on Prime. As the movie watching scenario was very similar to the series scenario it has been left out of the chapter for the sake of simplicity. To view this interaction scenario see appendix F.

The interaction patterns of these different use scenarios show us some similarities. To be specific we can identify three main interaction periods that a watching session can consist of. What differentiates these periods is period length and amount of commands pressed. These periods (A, B and C) can be seen in figures 28, 29. Period A has a medium interaction frequency, e.g. selecting streaming service or slowly flipping through TV channels. Period B has a high interaction frequency, e.g. typing on digital keyboard, or scrolling through a Netflix menu. Period C has a low interaction frequency, e.g. watching a movie pressing pause once or twice. Using these three different interaction periods as building blocks we can model any type of TV use session. Chapter 7 energy requirements builds on this by combining it with the energy requirements of the TV remote signalling to paint a complete energy consumption picture.

An important distinction to make between these two interaction scenarios is the difference in commands pressed. With TV watching the channel and volume commands are pressed most whilst with the series watching the navigation commands are used most frequent. The original concept as proposed by Kinergizer was to change the volume and channel buttons to a generating scroll wheel. What these scenarios show us is that if we want to support streaming through the TV user interface we need to also harvest navigation. Because otherwise the percentage of generating commands will be too low.

What we can say for sure is that no matter if you are streaming or watching TV there is a chance that you hardly have to search or navigate to find what you want to watch. The most extreme example is that you turn on the TV and it is already on the right channel with the correct volume. The design must account for this possibility.

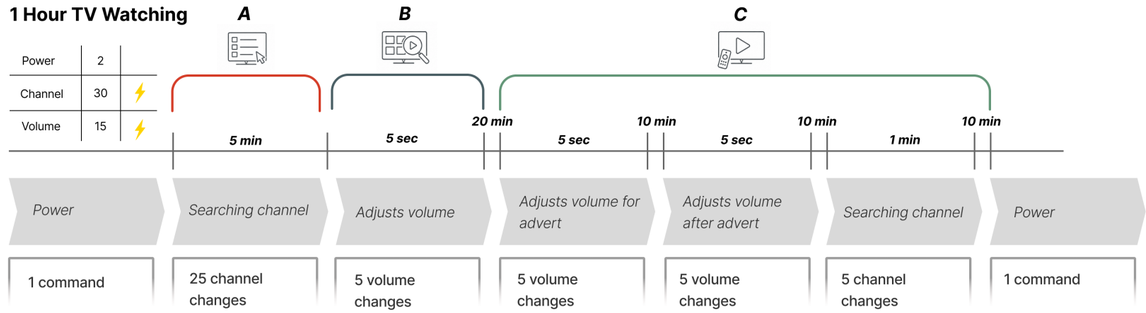


Figure 28 TV watching interaction scenario

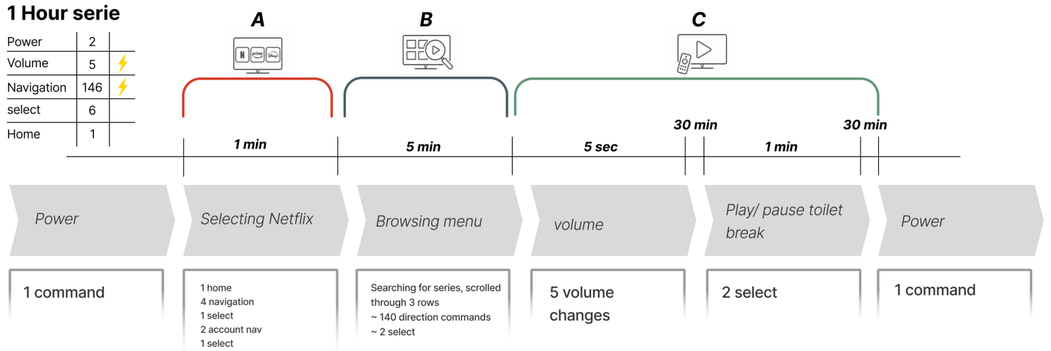


Figure 29 Serie (Netflix) watching interaction scenario

7. Energy Requirements of TV Signalling

Understanding the energy requirements of a TV remote is critical to determine the feasibility of the energy harvesting concept. As seen in chapters 5 and 6 energy generation is intermittent and irregular, dependent on the user. This chapter explores the different factors influencing the energy requirements and what options we have for energy consumption optimisation.

7.1 TV Signalling Context

To understand the energy requirements we must consider two different kinds of signals. Infrared (IR) and Bluetooth low energy (BLE). IR signalling has been the industry standard for a long period of time, but recently TV remotes have become hybrid systems where BLE is integrated to support features such as a microphone, which requires two-way communication and a more complex signal.

The main differences between IR and BLE are:

- BLE does not require a line of sight
- BLE has longer range
- BLE is more complex and expensive to integrate
- Different energy consumption

In a hybrid TV remote the basic setup is as follows:

- Power button: IR
- Basic commands e.g. volume, navigation, select: IR or BLE
- Smart features e.g. microphone, track pad: BLE

The power button needs to be IR to wake the TV up as the BLE MCU is in a deep sleep for most of the day. IR signalling does not have this limitation. Having both IR and BLE allows the remote to be compatible with both old and new devices. (Wangfred, 2026)

The balance of the BLE vs IR command distribution will be discussed later in the chapter.

7.2 Infrared Signalling

Protocol

An IR signal works as follows, an LED diode fires a sequence of infrared light (~940 nm) pulses in short bursts. If directed correctly, the signal is received and decoded into a command. These IR bursts are binary and come in different kinds of protocols, the most common being the NEC code, RC5 and RC6. This analysis focuses on the NEC protocol (Gorodechny, 2022).

Figure 30 is an example of an IR signal created by a single keypress. The protocol uses pulse distance encoding of the message bits. Each burst is 562.5μs at a carrier frequency of 38kHz.

- Logical ‘0’ – a 562.5μs pulse burst followed by a 562.5μs space, with a total transmit time of 1.125ms
- Logical ‘1’ – a 562.5μs pulse burst followed by a 1.6875ms space, with a total transmit time of 2.25ms

The message is transmitted as follows: a 9ms leading pulse burst, a 4.5ms space, 4, 8 bit sequences consisting of the address and command and their logical inverse, followed by a signal pulse to end the transmission.

Because the address and command are followed by their logical inverse each IR burst, following the NEC protocol, has the same total duration and LED on time. This means that each IR transmission is 67.5ms plus the final 562.5μs burst.

If a button on the remote is held down the LED will send a repeat code every 108ms as long as the button is pressed, as seen in figure 31. (NEC, n.d.)

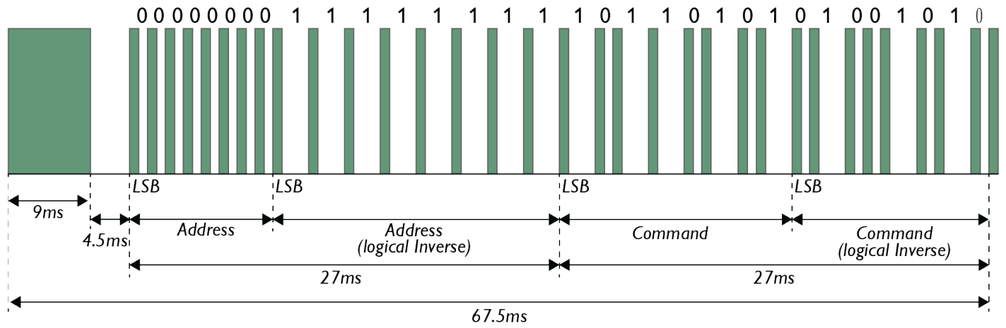


Figure 30 NEC protocol

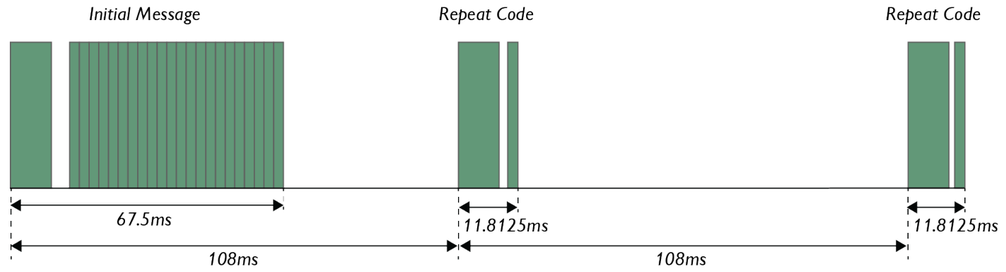


Figure 31 NEC protoco, repeat signall

Energy per command

To calculate how much energy a single button press costs we must know how long the LED is on. As stated each burst contains a 9ms header 32 pulses of 562.5 μs followed by a final pulse.

$$9ms + 32 \times 562.5\mu s + 562.5\mu s = 27.5ms$$

During this 27.5ms of LED on time the LED isn't continuously on. It operates at a 1/3 carrier duty cycle to increase battery life and range. This means that the LED is on for 1/3 of the 27.5ms.

$$27.5ms \times 0.33 = 9.075ms$$

The LED peak current can vary depending on the desired performance of the LED. For this analysis a peak current of 100 mA is used, derived from the data sheet seen in appendix G. A remote control circuit voltage is most commonly 3V, resulting in the following energy per command.

$$3V \times 0.1\ A \times 0.009\ s = 0.0027\ J = 2.7mJ$$

Validation measurements per conmmand

To validate this calculation three different IR remotes were connected to a power analyser to measure the energy of a single button press. With each remote the buttons were pressed multiple times, after which an average was taken. Test setup and full results of these measurements can be seen in appendix H.

All three remotes had an average of around 10mJ per press, which is significantly higher than the calculation. After further inspection it was found that if a button was pressed as fast as possible the average energy would drop to 5mJ. This was only possible with remote B. Another interesting find was that the power button of remote C had an average energy of 30mJ. The reason for both these deviations is most likely repeat codes. Because the power button is very important remote C is probably programmed to send multiple signals to ensure the command is received. With remote B we see that a normal button press can already be long enough to trigger repeat codes.

Applying the measured IR energy cost of 5mJ per command to the serie watching interaction scenario gives a total command energy of 775mJ for the session as seen in table 1. The scenario generates energy on 146 of those commands, producing 438mJ. This results in an energy deficit of 337mJ for commands alone, before idle consumption is considered. If the IR transmission is optimised the balance would come closer to 1:1.

		Energy consumed/ generated (mJ)
Commands Sent (#)	155	775
Generating Scrolls (#)	146	438
Energy Balance (mJ)		**-337**

Table 1 Energy balance of IR transmission

IR idle current

A conventional IR remote is not simply dormant between button presses, its microcontroller must continuously scan the keypad matrix to detect input, requiring the processor to alternate between an active scanning state and a low-power sleep state. The Holtek HT68F2420, a IR remote MCU, draws 10 μA whilst actively scanning and as little as 0.2 μA in its deepest sleep state at 3 V (Holtek Semiconductor, 2025). The actual average current depends on how frequently the keypad is polled, but regardless, a baseline consumption is always present.

Validation measurements idle current

For two of the three infrared remotes the idle current was measured. After 1 hour of idle measurement this resulted in an average idle current of 25μA. This indicates that the keypad matrix is most likely continuously being scanned and not entering deep sleep, even though no button has been pressed. Furthermore this active scan current is higher than the current the figure Holtek provides. This is could be because the measured remotes simply don't have the most efficient processors installed.

Polling architecture

In a conventional IR remote the microcontroller cannot simply sleep between button presses. It needs to continuously scan the keypad matrix to detect input, cycling rapidly between an active scanning state and a light sleep state. This polling loop keeps the chip in a semi-active state at all times, which is what drives idle current up to the 10-25 μA range (Freescale Semiconductor, 2006). Sub-microamp deep sleep is technically available on these chips but never reached in practice.

An alternative is interrupt-driven wake-up, where the chip enters true deep sleep and a button press directly triggers a hardware interrupt that wakes it, eliminating the polling loop entirely. This approach is discussed in the BLE section below in the context of the chip selected for this concept.

Conclusion

In conclusion the energy of a single IR button press is determined by a trade-off between energy efficiency and certainty of the signal being received. 5mJ is a safe assumption for an acceptable IR signal, with the possibility of it being tuned to be more energy efficient. This would result in a 1:1 energy balance.
The idle current of commercial remotes tells a different story. The measured average of 25 μA corresponds to 6480mJ of idle consumption over a full day. Even an optimised commercial chip such as the Holtek HT68F2420, running its keypad scan at 10 μA, would consume 2,592mJ per day in idle (Holtek Semiconductor, 2025). For context, the harvester generates approximately 3mJ per scroll. A purely IR remote is therefore not viable as a battery-free or battery-reducing concept.

7.3 Bluetooth Low Energy Signalling

BLE can work in two ways as seen in figure 32. Option one: a broadcaster transmits data to an unspecified observer. Option two: a central device makes an active connection with a peripheral device, allowing them to communicate. The second method is what we are most familiar with, e.g. our Bluetooth headphones, computer mice and TV remotes. The reason a TV remote requires a connection is the aforementioned benefits of two-way communication and that it prevents you from accidentally communicating with e.g. your neighbours TV. In the context of a TV remote the TV is the central device and the remote the peripheral. (Hlapisi, 2023)

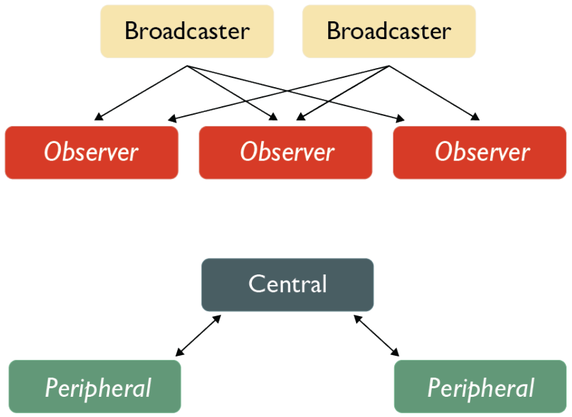


Figure 32 Types of Bluetooth connections

Connecting

To form a connection between the TV remote and the TV, the following steps are required:

1. The power button is pressed and the TV remote (peripheral) enters a state called advertising, where it periodically sends packets of data requesting a connection whilst simultaneously listening to connection request from the central device (TV).
2. The TV (central) is woken up by the IR signal and starts scanning for peripheral devices that want to connect.
3. When the TV recognizes the remote as a device it wants to connect with it switches to the initiating state
4. In the initiating state the TV sends a connection request back to the TV remote. The connection is established once the TV remote accepts the request. (Hlapisi, 2023)

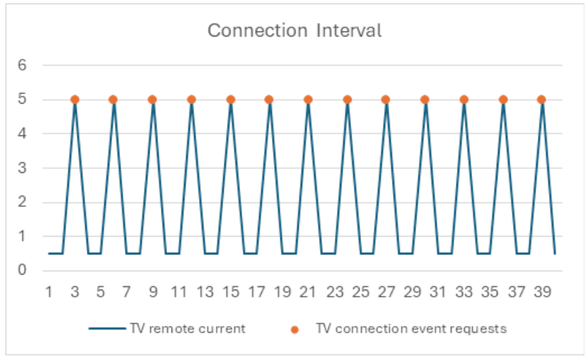
Different states

To determine the energy usage of BLE signalling it is important to understand the different states a BLE MCU of a TV remote can be in and what the current is.

- **Deep sleep:**
  The deep sleep is the state the MCU will spend most of its time in. When the TV isn't in use the TV remote isn't connected and in a very low power mode.
- **Advertising/ initiating state:**
  The advertising state consists of an idle current and current spikes when data packets are sent and eventually received when the remote and TV connect. The advertising and initiating states are grouped here, as this phase only occurs for a very short period.
- **Connected state:**
  In the connected state the TV remote first receives a data packet from the TV (RX) and then sends one back (TX) at a certain interval, which is called a connection event that happens at a certain connection interval. Once again there is an idle current in between these connection events. The data packets that maintain the connection are mostly empty, once a command is pressed the next data packet sent is filled with the information of the command. If there is too much time in between buttons pressed the connection is deemed lost. This is called the connection supervision timeout and is a multiple of 10ms in the range of 100ms to 32s. (Silicon Labs, n.d.) When a command is pressed the chip does not need to be actively monitoring the button. An interrupt triggered by the button press wakes the chip instantly, without any continuous scanning (NXP Semiconductors, 2007). This is what allows the connected idle current to stay in the low microamp range, in contrast to the 10-25 μA typical of commercial remotes discussed in the IR section.

Example of different currents per state based on an energy efficient Silicon Labs EFR32BG22 chip. (Silicon Labs, n.d.)

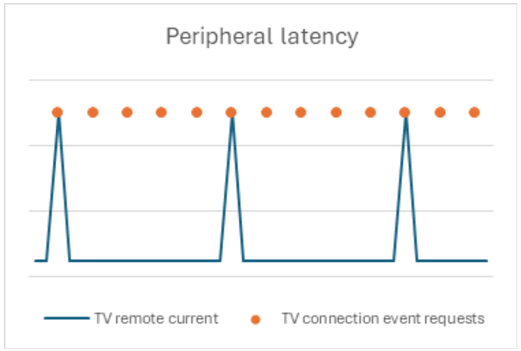
- Deep sleep current: 0.17μA
- Advertising and connected idle: 1.6μA
- Avg. peak current RX: 3.6mA
- Avg. peak current TX: 4.1mA



Graph 8 Connection interval explained

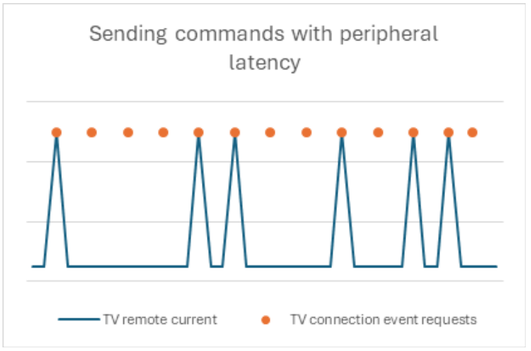
Connection interval & peripheral latency

The connection interval is an important variable for energy cost and product usability. A fast connection interval yields fast response times but high energy cost. The possible connection interval in the advertising state is 20ms to 10.24s and in the connected state 7.5 to 4s. An example of what this might look like can be seen in figure 8. Here every TV connection event request (orange dots) is met by the remote sending a packet back. This results in the spike in current of the TV remote (blue line). It should be noted that this graph is not an actual current measurement.



Graph 9 Peripheral latency explained

A particularly effective tool for energy saving is peripheral latency. As stated, the TV sends the TV remote a data packet at a certain interval, after which the TV remote sends one back. Peripheral latency reduces the number of data packets the TV remote sends back when it has no data to transmit, thus reducing the average current. For example, if peripheral latency is set to 4, the TV remote is allowed to skip 4 consecutive connection events. This can be seen in graph 9. The key advantage is that this does not affect the TV remote's responsiveness, because when a command is pressed the remote can send a data packet back with the first connection event it receives from the TV, which it would otherwise have skipped. As seen in graph 10.



Graph 10 Responsiveness of peripheral latency

If we have a fast connection interval together with a high peripheral latency it means that we can have a responsive remote with a low energy cost. The only danger is that the TV can deny the remote the peripheral latency which would result in a unforeseen high energy cost. (Afaneh, 2026)

7.4 Bluetooth Low Energy System Design

To calculate the total energy consumption of a BLE TV remote the interaction patterns from chapter 6 are combined with the signalling variables discussed in this chapter: idle current, deep sleep current, TX/RX current, connection interval and peripheral latency.

The component used as the basis for the calculations is the Silicon Labs EFR32BG22, a Bluetooth 5.2 SoC selected for its low sleep mode current and event-driven architecture, both well suited to a TV remote use pattern (Silicon Labs, 2024). All current figures are taken from its datasheet and associated application notes.

An Excel model was built using the interaction patterns from chapter 6 as input. It assumes power on and off are sent via IR and all other commands via BLE. The model calculates packets sent per period as period duration divided by the effective connection interval, plus commands pressed. Each connection event costs 1.5ms at command current regardless of whether a button was pressed, with the remainder of the period at connected idle current. The rest of the day runs at deep sleep current. Energy is current × time × voltage, summed across all phases. The connection supervision timeout is not included as its contribution was considered negligible. The full calculation sheet is in appendix I. This model is an approximation.

Example scenario

In table 2 you can see the common input variables of the proposed BLE setup used in the energy calculation. And in table 4 the output per interaction period. See table 3 for the sheet legend. In this example the 1 hour Netflix session interaction scenario is used as input for the frequency and amount of commands pressed.

If we set the peripheral latency to 0 instead of 100 we see that the energy consumption increases in period C where the remote has an active connection. This is just one example of experimenting with a variable. As seen in table 5

COMMON INPUT VALUES	
Energy generated	
Energy Generated/Scroll (mJ)	4
Base BLE Specs	
Command Current (mA)	4
Connected Idle Current (mA)	0.0016
Deep Sleep Current (mA)	0.00017
Packet Duration (s)	0.0015
Connection Timeout (s)	Not Condidered
Connection Interval (s)	0.25
Peripheral Latency (#)	1
Effective Connection Interval (s)	0.25
Voltage (V)	3

Table 2 Input variables BLE and energy generation

Results

The main findings of the model were:

- Under normal interaction patterns the remote generates more than it consumes.
- Deep sleep and connected idle currents are the most impactful variables, as these dominate the time budget. Peripheral latency is the second most important, as it reduces the number of active connection events during idle periods.
- BLE works well during high interaction periods. If interaction frequency drops too low, idle consumption eventually overtakes generation over the course of a day.

What the model shows is that creating a batteryless TV remote could be feasible if it is used consistently. However, it must be assumed that there are use scenarios where the remote generates no energy. This means that the TV remote needs a battery to fall back on if the user isn't generating enough.

Discussion

This calculation sheet is an approximation intended to give an indication of the order of magnitude involved.

1 HOUR NETFLIX SESSION					
	Period A	**Period B**	**Period C**	**Rest of the day**	**Day Total**
Period Duration (s)	60	300	3600	82440	
Commands Pressed ((#))	9	142	2		
Packets Sent (#)	11.4	154	146		
Total Packet Duration (s)	0.017	0.231	0.219		
Energy Consumed (mJ)	**0.49**	**4.21**	**19.91**	**42.04**	**66.66**
Generating Scrolls (#)	6	140	0		
Energy Generated (mJ)	**24.00**	**560.00**	**0.00**		**584.00**

Table 4 Excell energy consumption model with peripheral latency

1 HOUR NETFLIX SESSION					
	Period A	**Period B**	**Period C**	**Rest of the day**	**Day Total**
Period Duration (s)	60	300	3600	82440	
Commands Pressed ((#))	9	142	2		
Packets Sent (#)	249	1342	14402		
Total Packet Duration (s)	0.374	2.013	21.603		
Energy Consumed (mJ)	**4.77**	**25.59**	**276.41**	**42.04**	**348.81**
Generating Scrolls (#)	6	140	0		
Energy Generated (mJ)	**24.00**	**560.00**	**0.00**		**584.00**

Table 5 Excell energy consumption model without peripheral latency

Input Data:	
Fixed input Data:	
Calculated:	

Table 3 legend

7.5 Backup Battery

Low energy consumption design in practice

The possibility of running BLE on an inconsistent energy supply is supported by the dissertation of Jasper de Winkel (2023) at TU Delft. He developed FreeBie, a system that maintains a BLE connection on purely harvested energy by saving the protocol state to non-volatile memory when power runs out, then restoring it when energy is available again. The connection survives power gaps without needing to re-pair, which is exactly what a scroll-wheel powered remote needs.

His results back up the approach taken here. At high peripheral latency, FreeBie used 2.46 times less energy than a standard BLE stack while still responding immediately to button presses. With the processor fully switched off between connection events, idle power dropped to roughly 9.5 times lower than conventional BLE sleep mode. This confirms that deep sleep current and peripheral latency are the two variables that matter most, which is consistent with what the model in this chapter shows. In a 24-hour test FreeBie only had to fully reconnect seven times. While not a direct validation of the model here, it does show that a human-powered BLE remote is not just theoretically possible.

BLE energy measurements

Measuring the BLE energy consumption of a TV remote is more complex than that of a IR TV remote. Firstly the remote requires an active connection with a central device (TV) if you want to measure the current of all the different states. Secondly as the Bluetooth chip is more complex than the IR chip (more states, connection parameters, peripheral latency settings) the amount of unknown variables is larger. As most smart TV remotes are battery powered they might not have the incentive to be very energy efficient.

It is possible to acquire the proposed BLE chip, set it up, and measure the energy consumption. However due to time constraints and this being an industrial design project and not an embedded software one doing this is deemed out of scope.

A Samsung SolarCell remote (BN59-01385B) was connected to a power analyser without an active TV connection. The measured idle current was approximately 100 μA, equivalent to 25,920 mJ per day (0.1 mA × 3V × 86,400s). During advertising mode, where the remote actively searches for a TV to pair with, the average current rose to approximately 2.1 mA, consistent with the periodic BLE advertisement bursts visible as a blinking LED on the remote. A button press produced a current spike of approximately 60 mA, consistent with an IR transmission and in line with the 5 mJ per command figure established earlier in this chapter.

The 100 μA idle is considerably higher than the 1.6 μA deep sleep figure of the EFR32BG22. The exact cause cannot be determined from this measurement alone, as the current was not isolated to a specific component. It is also worth noting that this figure was measured without an active TV connection, so it does not represent the connected idle state that would dominate consumption during normal use. What the measurement does show is that a commercially available, energy-conscious remote does not idle anywhere near the deep sleep figures quoted for low-power BLE chips in isolation. This supports the wider point that the idle consumption of a finished product depends heavily on chip selection, firmware design and supporting circuitry, and cannot be assumed from a datasheet figure alone.

In a hospitality context the remote must always work immediately, as established in chapter 3. This means a small backup battery is needed to cover periods where no energy is being generated. A Maxell ML2032 rechargeable coin cell is proposed for this. It runs at 3V with a specified capacity of 65mAh, giving roughly 702 J of usable energy (Maxell, n.d.). Unlike a primary CR2032, the ML2032 requires a small charging circuit between the harvester's rectified output and the cell: a regulated charge voltage of 3.1–3.3V with current limited to approximately 2mA, to avoid damaging the cell.

In deep sleep the system draws approximately 0.2μA, which is 51.8mJ per day. At that rate the coin cell holds over 13,000 days (more than 35 years) of deep-sleep draw, though in practice the cell's own self-discharge, not deep sleep current, would be the limiting factor long before that point is reached. Each generating scroll produces approximately 3mJ, and a single one-hour Netflix session generates a net surplus of approximately 371mJ (438mJ generated minus 66.66mJ consumed), which is about 8 days of deep sleep consumption. Under normal use the battery effectively charges itself, with the coin cell only there as a buffer for worst-case periods.

In a different context, for example a consumer home remote, a different approach is possible, closer to what de Winkel (2023) describes, where the user scrolls a few times at the start to get things going. That would work for someone who has chosen the product and understands how it works. In that scenario a supercapacitor could replace the coin cell entirely and the battery could be removed.

It should be noted that the BLE idle figures used here come directly from the Silicon Labs datasheet and have not been measured. Actual consumption may differ. These numbers should be treated as an order of magnitude, not a precise prediction.

7.6 Energy Requirements Conclusion

This chapter has established what TV remote signalling costs in energy terms and whether the scroll wheel harvester can cover it.

A single IR command costs around 5mJ under realistic conditions. The idle consumption of a conventional IR remote, measured at 25μA and equivalent to 6480mJ per day, makes a fully IR remote incompatible with this concept. The cause is continuous keypad polling, which prevents the chip from reaching true deep sleep (Freescale Semiconductor, 2006). An interrupt-driven architecture removes the polling loop, bringing idle consumption down to 51.8mJ per day.

BLE is the preferred signalling method for everything except the power button, which stays IR to wake the TV from deep sleep. The energy model shows that a one-hour Netflix session consumes 66.66mJ while generating approximately 438mJ. The most important variables are deep sleep current and peripheral latency, as these dominate consumption during the long gaps between interactions. As per Erik Weteringen at Kinergizer, the harvesting system as currently tested is not yet optimised, the generation figures used here should be read as a conservative, achievable-today baseline rather than the ceiling of what the harvester can deliver. Under normal use in a hotel context the remote could sustain itself.

In a worst case where no energy is generated at all, the ML2032's stored charge would outlast any realistic deployment period on deep-sleep draw alone, with the cell's own self-discharge becoming the real constraint rather than usage. A single normal session recovers about 8 days of that. A battery-free version would require the user to scroll a few times before the remote is functional.

The BLE idle figures for the proposed chip have not been validated by direct measurement and should be treated as indicative. The measurement of the Samsung SolarCell remote supports this caution. Its idle current of 100μA is considerably higher than the deep sleep figure of the EFR32BG22, showing that finished products do not reach datasheet figures without deliberate firmware and circuit design. Validation with an evaluation board and a Nordic Power Profiler Kit II is recommended as future work.



8. Redefined Project Aim

This chapter marks the transition from the research phase to the design phase. It revisits the original project aim in light of what the research established and translates the findings into a set of design guidelines and requirements that the prototype needs to meet.

8.1 Redefined Project aim

The initial aim of this project, as set out in chapter 1, was to design a human-powered TV remote that eliminates user dependence on disposable batteries for first-time users in the hospitality sector. To get there, three areas required investigation: how much energy a thumb can generate through scrolling, what ergonomic constraints shape the scroll wheel design, and whether the energy generated is sufficient to cover the signalling requirements of a modern TV remote.

The research in chapters 2 through 7 addressed these questions. The ergonomic tests established the scroll wheel orientation, placement and resistance. The energy generation tests determined the output per scroll and the main variables that influence it. The signalling analysis confirmed that BLE with an interrupt-driven architecture and peripheral latency makes the energy balance feasible, with a small backup battery covering worst-case periods of non-use.

The research confirms that a human-powered TV remote is technically feasible. The question that remains is how the scroll wheel interaction should be designed to make this work in practice. The design guidelines and programme of requirements below capture what the research established as the starting point for the develop phase.

8.2 Design Guidelines

The research carried out in chapters 2 through 7 leads to the following design guidelines.

Interaction and ergonomics

The scroll wheel must be forward-facing and positioned at 100 mm from the base of the remote. The remote shape should be neutral to allow users to adjust their grip to suit their hand size. The remote must be one-handed and ambidextrous.

Energy generation

The harvester must be set to 25 Ω and generation must be intrinsic, with navigation included as a harvesting interaction alongside volume and channel.

Signalling

The power button must use IR. All other commands must use BLE with an interrupt-driven architecture and peripheral latency applied. Scroll wheel RPM sensing must be mechanical.

Backup power

The remote must work immediately when picked up and be intuitive to a first-time user without instruction.

Usability

The remote must work immediately when picked up, with no warm-up interaction required. It must be intuitive to a first-time user without instruction. Where possible the concept should communicate its energy-generating nature to the user in a way that encourages engagement without requiring an understanding of the underlying technology.

9. Designing for Generation

The research in chapter 3 established that intrinsic generation is the preferred approach for a hospitality context where users have no motivation to engage with the energy-harvesting side of the product. This chapter looks at what that means in practice for the scroll wheel configuration, and whether any extrinsic generation is worth adding on top. All ideation sketches can be seen in appendix J

9.1 Intrinsic Power

Intrinsic generation means energy is only harvested during normal product operation. The interaction pattern analysis in chapter 6 showed that navigation commands dominate streaming use, so volume and channel alone are not enough. Navigation needs to be included. That gives four functions to harvest: volume, channel, and up/down or left/right navigation.

Four scroll wheels

One wheel per function. This allows each wheel to be positioned for its movement direction, including horizontal for left/right navigation. The problems are that it requires four harvesters or a coupling system, the remote surface becomes visually complex, and the thumb has to move between four different positions. Not ergonomic. The only advantage of this concept is that left-right navigation is on the horizontal plane. As seen in figure 33.

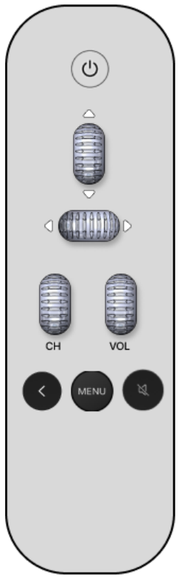


Figure 33 Four wheel concept

Two scroll wheels

Grouping navigation into one wheel and volume/channel into another reduces the number of harvesters needed. It would require some kind of select mechanism as seen in figure 34. It still requires either a coupling mechanism or two separate generators, and the ergonomic problem of the thumb needing to move between two positions remains, though it is less severe than with four wheels. A downside is that the left right navigation is operated by the scroll wheel moving up and down, which might be counter intuitive. A solution for this can be seen in figure 35, where the navigation scroll wheel can be pressed left and right for horizontal navigation. The down side of this is that you can't harvest left and right.





Figure 34 (left) Two wheel concept
Figure 35 (right) Two wheel concept with left right click

Single scroll wheels

One wheel for all four functions. The thumb stays in one place and only one harvester is needed. The downside is that switching between functions requires some kind of switch or mechanism. If the wheel itself is moving it would need a large opening to accommodate this. Despite this it is the best option for physical ergonomics and mechanical simplicity. As seen in figure 36.



Figure 36 Single wheel concept

9.2 Extrinsic Power

Although intrinsic generation is the priority, three extrinsic options are worth considering as supplements.

Product preparation energy boost

An energy boost at the start of a session, triggered by a product preparation action such as pulling out the remote or removing a tab, could guarantee starting power even if the backup battery is depleted. The downside is that it introduces a new behaviour that users in a hospitality context are unlikely to understand or expect without instruction.

Squeeze

Squeezing is a well-established human-powered interaction. Pierce and Paulos (2012) found that squeezing was rated as more natural and pleasant than cranking, and the knijpkat demonstrates that it is a behaviour users already understand in the context of generating power. Applied to a TV remote, a squeeze mechanism in the grip could generate a meaningful amount of energy. The main question is whether it fits the product semantics. A TV remote is not typically associated with squeezing, and introducing it risks feeling out of place rather than intuitive. It is noted as a viable direction but considered out of scope for this project.

Fidget

Both the scroll wheel orientation test and the remote shape test showed that participants were already fidgeting with the prototypes before testing had started. This suggests there is energy generation potential in the idle handling of the remote that does not require any deliberate action. A separate fidget dial or wheel could capture this, though it adds mechanical complexity and visual noise.

A simpler approach is a signalling kill switch on the existing scroll wheel. The user can fidget with the wheel while the remote is not in use, and the kill switch decouples the wheel from the TV signal so that idle movement generates energy without sending unintended commands. This keeps generation central to one component without adding new interaction elements, though users need to understand when the switch is active.

9.3 Conclusion Generation

The chosen direction is a single scroll wheel with a kill switch for supplementary fidget harvesting. Intrinsic generation through the scroll wheel is the priority, keeping the amount of new behaviour to a minimum. As Maeda (2006) notes, simplicity is best achieved by moving complexity elsewhere in the system rather than removing functionality. In this case that means keeping the outside of the remote visually and physically ergonomic with one scroll wheel, moving the complexity to the internal mechanism.

10. Selecting Function

This chapter addresses how a single scroll wheel can cover four different remote functions. Three switching mechanisms are considered, each with different implications for the mechanical complexity, ergonomics and housing geometry of the remote.

10.1 Separate Slide Switch

A slide switch positioned below the scroll wheel that dictates its current function. The wheel stays fixed on the axle and the switch is operated independently, as seen in figure 37.

The main advantages are simplicity and cost. No additional moving parts are needed beyond the switch itself, and the housing only requires a small gap rather than a large opening. Electronically it is straightforward.

The drawback is ergonomic. The thumb has to move between the switch and the scroll wheel to change function, which means two separate interaction points on the remote surface.

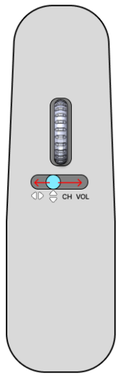


Figure 37 Separate slide switch concept

10.2 Sliding Wheel Connected to Switch

Here the function is determined by the position of the scroll wheel on the axle. The wheel slides laterally and a physical slide switch, connected to the wheel, provides both position sensing and position holding in one component.

Because the wheel itself is the thing that moves, the function switch is more visually integrated than a separate switch. A larger object changing position may also communicate the mode change more clearly. The housing requires a larger opening to accommodate the lateral movement of the wheel. As seen in figure 38.

The main downside is that the mechanism is partially visible through the housing, which gives it a somewhat exposed look. It works well for how mechanically simple it is, but the aesthetic is not refined.



Figure 38 Sliding wheel connected to switch

10.3 Magnets

This concept also uses a wheel that slides along the axle, but instead of a physical switch it uses magnets embedded in the wheel and four parallel reed switches in the housing to detect position. A reed switch consists of two metal contacts that close in the presence of a magnetic field, completing the circuit. No additional current is required for position sensing, which suits the energy budget of this concept well.

Because the wheel is not mechanically connected to a switch, there is no added friction from the switching mechanism. The housing does not need additional slots or gaps for a switch arm, which keeps the opening cleaner and reduces the risk of dirt or debris entering. The scroll wheel appears to float on the axle with no visible connection to the housing, giving a cleaner look than the wheel slide switch.

Reed switch test prototype v1

A breadboard prototype was built as a proof of concept, as seen in figure 39. The goal was to confirm that the reed switches respond reliably at the distances involved in the housing geometry. Distances appeared to be in the right range for reliable switching. Step two was positioning four reed switches in parallel to each other and testing if it was possible to have only one activate at the same time as seen in figure 40. The result was positive.

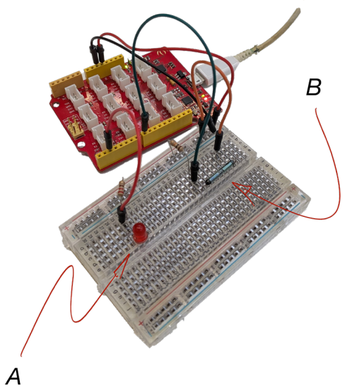


Figure 39 Single reed switch, A: LED, B: reed switch

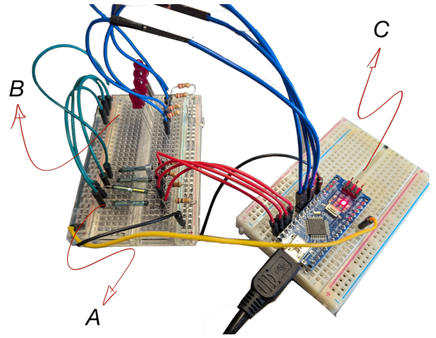


Figure 40 Four reed switches Left, A: reed switch, B: LED, C: Arduino Nano

Reed switch test prototype v2

The next step was to move from a breadboard to a soldered circuit on a perforation board cut to fit inside a printed housing, as seen in figure 41. The electronics were switched to an Arduino Nano to fit within the housing dimensions. LEDs were placed at the end of the board so they could protrude through the housing wall. The top shell was given a bathtub profile to seat the scroll wheel above the reed switches. The scroll wheel was a single printed part with magnet inserts, sliding and rotating on a 3 mm round axle mounted in ball bearings.

Three different reed switches were tested varying in size and sensitivity. The main finding was that magnet strength and the distance between magnet and switch had a larger effect on performance than the switch type itself.

Limitations reed switch test

The Arduino mounting made the assembly too tall for the housing to close fully. With the scroll wheel and reed switches both fixed in position there was no way to adjust their relative positions during assembly, causing multiple switches to activate simultaneously in some wheel positions. There was also no linear detent to hold the wheel in place between functions. The harvester was not included in this version, and the round axle cannot transfer rotation to drive it. The glass tube reed switches proved fragile when the housing did not close cleanly.

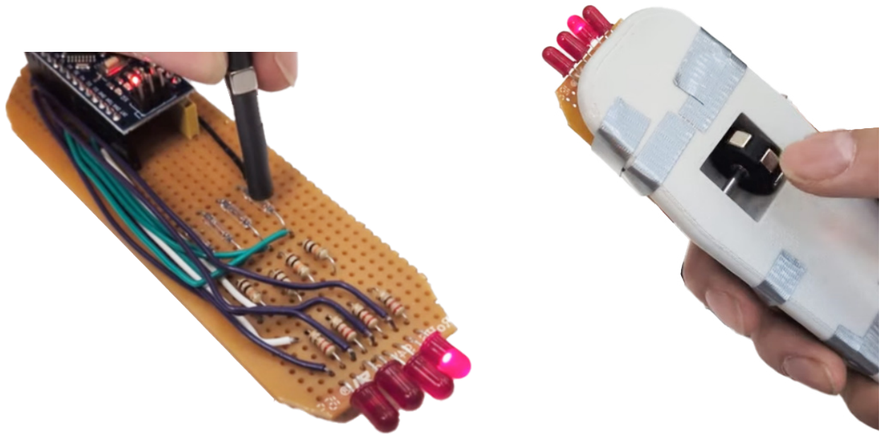


Figure 41 Left, A: magnets, B: reed switches, Right, circuit board in housing

10.4 Selecting Function Conclusion

The magnet and reed switch concept is the preferred solution. It requires no additional current for position sensing, introduces no extra friction, keeps the housing clean with no additional openings, and produces the most refined appearance of the three options. The v1 prototypes confirmed the concept is physically viable at the relevant distances. The limitations identified in v2 are mechanical rather than fundamental and are addressed in the prototype described in chapter 11.

11. Design Direction

This chapter describes the development of two prototype iterations. It covers the mechanical decisions made in each version, the reasoning behind key changes and a structured user test conducted with the first prototype to identify what needed to improve in the second.

11.1 Designing for Interaction

The biggest design gap at this stage is the interaction between the user and the scroll wheel. Whether the single wheel with sliding function selection is intuitive and ergonomic in practice has not yet been tested with a realistic prototype. That is the goal of this prototype, and it will be validated through user testing.

The actual BLE/IR chip is not integrated. Doing so would produce the most realistic user test, as the remote would signal directly to a TV, but it is out of scope for three reasons. The signalling architecture has already been established in chapter 7 and the chip is proven technology, so there is no need for a proof of concept in that direction. And integrating it within the remaining project time is not realistic given the firmware work involved.

The prototype is developed in two iterations. The first is a refined version of the reed switch setup from chapter 10, adding linear detents to hold the scroll wheel in position between functions. LEDs in the housing act as indicators for the current wheel position, replacing the TV signal in the user test. The harvester is also integrated in this iteration, not to measure energy output but to provide the correct mechanical resistance during testing. The exterior of the first iteration is driven by the space the internals require rather than ergonomic or aesthetic considerations. The housing is sized around the components.

The second iteration refines the model with a more ergonomic and aesthetically considered exterior, and integrates a rotary encoder to read scroll direction and speed. This is needed to simulate the full remote interaction during user testing and to give more useful data on how users interact with the wheel.

11.2 Integral Prototype v1

For the first iteration of the final prototype the bathtub recess around the scroll wheel was dropped in favour of a through-hole design where the wheel protrudes from a hole in the housing rather than sitting in a recess, as seen in figure 42. This improves hygiene as dirt and grime can no longer collect at the bottom of a cavity. Moving to a through-hole required the reed switches to be repositioned vertically either in front of or behind the wheel.



Figure 42 Left: Final prototype v1, Right: Final prototype v1 internals

Internals

This version introduced a third housing component sandwiched between the upper and lower shells, as seen in the exploded view in figure 43. This insert holds the axle, scroll wheel and harvester and was SLA printed rather than FDM to achieve the precision the fit requires. The harvester is integrated in the same way as in the original Kinergizer mouse prototype.

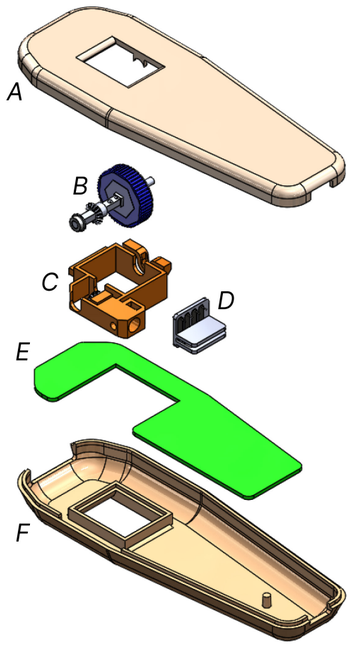


Figure 43, A: Top housing, B: Scroll wheel on axle, C: Harvester housing insert, D: Reed switch holder, E: Circuit board, F: Bottom housing

The scroll wheel consists of four concentric parts, as seen in figure 44. At the centre is a tube that slides over the square axle. Around this sits a hexagonal section that houses the spring ball plunger responsible for the position detents. The next layer is a ring containing the four magnets. Finally an outer ring with a grip profile covers the magnet ring and forms the tactile surface the user interacts with. This layered construction keeps the functional components self-contained within the wheel and makes the assembly straightforward.

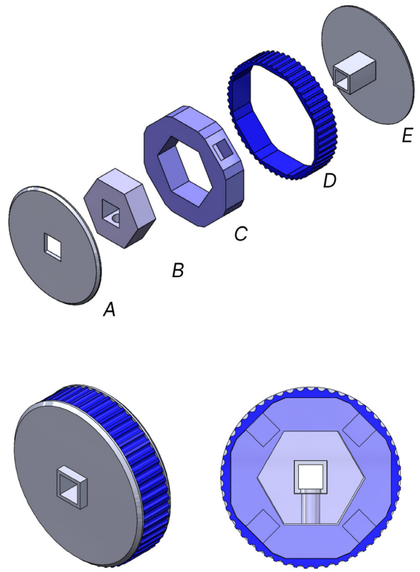


Figure 44, A: Wheel side, B: Spring plunger holder, C: Magnet ring, D: Grip ring, E: axle sleeve and side

Plastic-encased reed switches replaced the bare glass tube versions from the initial reed switch tests, making them more durable and easier to handle during assembly. Because the optimal sensing distance for these specific switches had not yet been determined they were mounted in a separate holder that clamps onto the circuit board with friction, allowing their position to be adjusted after assembly. The repositioned sensors and their holder can be seen in figure 46, which also shows the cross-section of the through-hole geometry and how the wheel sits relative to the switches.

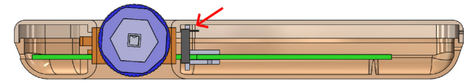


Figure 45 Cross section prototype with vertical reed switches

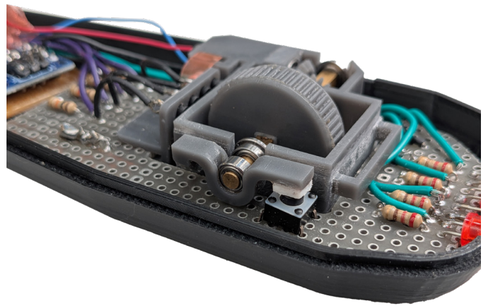


Figure 46 Select function of scroll wheel

Smaller magnets in the wheel combined with the repositioned sensors ensured that only one reed switch is activated in each position. The select click function was also added in this version: the axle has 1 mm of vertical play and pressing down on the scroll wheel transfers this movement through the axle onto a button arm actuating the click, as shown in figure 46.

Finally Stickers are placed on the upper shell to indicate the functions of the scroll wheel and imitate buttons, to create the right context.

Limitations

Tolerances were not always met between the insert and the upper and lower housing, likely due to the differences of FDM and SLA printing. After a week or more of use the square sleeve inside the scroll wheel became less tight on the axle, causing the wheel to slide at a slight angle. This introduced extra friction and worsened the interaction feel. This will need to be addressed in the next iteration. During soldering the wrong Arduino variant was soldered onto the board meaning half of the circuit had to be cut away. The board now consists of two separate pieces though this does not affect functionality.

11.3 User Test Integral Prototype v1

To evaluate the intuitiveness and ease of use of the scroll wheel TV remote prototype, a structured measurement instrument is needed. Following consultation with James Broadhead, whose research on battery-free interactive systems includes extensive user evaluation, three established frameworks were considered: the NASA Task Load Index (NASA-TLX), the Technology Acceptance Model (TAM), and the System Usability Scale (SUS). It was decided the System Usability Scale test was most suited, the reasoning behind this can be found in appendix K together with the full user test questionnaire in appendix L.

Setup

A pilot user test was conducted with five participants using integral prototype v1. The test served two purposes: to identify improvements for integral prototype v2, and to establish the format for the larger user test planned post greenlight. It was not intended as a full validation of the concept, but as an early read on where the interaction works and where it does not.

Participants were five young adult males. They were asked to complete a set of tasks with the prototype and answer five questions about their experience. A System Usability Scale (SUS) score was also recorded for each participant. The SUS is a standardised ten-item questionnaire that produces a score between 0 and 100, where scores above 68 are considered above average and scores above 80 are considered good (Brooke, 1996).

Results

SUS scores ranged from 57.5 to 85, with a mean of 76.5. Three participants scored 82.5 or above. The scroll wheel questions were rated highly by almost all participants.

The main usability issues that emerged were consistent across participants. The select function was unclear to several participants, and left/right navigation was the most commonly flagged source of confusion, with participants either unaware that horizontal scrolling was possible or finding the mapping unintuitive. For one user the sliding mechanism was not immediately obvious on first contact, with one participant using a different hand to shift the wheel position at the start of the test.

Ergonomic feedback was generally positive but pointed to the shape needing refinement, with participants noting that the through-hole could be more visually prominent and that the grip could be rounder and wider at the base. The lightning bolt iconography was deemed as insufficient for communicating the energy-harvesting function.

Discussion

The test points to four areas to address in v2. The select function needs to be more obvious. The left/right navigation mapping needs to be reconsidered or communicated more clearly through iconography. The housing shape needs refinement based on the ergonomic feedback, which is already incorporated in the v2 housing redesign. The energy harvesting iconography needs to be more prominent and better integrated into the form.

A limitation of this pilot is that all five participants were young adult males, which is not representative of the broader user population the concept targets. The larger user test post greenlight will use integral prototype v2 and will aim for a more diverse participant group.

11.4 Integral Prototype v2

V2 builds on the architecture of v1 with three main improvements: replacing the LED indicators with a screen readout driven by a rotary encoder, refining the external housing based on the ergonomic test findings, and tuning tolerances throughout the internals.

The electronics carry over from v1, with the same reed switches and Arduino Nano soldered onto a new perforation board. The full parts list and technical drawings can be found in appendix M. The complete prototype will be finalised and assembled post greenlight.

Encoder

A 12-pulse mechanical rotary encoder was selected for its low power consumption. It is placed in the button press arm, as this offered the most available space within the housing geometry without requiring changes to the core architecture. The test setup can be seen in figure 47, and in figure 48 in the housing.

Readout feedback

The LED indicators from v1 are replaced by readout on a computer screen, that will display message like, volume up or channel down. Reed switch position data and encoder data are combined in code to give the user a readout of their current scroll wheel function and input. A test setup with working code has been built to confirm this before full assembly.

Housing

The external housing is redesigned based on the findings of the ergonomic tests in chapter 4, see figure 49. The coffin shape of v1, which was driven entirely by the space the internals required, is replaced by a more considered form that maintains adequate room for the components while being visually more appealing. The left- right iconography is altered to be more clear on what direction does what based on the findings of the v1 user test.

User test

Unfortunately the v2 is not fully operational due to issues with the Arduino, which no second user test was performed. Multiple experts were consulted but alas they couldn't find the problem before the deadline

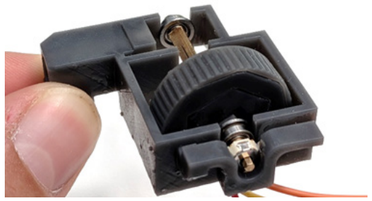


Figure 47 Encoder in harvester insert

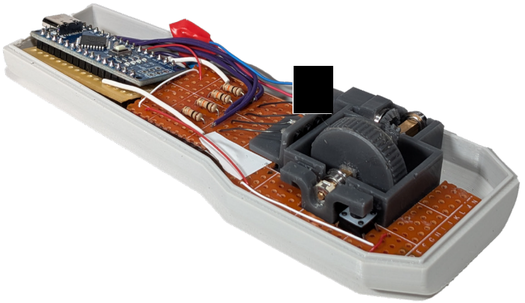


Figure 48 Prototype internals

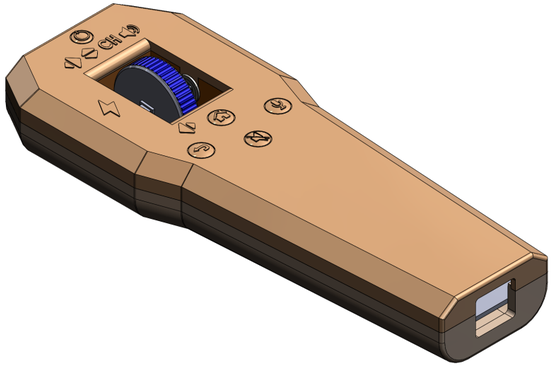


Figure 49 redesigned housing

12. Final Product Proposal

This chapter sets out the intended specification of the TV remote based on everything developed and tested in the project. It covers the interaction design, position sensing, energy generation, signalling architecture and power system of the proposed final product.

12.1 Product Proposal

The product is a television remote control that powers itself through the energy generated by its own use and can be seen in figure 50. Scrolling the wheel to change volume or navigate a menu drives a harvester inside the housing, which supplies the energy needed to send the command. The project began with the hospitality sector in mind, where hundreds of remotes across guest rooms have to be checked and have their batteries replaced by hand. See figure 50 for the final prototype.

What the project produced is broader than that starting point: a multifunctional intrinsic harvesting solution for remote controls. Energy from a thumb-driven harvester is scarce, roughly 3mJ per scroll after losses, so generation has to be maximised wherever possible rather than attached to one function while the rest of the remote only consumes. All four scrolling functions therefore run through the harvester. A single wheel was chosen over several because it keeps the thumb in one position, needs only one harvester, and keeps the remote visually simple rather than looking complicated before it is picked up.

The final product proposal describes the intended specification of the TV remote harvester based on the research and prototyping carried out in this project. The physical form and final dimensions are based on integral prototype v2, which will be finalised and assembled post greenlight. The proposal below summarises the key design decisions made throughout the project.



Figure 50 Final prototype in hand

Interaction

The remote is operated by a single multifunctional scroll wheel, forward-facing and positioned 100mm from the base of the remote. The wheel slides along its axle to switch between four functions: volume, channel, up/down navigation and left/right navigation. Pressing down on the wheel registers a select command. A kill switch decouples the wheel from the TV signal, allowing the wheel to be scrolled for energy generation during periods of non-use without sending commands to the television. The housing shape is kept neutral to accommodate a range of hand sizes and to allow one-handed, ambidextrous use, as seen in figure 51.



Figure 51 Final prototype in hand top view

Position sensing

Wheel position is detected by four reed switches mounted in the housing, as seen in figure 52, which respond to magnets embedded in the wheel. This method requires no additional current. A mechanical rotary encoder provides the scroll direction and speed reading. Linear detents between the function positions are provided by a spring ball plunger located in the scroll wheel, while the rotational detents come from the encoder mechanism itself.

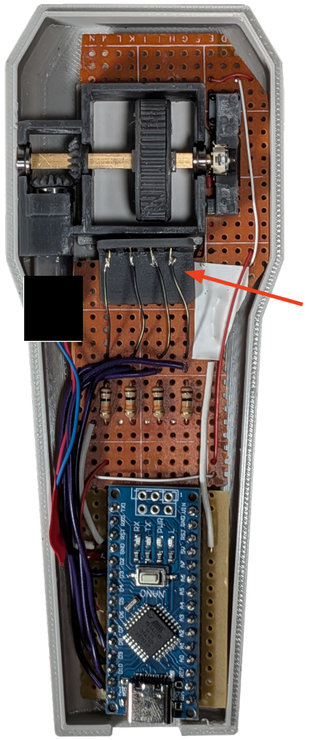


Figure 52 Final prototype internals top view

Signalling

Power on and off are sent via IR, ensuring compatibility with existing televisions and allowing the TV to be woken from deep sleep. All other commands are sent via BLE using a Silicon Labs EFR32BG22, as seen in figure 53. The firmware uses an interrupt-driven architecture, removing the continuous keypad polling found in conventional IR remotes. Peripheral latency is set to 100, giving an effective connection interval of approximately 25 seconds.

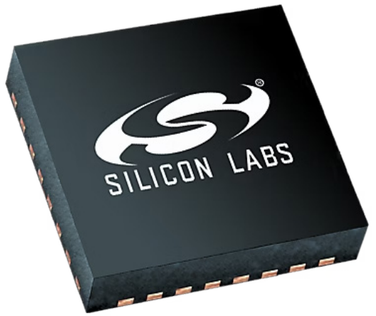


Figure 53 Silicion labs EFR32BG22 chip

Energy generation

Energy is generated by a DC motor harvester, using the same mechanism as the Kinergizer mouse prototype. The electrical resistance is set to 25Ω, which balances energy output against the mechanical resistance felt by the user. Estimated output is 6mJ per scroll at the harvester, reducing to approximately 3mJ after system losses. Generation is intrinsic only, so no separate charging action is required of the user. The kill switch enables supplementary fidget harvesting.

Power

A Maxell ML2032 rechargeable coin cell serves as the backup battery, seen in figure 54. Deep-sleep draw alone cannot deplete it within any realistic timeframe, and under normal use the remote sustains itself through generation. For a consumer variant a supercapacitor could replace the coin cell, removing the battery entirely.



Figure 54 Maxell ML2032 battery

12.2 Concept Assessment

Desirability

Integral prototype v2 has not been assembled into a working whole, so the desirability of the final form and interaction cannot be confirmed at this stage. The pilot user test carried out with prototype v1 was promising, as seen in figure 55, returning a mean SUS score of 76.5 across five participants, with the scroll wheel itself rated highly by almost all of them. The issues that emerged in that test, principally the unclear select function and the left/right navigation mapping, have been addressed in the v2 design.

The ergonomic tests in chapter 4 support the desirability of the interaction itself. Scroll wheel placement, orientation and resistance were all set on the basis of participant feedback rather than mechanical convenience, and the 25Ω operating point was chosen specifically because participants found lower resistances too heavy for a handheld product. The interaction is designed to require no instruction, which matters in a hospitality context where the guest has not chosen the product and has no reason to engage with the energy harvesting behind it.



Figure 55 1st user test

Feasibility

The mechanical side of the concept has been demonstrated at component level. Every individual subsystem of integral prototype v2 has been built and tested in isolation and each performs as intended. The harvester generates energy at the specified resistance, the scroll wheel slides along the axle and holds position on the spring ball plunger detents, the four reed switches detect wheel position reliably, the rotary encoder reads scroll direction and speed, and the readout code combines position and encoder data into a correct function and input display.

What has not been demonstrated is the reed switch and detent selection working together with the encoder in a single assembled housing. Assembly of integral prototype v2 was completed, as seen in figure 56, however it wasn't possible to get it working within the project timeline. The remaining work is integration rather than development, as no subsystem is unproven, but until the full assembly exists the interaction cannot be evaluated as a whole and the interference between subsystems inside the housing is untested.

The signalling side has not been demonstrated at all. The BLE and IR chip has not been integrated into any prototype, and the energy balance rests on a model built from datasheet figures rather than measurement. Both the chip and the signalling approach are proven technology, so the open question is not whether they work but whether they perform as modelled inside this housing under real use. Validating this requires an evaluation board, a power profiler and firmware work, all of which fall outside the scope of this project.

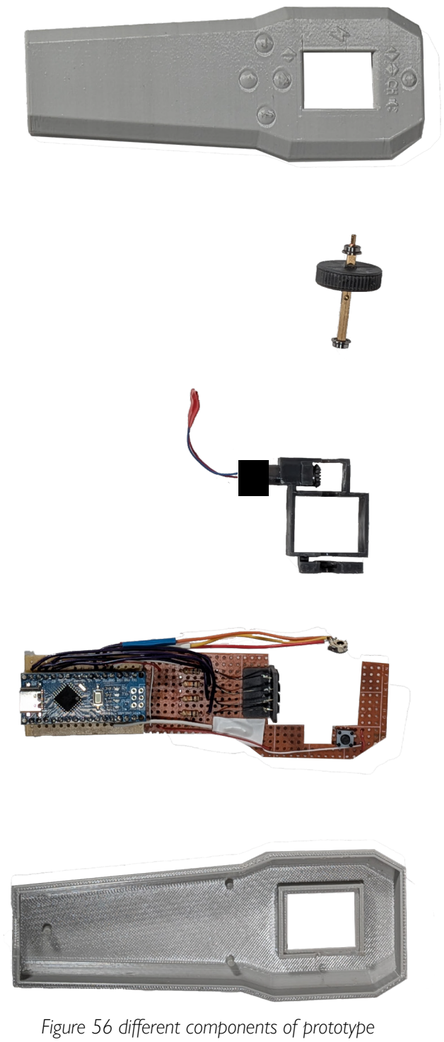


Figure 56 different components of prototype

Viability

The top housing, bottom housing, scroll wheel and harvester insert are all intended for injection moulding in a production version. The harvester insert as it currently stands has not been designed with injection moulding in mind. It was designed for 3D printing in order to reach a working proof of concept as quickly as possible, and would need to be redesigned for mould tooling, draft angles and wall thickness before production. The axle is currently turned and milled.

Technical drawings of the individual components can be found in appendix M. These drawings document the general dimensions of each part rather than a full dimensional specification. Given that the purpose of the prototype is to demonstrate the concept rather than to be manufactured, the drawings cover the measurements that follow from the research and the design decisions made in this project, such as scroll wheel position, magnet spacing and axle geometry. Dimensions that were determined by fit alone and carry no design intent are omitted.

The assembly is designed to be press fit together, as seen in figure 57, with the upper and lower shell snap fitting together. This stays close to typical remote control design and supports disassembly and material separation at the end of life.

Costing was out of scope for this project, so no component or tooling estimate has been produced. The Samsung SolarCell remote is used as a reference point instead, as it is also a energy harvesting smart TV remote. It is a commercially available remote with a solar panel energy harvesting system and retails at approximately 50 euros, which is treated here as a rough ceiling rather than a target. If we compare the components the human power remote has increase complexity and cost because of the harvester, scroll wheel and axle but it doesn't have the solar panel.

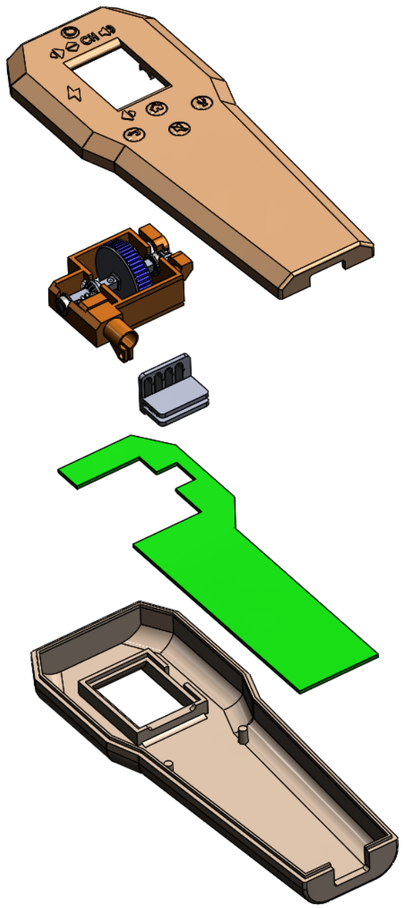


Figure 57 exploded of prototype

13. Conclusion & Discussion

This chapter brings together the findings of the project and reflects on what they mean. It answers the three sub-questions set out in chapter 1 and uses those answers to address the main research question. It then steps back and looks at the project critically, covering the limitations of the research, the assumptions built into the energy model and the gaps that remain between the current prototype and a finished product. It also identifies what the most important next steps are if the concept is to be developed further

13.1 Conclusion

This project set out to answer the question of how a thumb-operated scroll interaction can be designed to generate sufficient energy while remaining ergonomic and intuitive for first-time users. Three sub-questions structured the research.

How much energy can a thumb generate during scrolling, and what variables influence this most?
The harvester generates approximately 6mJ per scroll at 25Ω, estimated at 3mJ after system losses. Scrolling rpm is the dominant variable, with a larger effect on output than electrical resistance. Resistance cannot exceed 25Ω without affecting user comfort. The context awareness test showed that informing users they are generating energy increases rpm by around 30%, suggesting that communication of the concept directly affects how fast users scroll.

What ergonomic factors influence comfort and fatigue during repeated scroll wheel interaction?
A forward-facing wheel orientation positioned at 100mm from the base of the remote produces the most comfortable and natural thumb interaction. Resistance is the primary ergonomic variable, with 25Ω identified as the upper limit of acceptable resistance across test participants. The remote shape should be neutral to allow users with different hand sizes to find a comfortable grip without instruction.

Does typical TV remote use generate enough energy to sustain the product?
The interaction pattern analysis showed that volume and channel alone are insufficient harvesting functions. Navigation must be included. With all four functions harvesting, the energy model shows that a one-hour Netflix session generates approximately 438mJ while consuming 66.66mJ using BLE signalling with peripheral latency applied. A Maxell ML2032 rechargeable coin cell covers worst-case periods of non-use, with deep-sleep draw alone unable to deplete it within any realistic timeframe. Under normal use the remote sustains itself through generation. This balance depends on the chip reaching its datasheet deep sleep figures, which the measurement of a commercial BLE remote showed cannot be assumed.

Overall conclusion
The concept is technically feasible. The proof of concept prototype demonstrates a mechanical architecture and interaction that works. The pilot user test returned a mean SUS score of 76.5, suggesting the interaction is largely intuitive.

The hospitality context is however a more difficult fit than initially assumed. Energy output depends on user effort, and the test participants were consistently young, male and physically fit. The energy and comfort figures should be treated as optimistic. Whether the concept works reliably for the full range of hotel guests cannot be confirmed without in-context testing, which falls outside the scope of this project.

For a consumer product, where the user has chosen the product and understands what it does, the fit is more natural. In this context a battery-free version using a supercapacitor also becomes viable. Kinergizer has responded positively to the prototype and sees potential for continued development. The right market application still needs to be determined.

13.2 Discussion

Limitations of research

Several limitations apply across the research chapters that affect how confidently the conclusions can be drawn.

The participant pool throughout the ergonomic and energy tests was narrow. Participants were consistently young, male, physically fit and students at the IDE faculty. This is not representative of the hotel guest population the concept targets. The energy figures and comfort ratings should be treated as optimistic. A participant with weaker thumb strength or lower motivation will generate less energy and may find the resistance uncomfortable at levels that felt acceptable in testing.

The energy model in chapter 7 is based on datasheet figures that have not been validated by direct measurement of the interaction scenarios. Actual BLE idle consumption may differ from the Silicon Labs EFR32BG22 datasheet values, which would affect the energy balance. The measurement of the Samsung SolarCell remote illustrates the scale of this gap. Its idle current was considerably higher than the datasheet deep sleep figure, though it was measured without an active TV connection and the cause could not be isolated to a single component. Validation using an evaluation board and a power profiler is needed before any further development.

The interaction pattern scenarios in chapter 6 are based on assumed viewing behaviour. There is no public dataset on TV remote interaction frequency and the scenarios were put together by one person rather than derived from measured data. The energy model is only as reliable as these inputs.

The context awareness test in chapter 5 showed a 30% increase in scroll rpm when users were told they were generating energy. The test setup was artificial though, participants were being observed and the remote was bolted to a test rig. Whether this holds in real use is unknown.

The system losses figure in chapter 5 uses the rectifier efficiency estimate from Erik Weteringen at Kinergizer as a benchmark rather than a direct measurement, with the Yang et al. (2022) figure retained as a secondary reference point. The 3mJ post-loss estimate per scroll may differ depending on the specific components and wiring used in the final assembly, and Erik Weteringen noted that the harvesting system as tested is not yet optimised.

Limitations of final prototype

The prototype shows the interaction concept but is not a complete product. The BLE and IR signalling architecture has not been integrated. In the v1 user test function feedback was provided by LEDs, and in v2 this is replaced by a screen readout on a computer. Neither is the same as controlling an actual TV, and whether the interaction feels the same in real use is still an open question.

Due to unforeseen difficulties with the v2 prototype it wasn't operational before the deadline. This means no second user test was done with a more diverse group of participants.

The harvester is integrated for resistance only and its actual energy output in the final housing geometry has not been measured. The energy figures in the model come from earlier standalone tests, not from the assembled prototype.

Next steps

The first next step is finishing and testing integral prototype v2, including the full user test with a more diverse participant group.

The BLE energy model needs to be validated by direct measurement. This means setting up the EFR32BG22 with the proposed peripheral latency settings and measuring actual current draw with a power profiler. This will show whether the model holds or where it needs correcting.

The system losses figure should also be validated by measuring the actual output of the assembled harvester and circuit rather than relying on the Kinergizer chart-based estimate and the Yang et al. benchmark.

The right market application still needs to be determined. The hospitality context is a difficult starting point given the constraints around user motivation and reliability. Consumer applications, where the user has chosen the product and understands what it does, are more likely to work first. This is being explored in collaboration with Kinergizer, who have responded positively to the prototype and see potential for continued development.

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Appendix A - Project Proposal

Project Proposal form
IDE Master Graduation Project

In this proposal the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document needs to be prepared for the Kick-off meeting and should be submitted in MyCase.

Name student Julius Denley **Student number** 5022495

Project title Designing Human-Powered Interaction: Development and Evaluation of a Self-Powered

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

MSc programme ☐ Design for Interaction ■ Integrated Product Design ☐ Strategic Product Design

☐ Other *(in case of a double degree outside IDE)*: _____

Introduction

Describe the context of your project in the box below; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

Small interactive products such as remote controls are still largely dependent on batteries, even though their energy demands are low and their interaction patterns are relatively simple. Energy harvesting company Kinegizer sees a promising market in human-powered remote control products where the device input/commands generate the required power. The benefits of this are twofold, it is no longer necessary to change batteries, increasing dependability. Which in turn results in a remote that has no openings, increasing hygiene, ideal for an application in the hospitality sector.

As of now they have two prototypes, a computer mouse with a generating scroll wheel and a TV remote with a generating rotational dial. Technically Kinergizer says its feasible, however the ergonomics, intuitive use and design of the TV remote are still missing.

→ space available for images / figures on next page

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Introduction (continued): space for images



Figure 1: Computer mouse prototype



Figure 2: TV remote prototype

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Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice. (max 200 words)

The current Kinergizer prototypes require continuous or relatively fast rotation to generate sufficient energy, resulting in an interaction that is neither ergonomic nor intuitive. Power output depends strongly on how the wheel is used, making the system sensitive to differences in user behaviour and physical ability. This is problematic for design-for-all applications and unsuitable for contexts where devices must work reliably without explanation. In the hospitality sector however this is a must.

Currently there is little publicly available research on thumb-operated rotational controls that function both as an input mechanism and a source of micro-energy. Research and ergonomic testing will be required to fill this knowledge gap.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project (1 sentence. As you graduate as an industrial design engineer, your assignment will start with a verb (Investigate/Design/Validate/Create), and you may use the format:
*(Investigate/Design/Validate/Create) **a** (what will be the deliverable → prototype/roadmap/process/ intervention /approach/guideline/strategy/…) **to** (what should it do →(create/understand/evaluate/validate/ improve/execute/ analyse/…) (the objective → experience/value/process/product/…) **for** (whom → target group/client/…) **in** (what context).*

Design a human-powered TV remote to eliminate user dependence on interchangeable batteries for all first time users in the hospitality sector.

Explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words).

The project takes Kinergizer's existing TV remote and computer mouse prototypes as a starting point. Then through an iterative cycle of prototyping and testing (research through design) the aim is to create an ergonomic setup for consistent power and intuitive use by determining wat factors e.g. thumb posture, wheel size, resistance and placement, influence comfort and fatigue during rotatial wheel use. The end goal is to have a works-like, looks-like human powered TV remote prototype that can be used by everyone during first time use.

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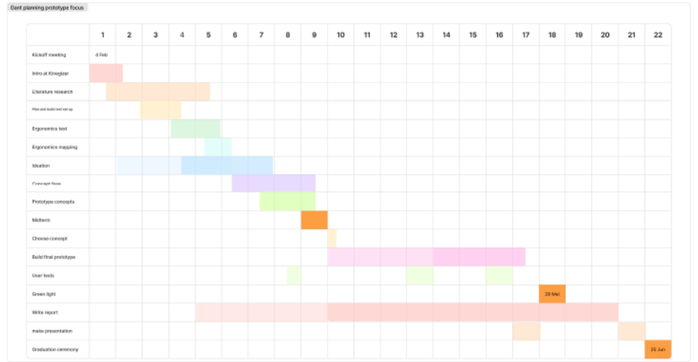
Appendix A - Project Proposal

Project planning

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include the **Kick-off**, **Midterm Evaluation**, **Green Light** and **Finalisation** (ceremony). Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities). Add (an image of) the planning in the box below. If it is not readable, you can add the planning as an attachment to My Case along with this Proposal.*



Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some (max 5) personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology (200 words max).

My main personal goal for my graduation project is to tackle each stage of the project with a similar intent as I do with the design phase. A project where each stage is done properly to the same standard. To achieve this I will need to find the motivating and enjoyable factor in each of these phase. I know there always is one, however sometimes it is difficult to see. Improving my structure and planning during this project will be essential and sticking to it just as important. As for my hard skills, this project will most likely include a lot more electronics than I'm used to. Improving my knowledge in this area is not only beneficial for this project but also my career as designer in general. Finally I want to continue developing my CAD and prototyping skills.

Appendix B - LG magic remote with scroll wheel

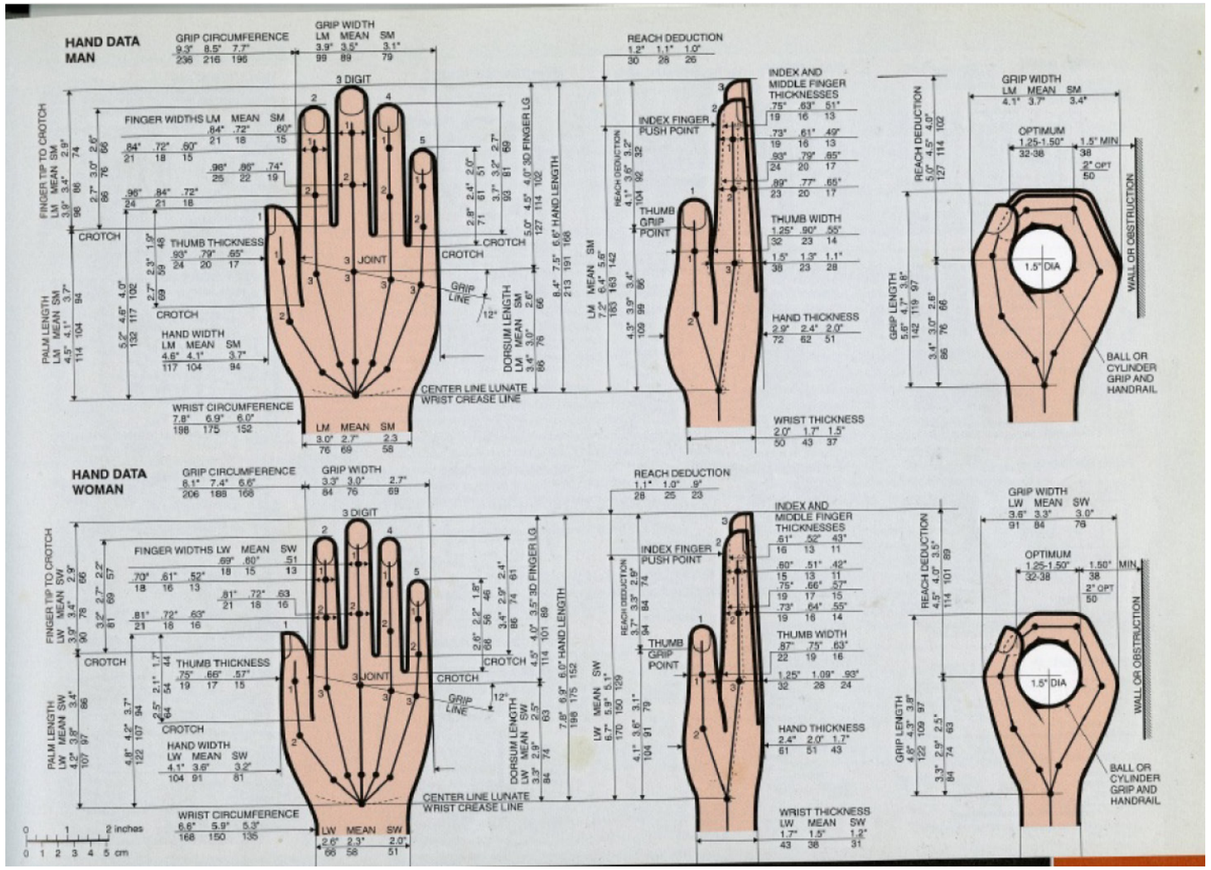


(LG Magic Remote | Smart Remote Control With Voice Functions | LG USA, n.d.)



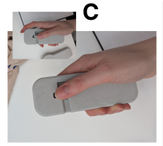
(Robson Braun Electronics, 2022)

Appendix C - Tilley hand model



(Tilley & Associates, 1993)

Appendix D - TV remote shape test results

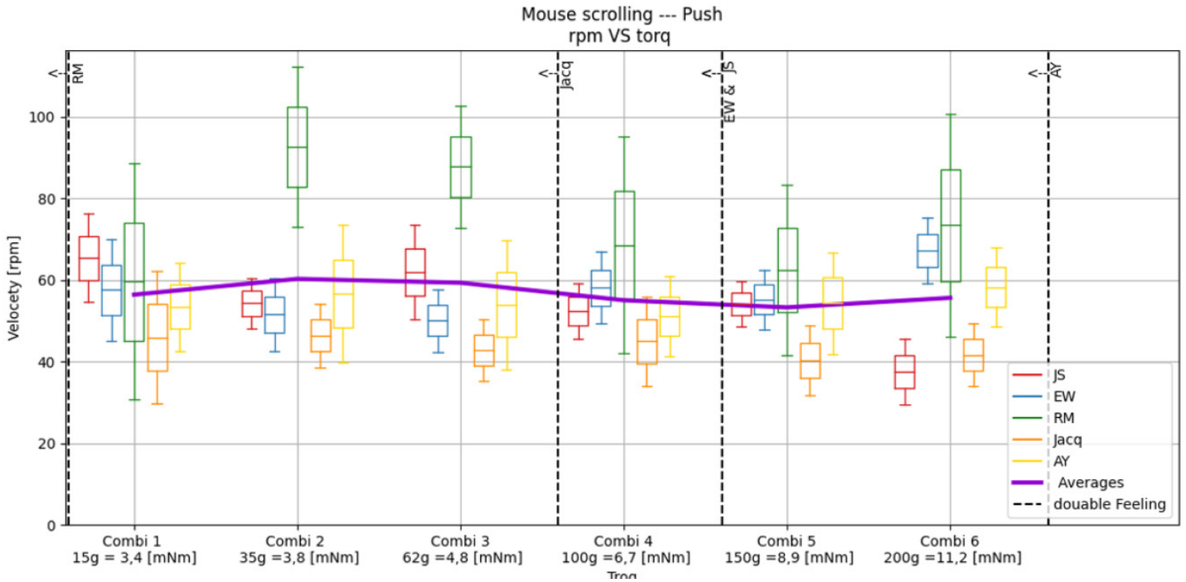
Photos	A	B	C	D	E
1	 Voelt niet helemaal	 "Dit is lekker"hand kan er omheen kan over de lengte vastpakken	 Afronding chill niet helemaal lekker	te dik allemaal te groot	Saai
2	 Veel chiller	 "die is lekker!" mr is ook smooth	 Chill want valt in kom hand		Ouderwets
3	 Selector en scroll te ver uit elkaar	Beter dan 4 maar kan niet goed bij wiel	Cone te dik en te breed, iets met links		Chill want aan de zijkant
4	 Neutrale positie beter	 Kan lastig bij wiel	angle beter en betere dikte		Mwah te groot
5	 Opzich wel fijn, grip chiller	 Hand vat beter kan er wel bij	Houdt nicer vast		Dikke deel te klein
6	 Grip chiller	Well chill	 Bullshit		Chilll

General remarks

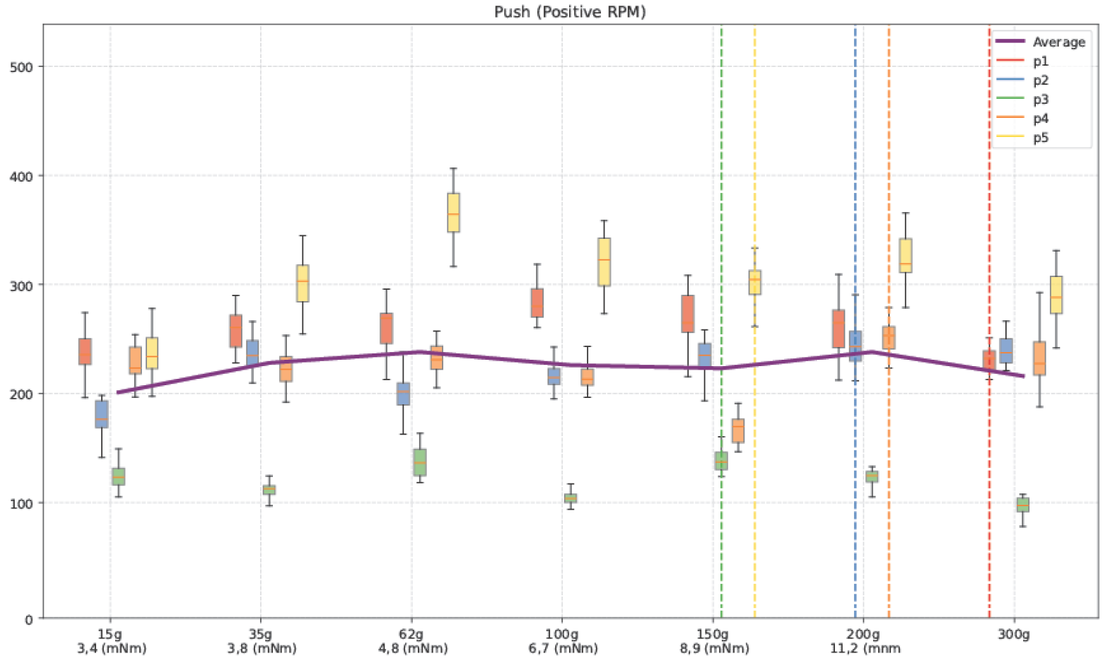
- Need some kind of jig to get the same photos
- prototypes are too small and to big
- everybody has different preference
- Need more people
- 3&4 disk to big
- ergonomic grip te bepalend voor vasthouden
- cone to wide, need sharper angle

Je moet helemaal geeen
knop functie willen, want
je wil er gewoon aan kunnen zitten

Appendix E - RPM push data

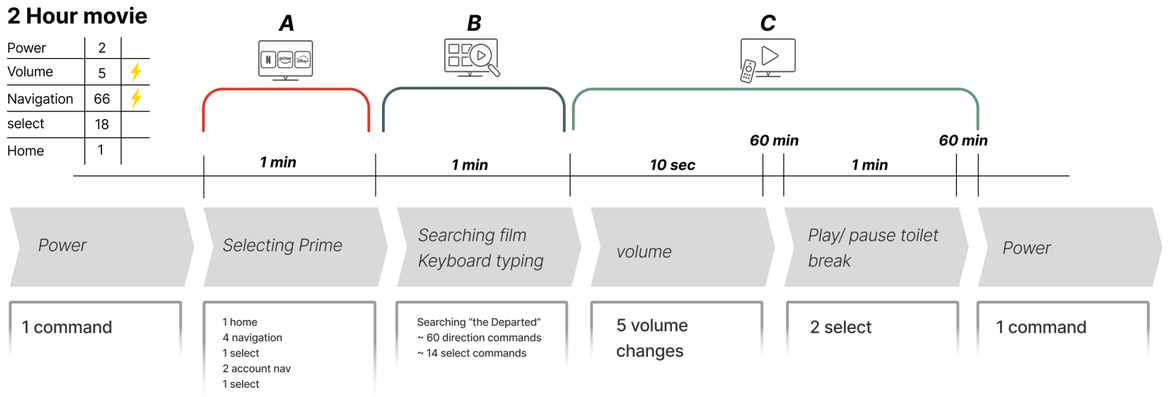


Result index finger push rpm



Result thumb push rpm

Appendix F - 2 hour move interaction scenario



Movie (Prime) watching interaction scenario

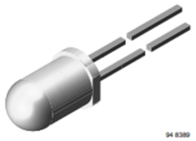
Appendix G - IR diode data sheet

VISHAY. www.vishay.com

TSAL6200

Vishay Semiconductors

High Power Infrared Emitting Diode, 940 nm, GaAlAs, MQW



FEATURES

- Package type: leaded
- Package form: T-1¾
- Dimensions (in mm): Ø 5
- Peak wavelength: λ_p = 940 nm
- High reliability
- High radiant power
- High radiant intensity
- Angle of half intensity: φ = ± 17°
- Low forward voltage
- Suitable for high pulse current operation
- Good spectral matching with Si photodetectors
- Material categorization: For definitions of compliance please see www.vishay.com/doc?99912

DESCRIPTION

TSAL6200 is an infrared, 940 nm emitting diode in GaAlAs multi quantum well (MQW) technology with high radiant power and high speed molded in a blue-gray plastic package.

APPLICATIONS

- Infrared remote control units with high power requirements
- Free air transmission systems
- Infrared source for optical counters and card readers

PRODUCT SUMMARY

COMPONENT	I_e (mW/sr)	φ (deg)	λ_p (nm)	t_r (ns)
TSAL6200	72	± 17	940	15

Note
- Test conditions see table "Basic Characteristics"

ORDERING INFORMATION

ORDERING CODE	PACKAGING	REMARKS	PACKAGE FORM
TSAL6200	Bulk	MOQ: 4000 pcs, 4000 pcs/bulk	T-1¾

Note
- MOQ: minimum order quantity

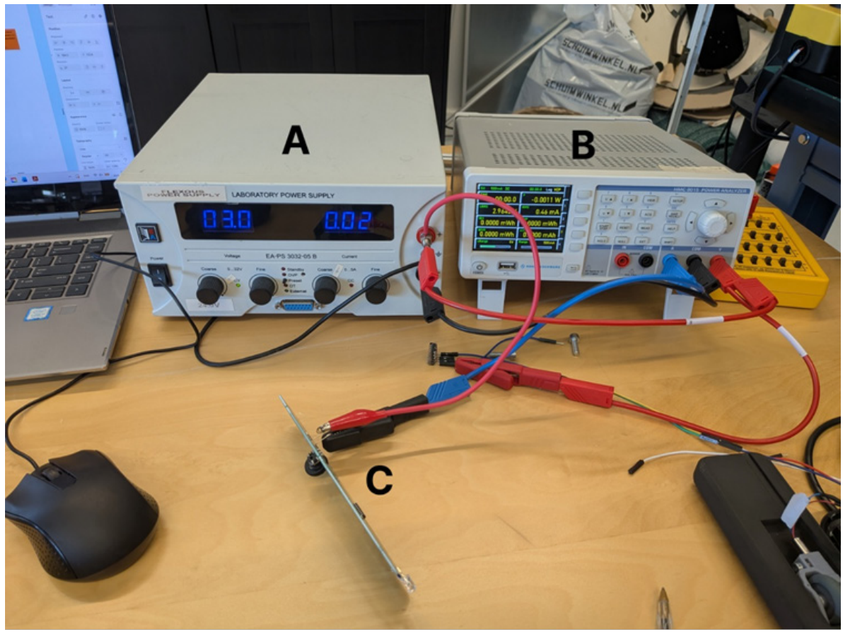
ABSOLUTE MAXIMUM RATINGS (T_{amb} = 25 °C, unless otherwise specified)

PARAMETER	TEST CONDITION	SYMBOL	VALUE	UNIT
Reverse voltage		V_R	5	V
Forward current		I_F	100	mA
Peak forward current	t_p/T = 0.5, t_p = 100 µs	I_{FM}	200	mA
Surge forward current	t_p = 100 µs	I_{FSM}	1.5	A
Power dissipation		P_V	160	mW
Junction temperature		T_j	100	°C
Operating temperature range		T_{amb}	-40 to +85	°C
Storage temperature range		T_{stg}	-40 to +100	°C
Soldering temperature	t ≤ 5 s, 2 mm from case	T_{sd}	260	°C
Thermal resistance junction/ambient	J-STD-051, leads 7 mm soldered on PCB	R_{thJA}	230	K/W

For technical questions, contact: emittertechsupport@vishay.com
THIS DOCUMENT IS SUBJECT TO CHANGE WITHOUT NOTICE. THE PRODUCTS DESCRIBED HEREIN AND THIS DOCUMENT ARE SUBJECT TO SPECIFIC DISCLAIMERS, SET FORTH AT www.vishay.com/doc?91000

(Vishay Semiconductors, 2014)

Appendix H - IR Energy consumption test setup and results



IR remote — power analyser measurements

Energy per button press and idle current, converted from mWh × 3600

Remote A		Remote B		Remote C	
Test	**mJ / press**	**Test**	**mJ / press**	**Test**	**mJ / press**
5 presses	**8.5**	5 presses	**9.2**	5 normal presses	**9.2**
10 presses	**12**	10 presses	**6.5**	5 fast presses	**4.7**
20 presses	**13**	20 presses	**5.6**	5 power button	**29**
Idle measurements		**Idle measurements**		**Idle measurements**	
1 min idle	4.68 mJ → 26 µA @ 3V	1 min idle	4.68 mJ → 26 µA @ 3V	1 min idle	4 mJ
55 min idle	0.0718 mWh → 26.1 µA	1 h idle	0.1368 mWh → 45.6 µA		

Remote A Fast presses not possible — normal hold likely triggers repeat codes. Both idle readings consistent at ~26 µA.
Remote B mJ/press drops with higher press count, consistent with repeat codes at normal speed. 1 h idle at 45.6 µA suggests the MCU may not be reaching deep sleep.
Remote C Power button at 29 mJ likely sends multiple repeats by design. Fast presses (4.7 mJ) are closest to the theoretical single-command energy without repeat codes.

IR TV remote energy consumption results

Appendix I - BLE energy consumption model calculation sheet

$$Effective\ Connection\ Interval = Connection\ Interval \times Slave\ Latency$$

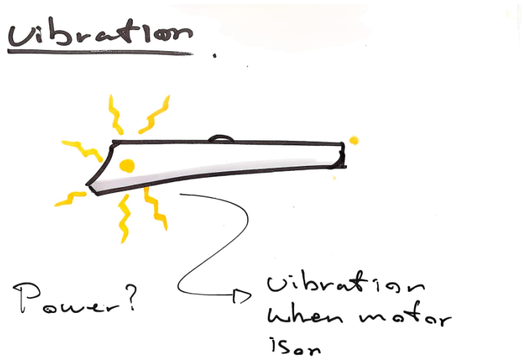
$$Packets\ Sent\ = \frac{Period\ duration}{Effective\ Connection\ Interval} + Commands\ Pressed$$

$$Total\ Packet\ Duration = \ Packets\ Sent\ \times\ Packet\ Duration$$

$$\begin{aligned} Energy\ Consumed \\ &= (Total\ Packet\ Duration \times Command\ Current \\ &+ (Period\ Duration - \ Total\ Packet\ Duration) \times Connected\ Idle\ Current) \\ &\times Voltage \end{aligned}$$

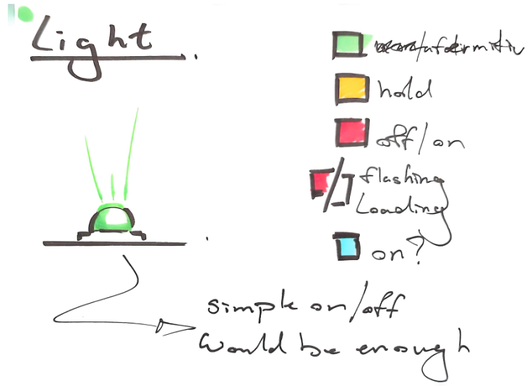
$$Energy\ Generated = Generating\ Scrolls \times Energy\ Generated/Scroll$$

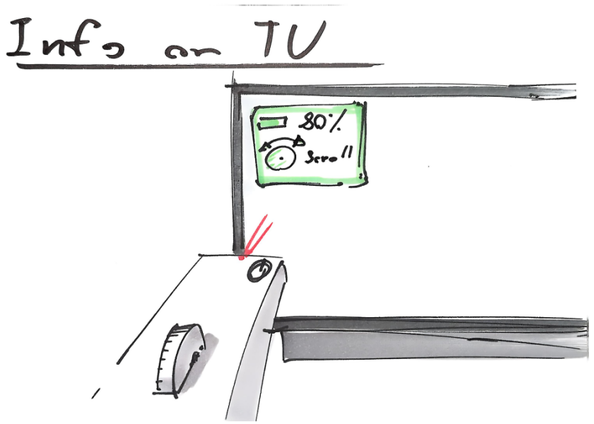
Appendix J - How Can You (HCY) Ideation

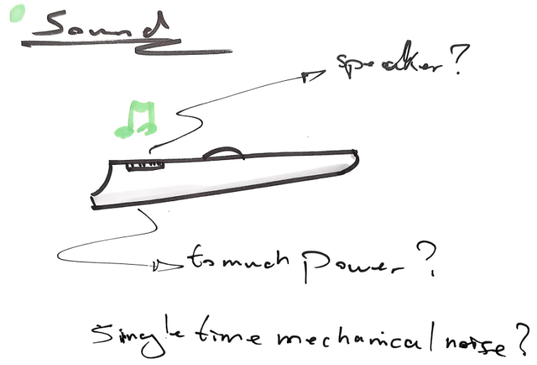


HCY let a product communicate its on with the user

Julius Denley



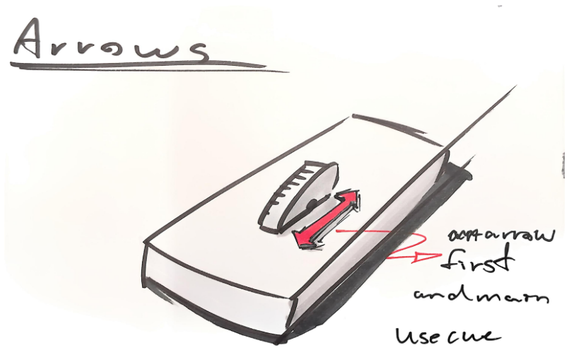


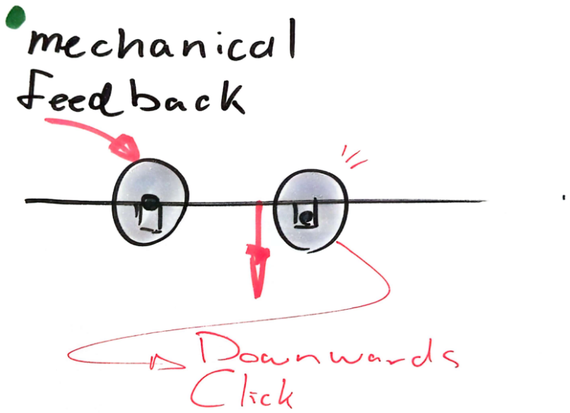


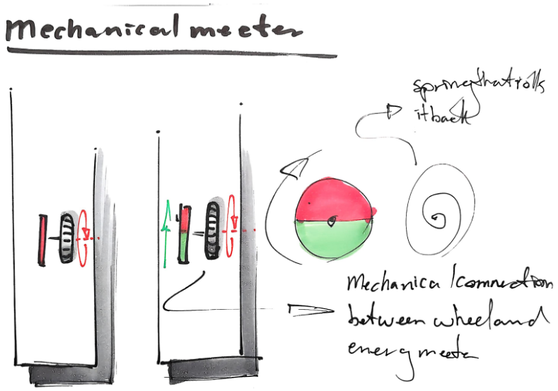
Appendix J - How Can You (HCY) Ideation

HCY let a product communicate with the user without power

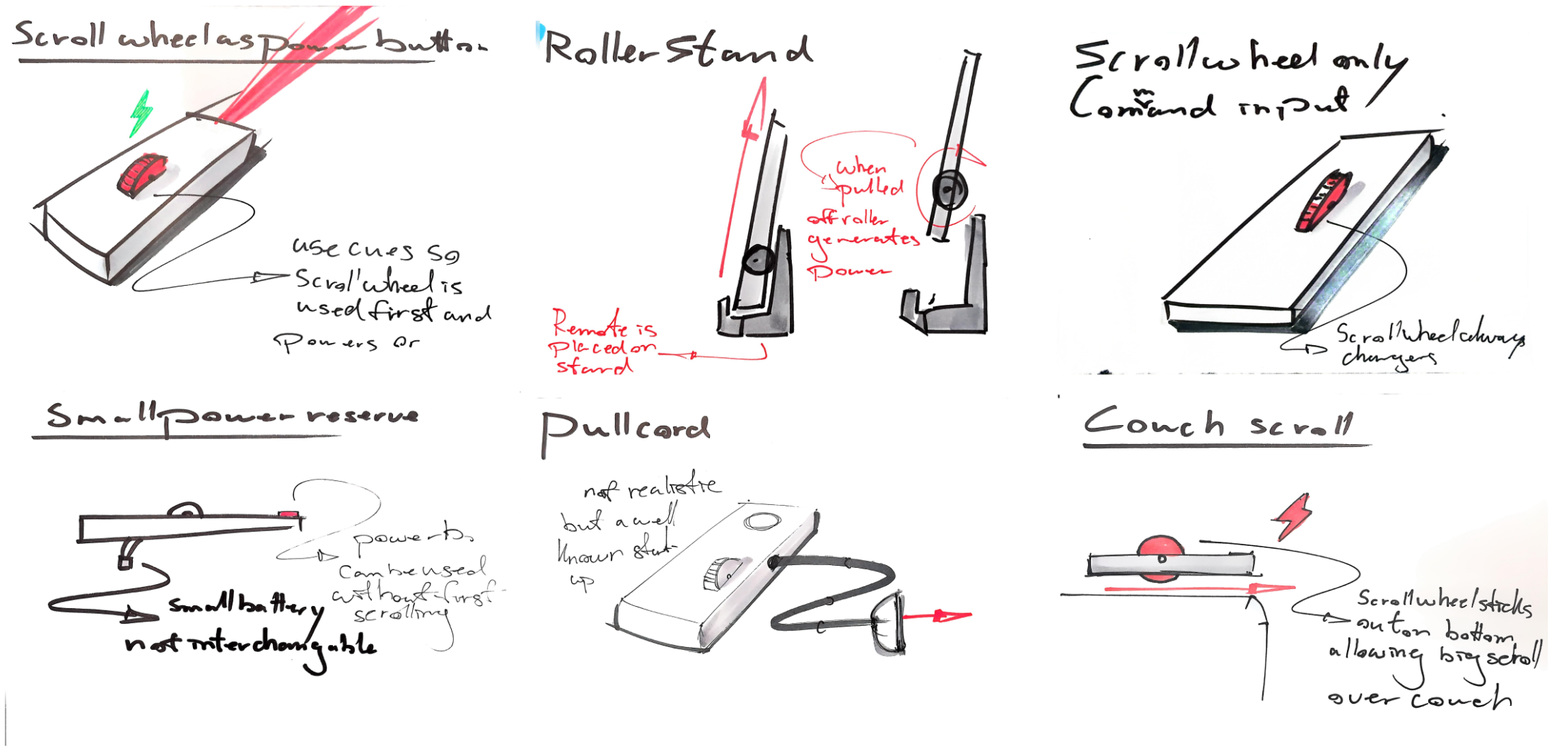
Julius Denley







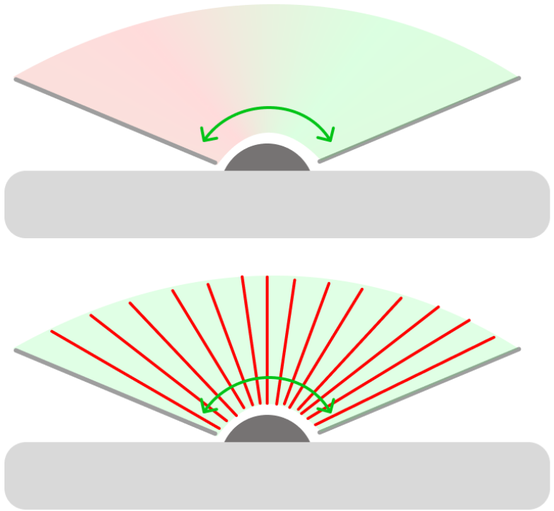
Appendix J - How Can You (HCY) Ideation



How can you get direct input without scrolling first

Julius Denley

Appendix J - How Can You (HCY) Ideation





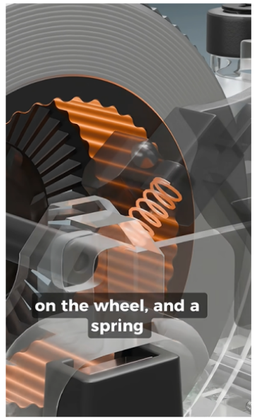
way to much input for volume scrolling

Julius Denley

Two main issues

Julius Denley



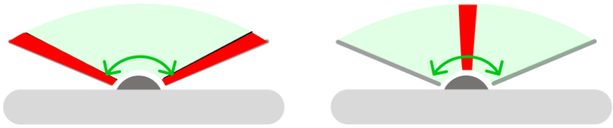


3-4 swipes for full wheel rotation

Julius Denley

How can you get different inputs out of a scrolling wheel

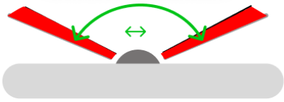
Julius Denley





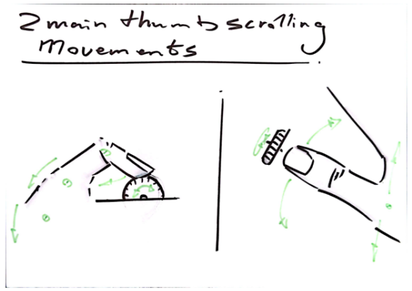
People can miss input points because they are to far

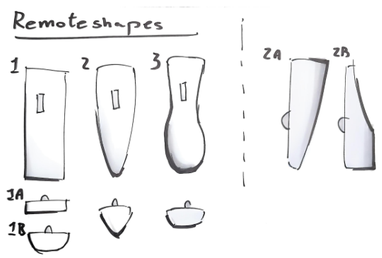
People only scroll a little bit in the middle

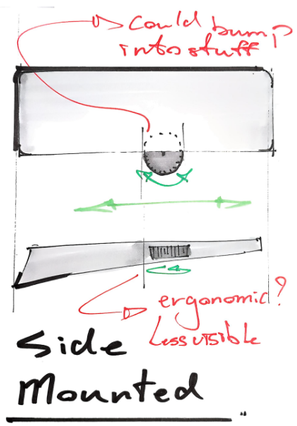


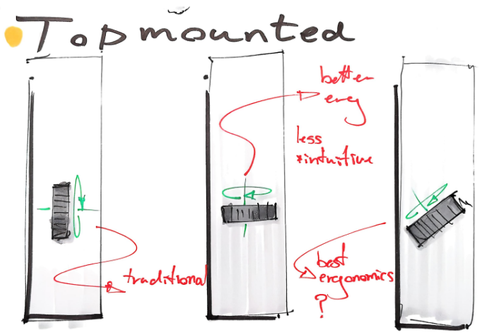
Needs to be a cam that supports the long movent

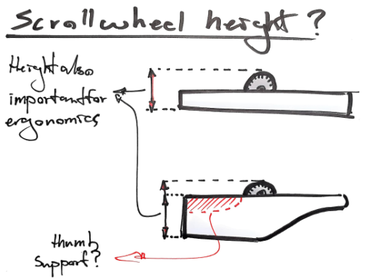
Appendix J - How Can You (HCY) Ideation

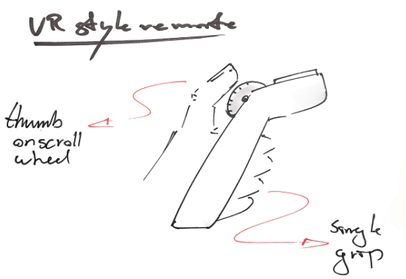


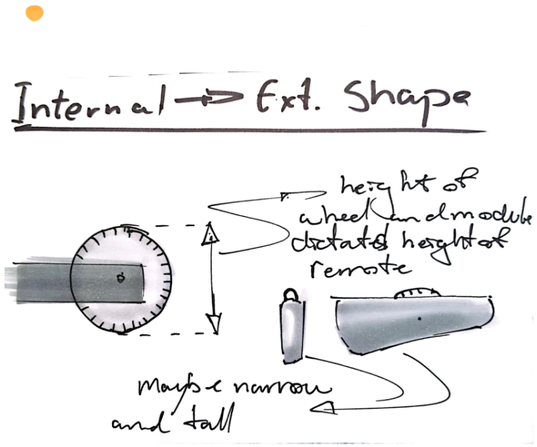


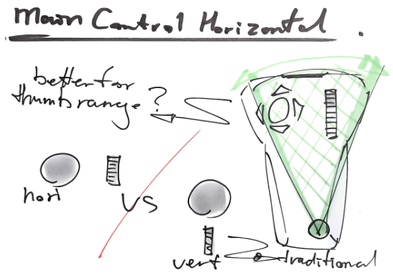


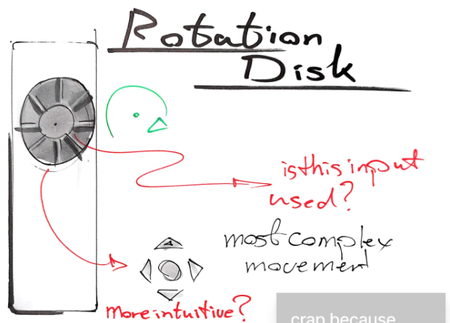












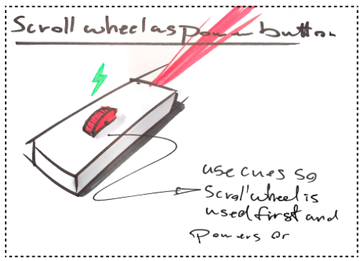
HCY get the best ergonomic position for a thumb.

Julius Denley

crap because weak muscles are used

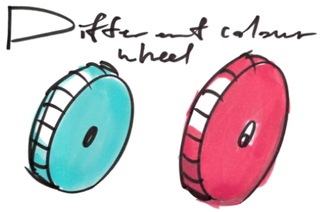
Julius Denley

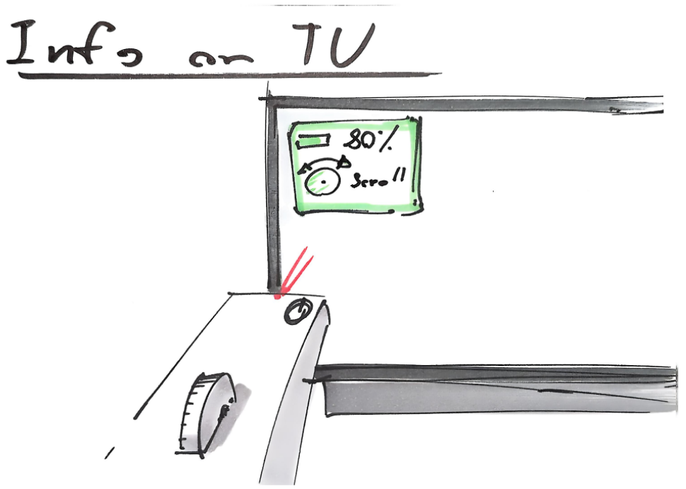
Appendix J - How Can You (HCY) Ideation



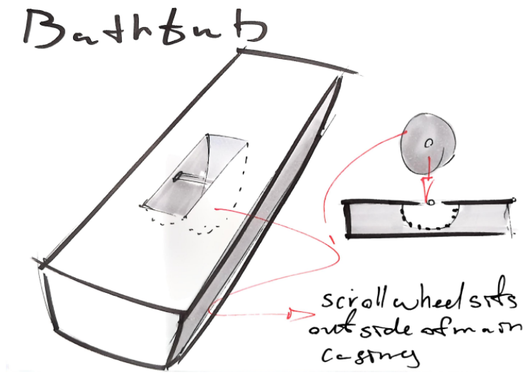
How can you communicate human power with first time user

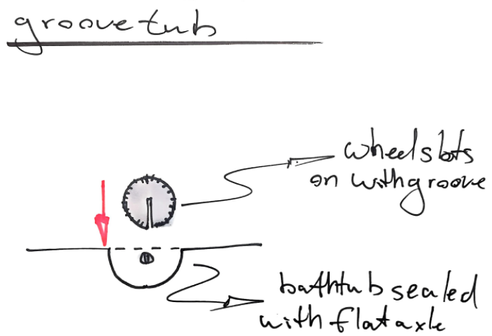
Julius Denley

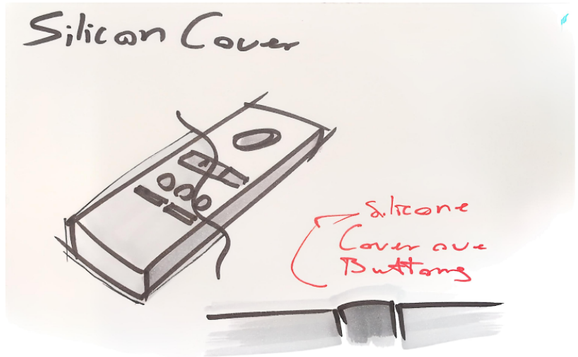


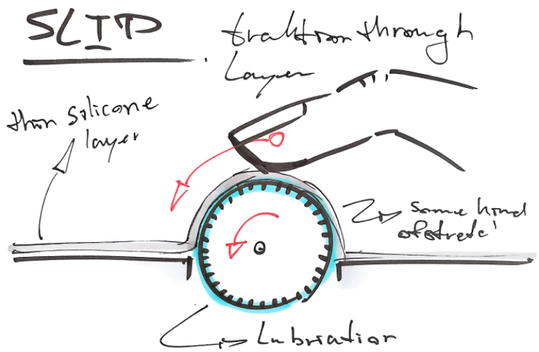


Appendix J - How Can You (HCY) Ideation









How can you make a remote control hygienic

Julius Denley

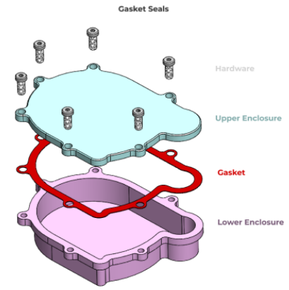
How can you make a remote control water tight

Julius Denley



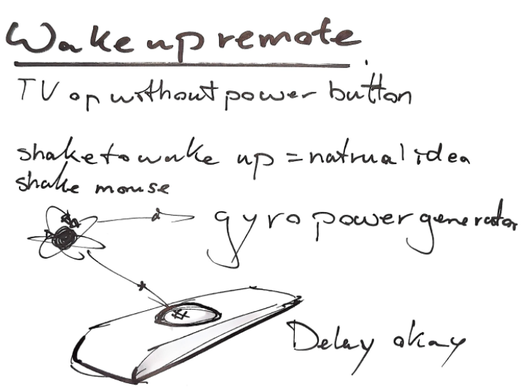
https://app.fiveflute.com/s/tolerance/new?_gl=1*1qpn6dt*_ga*MjY0NzMyNjcxLjE3NzA3MzM1MDA.*_ga_KBLZPC3MT0*czE3NzA3MzM1MDAkbzEkZzEkdDE3NzA3MzM2NzUkajYwJGwwJGgw

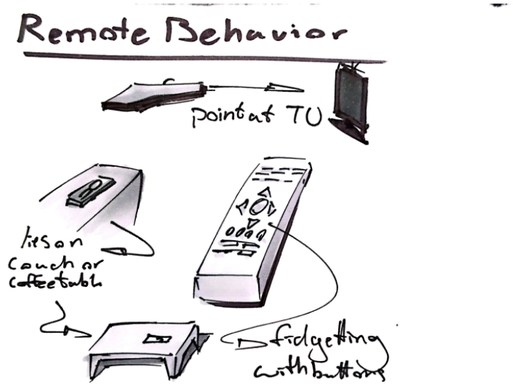
https://www.fiveflute.com/guide/how-to-design-waterproof-products/



https://www.fiveflute.com/guide/how-to-design-waterproof-products/

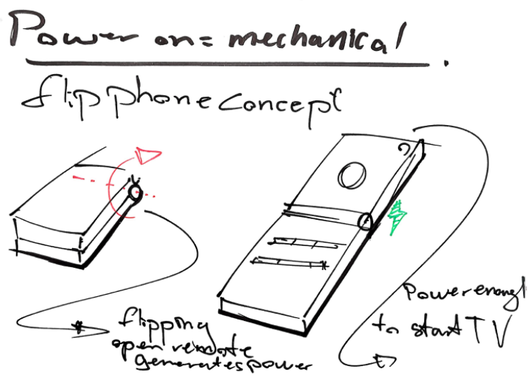
Appendix J - How Can You (HCY) Ideation

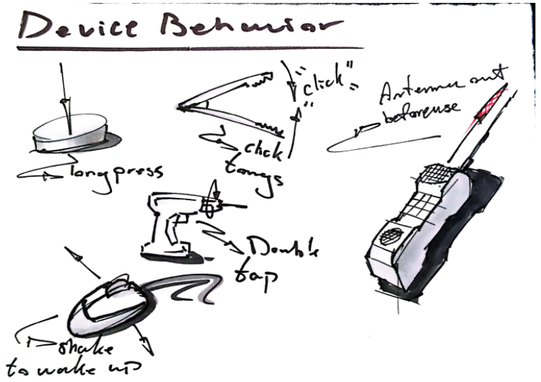


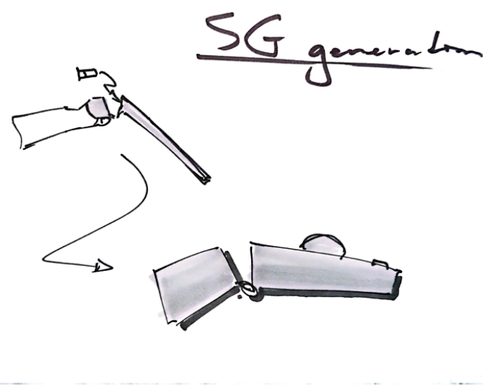


HCY use existing behavior for power generation

Julius Denley

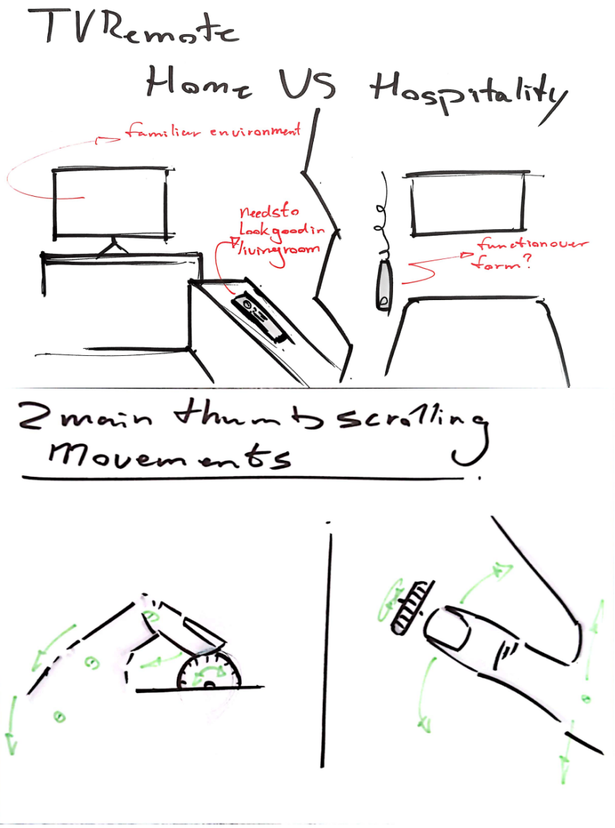




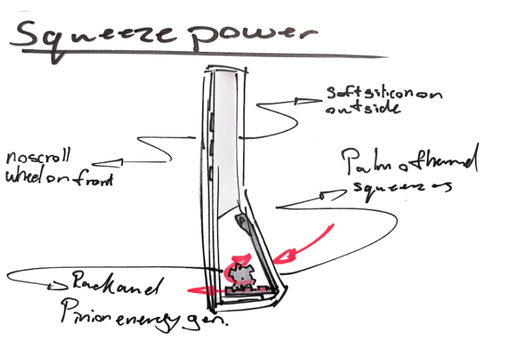


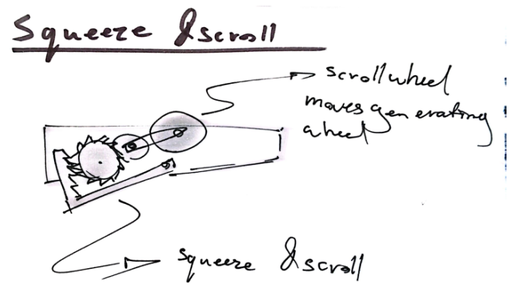
Appendix J - How Can You (HCY) Ideation

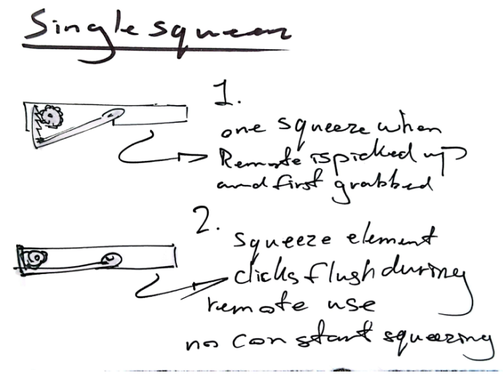
eneral thoughts

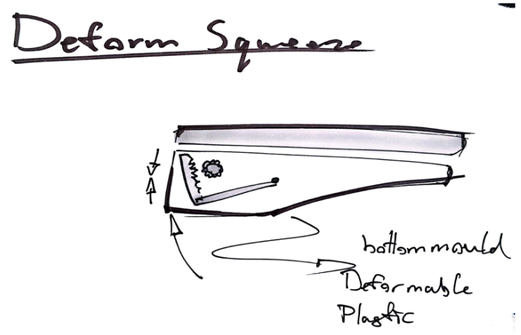


Squeeze





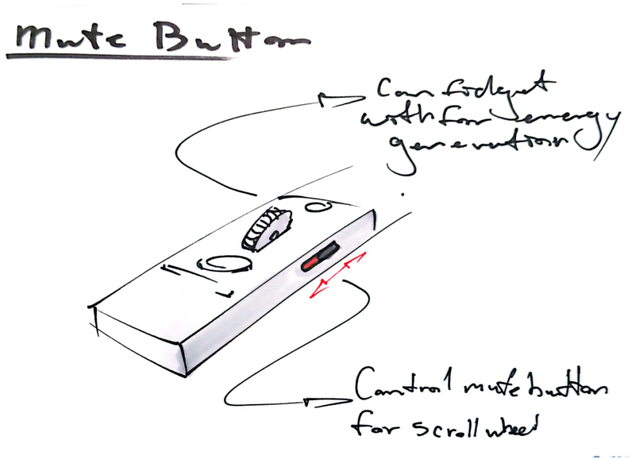


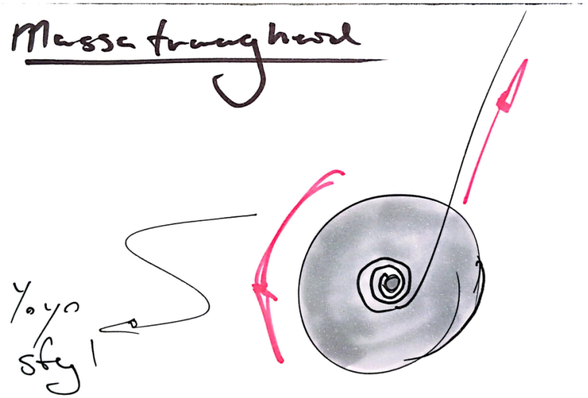


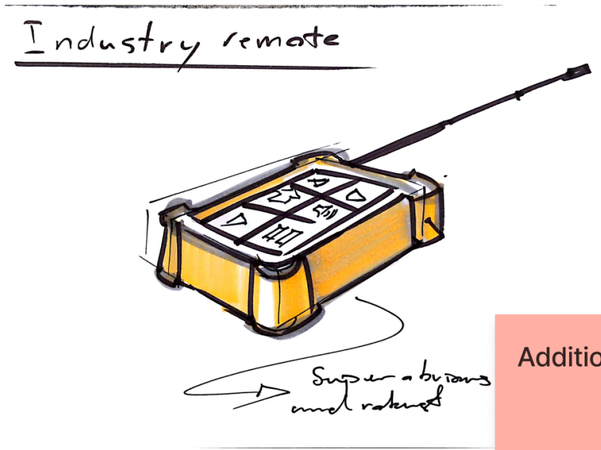
Additional ideas

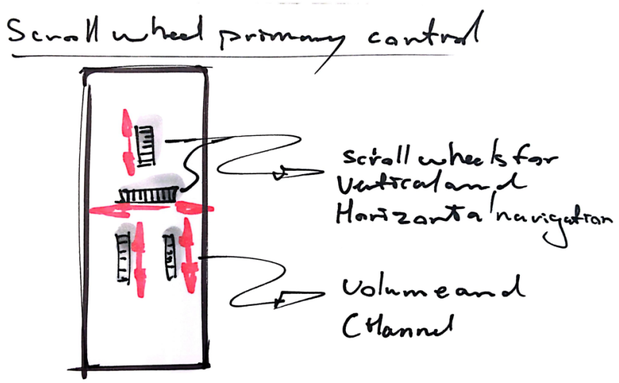
Julius Denley

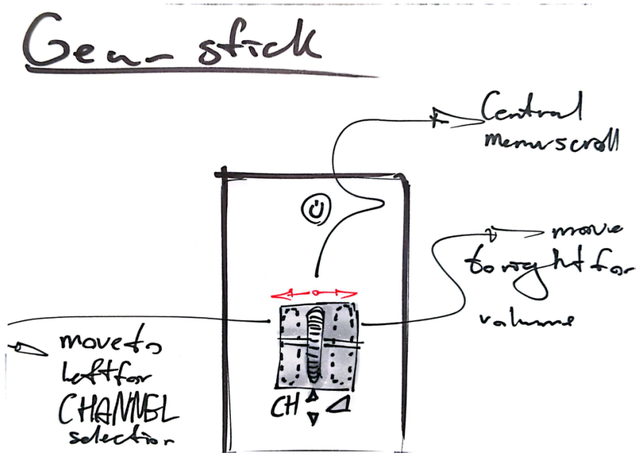
Appendix J - How Can You (HCY) Ideation

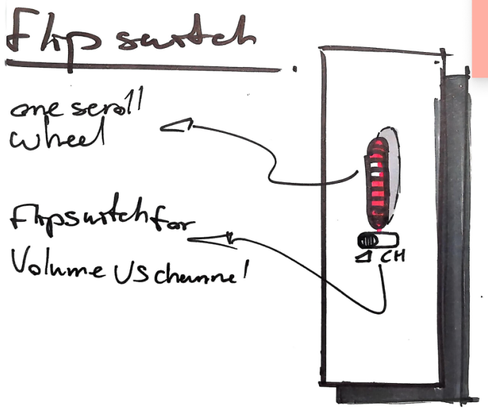












Additional ideas

Julius Denley

Appendix K - User test theory

Nasa Task loading test

The NASA-TLX, developed by Hart and Staveland (1988), measures subjective workload across six dimensions including physical demand, mental demand and frustration. Its strength is separating physical and cognitive load, which is relevant for a physically operated device. However, the full NASA-TLX requires a paired-comparison weighting procedure that is time-consuming and adds complexity disproportionate to a short prototype session. The raw TLX version (Hart, 2006) removes this step but still produces six separate subscale scores rather than a single usability measure, making it better suited to workload research than to evaluating intuitiveness.

Technology acceptance model

The Technology Acceptance Model (Davis, 1989) identifies perceived usefulness and perceived ease of use as the primary determinants of technology adoption. TAM is well suited to evaluating long-term adoption intent but less appropriate for a single prototype session where participants have no prior experience with the concept. It is better applied after repeated use over a longer period.

System usability scale

The System Usability Scale (SUS), developed by Brooke (1996), produces a single composite usability score from ten Likert items and was designed specifically to be used after short exposure to a system. A score above 68 is considered above average and above 80 excellent (Bangor et al., 2008). It is technology-independent, validated across hardware and physical products, and completable in under two minutes.

Choice of method

The SUS is selected as the primary instrument for this test because it directly measures ease of use and learnability, matches the scope of a short prototype session, and produces a clear comparable score. NASA-TLX and TAM remain relevant for future test rounds: NASA-TLX when the focus shifts to the physical effort of harvesting, and TAM once participants have had repeated exposure to the concept and can form a reliable view of adoption intent.

Appendix L - User test Form

Appendix K User test 1 Form

Test form User test LED

Participant ID: _____ **Date:** _____ **Session #:** _____

A.1 Introduction — read aloud

Thank you for taking part. Today you will try out a prototype of a new TV remote control. The remote works differently from a normal one: instead of separate buttons for volume and navigation, it uses a single scroll wheel. The prototype is still in development, so not everything is finished yet. We are testing the design, not you there are no right or wrong answers. Please think aloud as you go: say what you are trying to do, what you expect to happen, and anything that surprises you. You can stop at any time.

A.2 First impression

Place the prototype in front of the participant. Ask them to look at it before picking it up.

Q1. Before picking it up, where do you expect the different functions to be on this remote?

Now hand it to the participant and ask them to hold it naturally.

Q2. How does it feel in your hand? Anything unexpected?

B.3 Tasks

Task 1: Turn the volume up	
Instruction to read	“increase the volume. The LED will confirm the active position.”
Completed	Independently / With hint / Not completed
Errors / observations	

Appendix L - User test Form

Task 2: Navigate right	
Instruction to read	"navigate right."
Completed	Independently / With hint / Not completed
Errors / observations	
Task 3: Navigate up	
Instruction to read	"Navigate up."
Completed	Independently / With hint / Not completed
Errors / observations	

Task 4: Select	
Instruction to read	"Now press select."
Completed	Independently / With hint / Not completed
Errors / observations	

C.4 Follow-up questions

Ask these after all tasks. Note key phrases verbatim.

Q3. Did the wheel behave the way you expected?

Q4. Was there anything confusing about switching between the different functions?

Q5. What is the one thing you would change?

D. Questionnaire — participant fills in independently
D.1 Scroll wheel

For each statement, circle the number that best matches your experience. 1 = strongly disagree, 5 = strongly agree.

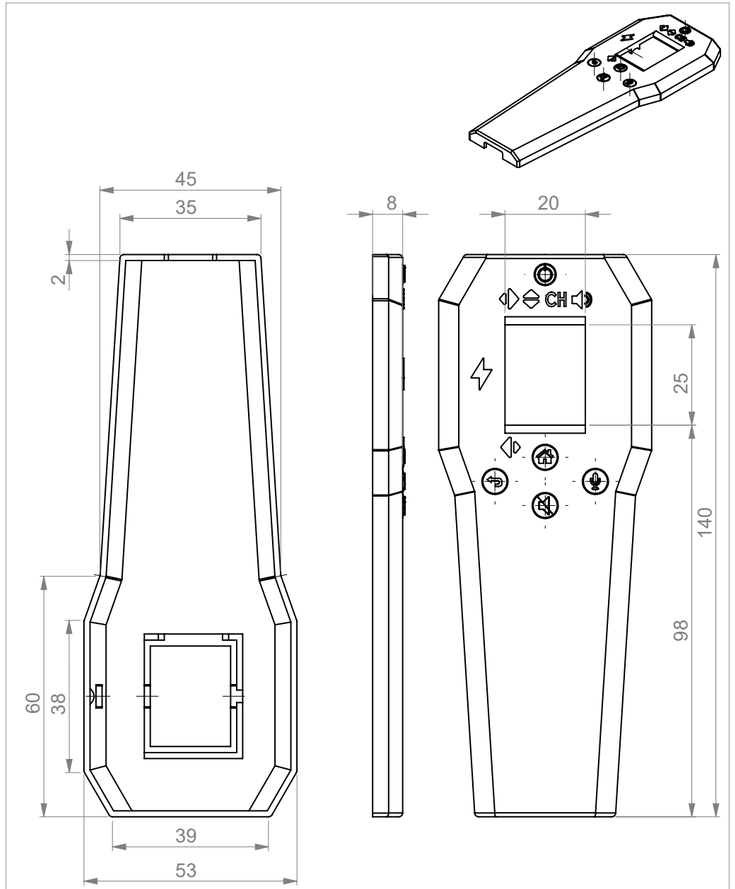
Statement	**Strongly disagree (1)**	**2**	**3**	**4**	**Strongly agree (5)**
1. The wheel was comfortable to turn.	1	2	3	4	5
2. I could feel clearly when I had moved to a new function position.	1	2	3	4	5
3. The effort required to scroll felt appropriate.	1	2	3	4	5
4. I felt in control of what the wheel was doing.	1	2	3	4	5

D.2 System Usability Scale

Brooke (1996). Circle the number that best matches your view of this remote. 1 = strongly disagree, 5 = strongly agree.

Statement	**Strongly disagree (1)**	**2**	**3**	**4**	**Strongly agree (5)**
1. I think I would like to use this remote frequently.	1	2	3	4	5
2. I found this remote unnecessarily complex.	1	2	3	4	5
3. I thought this remote was easy to use.	1	2	3	4	5
4. I think I would need help to be able to use this remote.	1	2	3	4	5
5. I found the different functions of this remote were well integrated.	1	2	3	4	5
6. I thought there was too much inconsistency in how this remote works.	1	2	3	4	5
7. I would imagine most people would learn to use this remote quickly.	1	2	3	4	5
8. I found this remote very awkward to use.	1	2	3	4	5
9. I felt very confident using this remote.	1	2	3	4	5
10. I needed to learn a lot before I could get going with this remote.	1	2	3	4	5

Appendix M - Final prototype drawings



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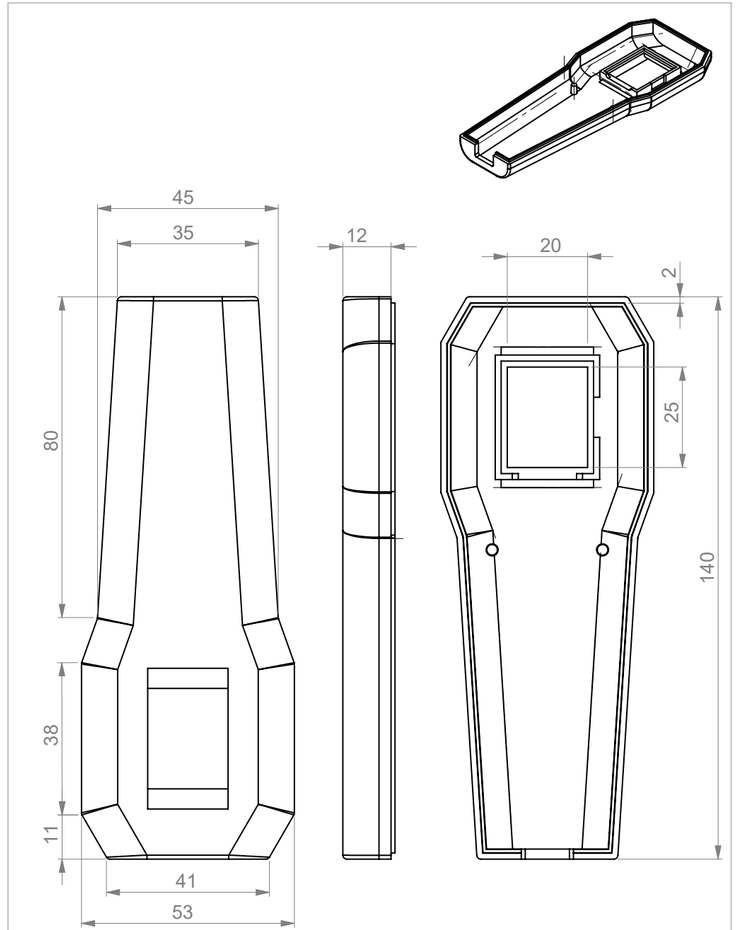

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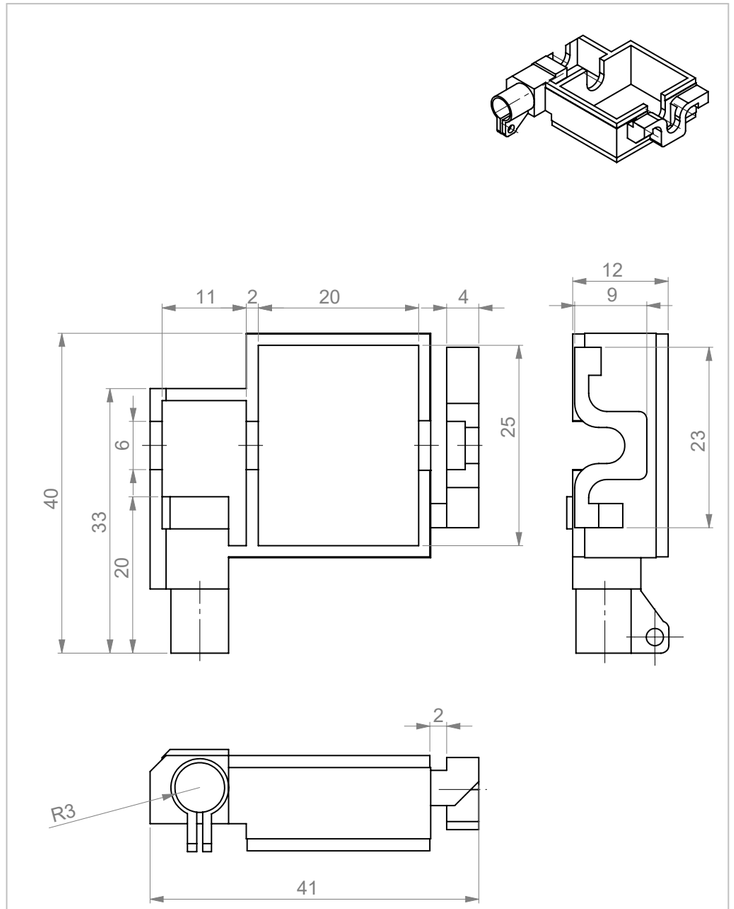
Appendix M - Final prototype drawings



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TU Delft Delft University of Technology

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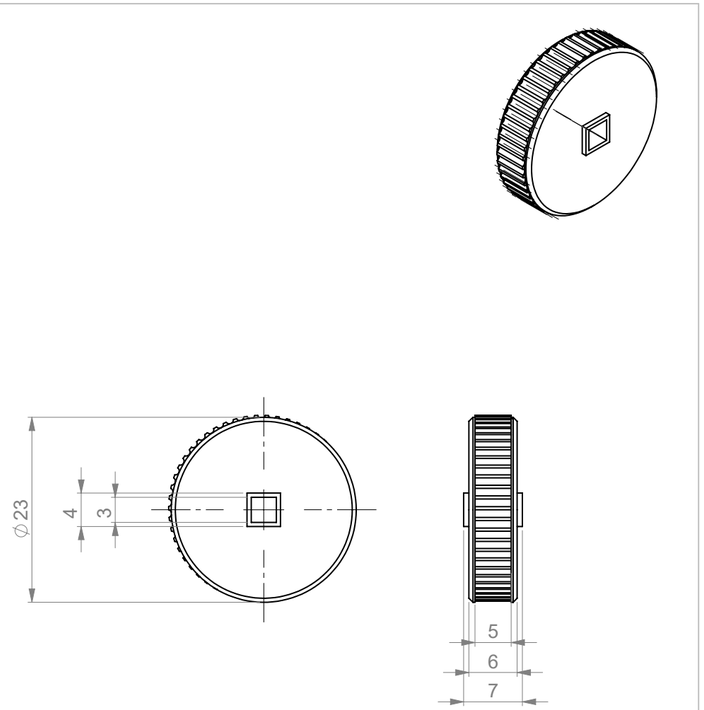

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TU Delft Delft University of Technology

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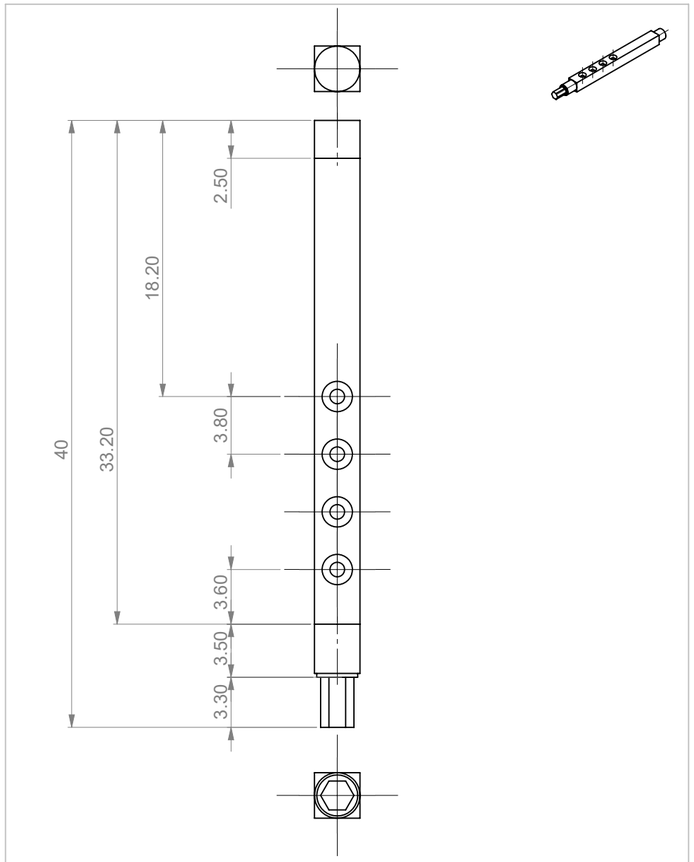
Appendix M - Final prototype drawings



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