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Cover: Rendering of CAD model of the improved removable attachment device to attach objects to the Fabric

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Abstract

There is often a need to attach objects to the fabric surface for storage, usage or securement. Multiple products have existed for years that fasten things together, like buttons, clips, pins, hooks, buckles, magnets, straps, and relatively new ones like hook-and-loop and Dual lock. However, all these products need some defined pre-installation (pre-process), like the stitching of button, buckle or hook-and-loop strip on the fabric before use. New technology is developed which do not require any pre-installation, allowing to attach to any fabric in any placement. It is a stand-alone mechanical system that can removably attach a handheld object to the fabric. First responders, who carry multiple equipments in a dynamic environment, can utilise the benefit of flexible placement and quickness. However, often exposed to extreme force conditions, they need a strong attachment where the existing design is limited. The thesis aims to improve the existing design of the technology to maximise its force-carrying capacity to achieve a strong and secure attachment to workwear.

The development is carried out in three main phases. In the first phase, an analysis of the functionality, design and performance develops a theoretical understanding. The second phase experimentally investigates the performance to identify problems and possible causes. The first two phases create a basis for design improvement. The last phase explores potential designs to achieve enhanced performance. A new solution is proposed, enhancing the strength by about 2.5 times of the original technology and two times of Hook-and-loop fasteners. The improved design incorporates new concepts and utilises adaptations of old design along with parametric changes. The technology leverages modularity for sizing as well as configuration. A device configuration method is proposed to adopt the technology to various objects, sizes and force requirements. Moreover, the work delivers theoretical models, the experimental process for performance measurement and system configuration and sizing guidelines.

Keywords: Attachment device, Fastening systems, Experimental product development, Adaptive re-design, Fasteners.

Preface

The master thesis was carried out by two product development master students for Company X, during the spring 2021. The required information and resources were provided by the company and Chalmers University of Technology, but the work and decision-making process was carried out independently. Due to confidentiality, all identifiable information regarding the company is removed in addition to sensitive information. The company is referred to as 'Company X' and the technology in focus as 'Spindel-tech', a fictitious name. For the same reason, citations to publicly available work which can identify the company are also omitted and replaced with placeholders to indicate citation.

Aarush Bhardwaj and Pranjal Jhaveri, Gothenburg, June 2021

Acknowledgements

We would like to convey our gratitude to all the people who encouraged us, and contributed to the project. We gratefully appreciate the company supervisor and other company personnel for supporting the project with the information, tools and resources required. A weekly dialogue with the company facilitated regular reflection on the work.

A special thanks to Prof. Johan Malmqvist, our thesis supervisor, who constantly guided us throughout the process and supported the work with all the resources required at Chalmers University of Technology. His insights and regular feedback helped us learn along the process of the thesis work.

Aarush Bhardwaj and Pranjal Jhaveri, Gothenburg, June 2021

Nomenclature

Design Parameters

α [°] Separation of abutments (Angular separation w.r.t gear rotation axis)
δ [°] Distance to cave (From Top abutment)(w.r.t gear rotation axis)
γ_o [°] Full Rotation angle of wire during actuation (w.r.t gear rotation axis)
γ_o^{lever} [°] Rotation angle of lever (or driving gear) about its axis
θ [°] Angle of slope
D_{sys} [m] Diameter of system, refereed to as size of system
H_w [m] Height of Wire pathway
L_{lever} [m] Length of lever from centre of system
n [1] Number of modules in a system, referred in text as <n>m, i.e. 4m, 5m
R_g [m] Radius of module gear
R_m [m] Radius of top cover (module)
R_w [m] planar Arc radius of wire (Wire radius)
r_w [m] Cross-sectional radius of wire (Wire thickness)
R_{base} [m] Radius of lever gear
t_{sys} [m] Thickness of system

Material properties

μ [1] Friction co-efficient between wire material and top cover material
σ_y [MPa] Tensile yield strength of wire
E [GPa] Young's modulus of wire material
t [m] Thickness of fabric
UTS [MPa] Ultimate Tensile strength of wire

Derived parameters

β_1 [°] Angle of first penetration (Angle of approach by wire tip to fabric)(0[°] when parallel, maximum 90[°] when approaching perpendicular)
β_2 [°] Angle of second penetration (Similar definition as β_1)
ϕ [°] Angle of change of Rotation plane; or Attached state plane angle (from resting plane)
ρ $[m]$ Bending radius for three-point bending in actuation
A $[m^2]$ Cross sectional area of wire
D_p [m] Depth of penetration
I $[m^4]$ Second moment of area
J $[m^4]$ Polar second moment of area

Usage parameters

γ [°] Rotation angle of wire (between 0 to γ_o)
Φ [°] Orientation of system (0° reference aligns with radial placement of a module)
D_f [m] $= (D_{fx}, D_{fy}, D_{fz})$ Position vector of the equivalent point of attachment to fabric [from Top abutment]
d_{obj} [m] Distance of centre of mass of object from attachment surface

F [N] $= (F_x, F_y, F_z)$ Generalised force applied on wire (equivalent)
f_f [N] Minimum directional functional failure strength of module
f_f^{sys} [N] Minimum directional functional failure strength of system
f_u [N] Minimum directional ultimate strength of module
f_u^{sys} [N] Minimum directional ultimate strength of system
F_w [N] Actuation force for each module
F_w^{sys} [N] Actuation force for system applied by user (i.e. by hand to lever)
F_{ext} [N] $= (F_{ext,x}, F_{ext,y}, F_{ext,z})$ Generalised force applied on the object/system
$f_{f,dir}$ [N] Directional functional failure strength of module $[< dir > \in \{x+, x-, y+, y-, z+\}]$
$f_{f,dir}^{sys}$ [N] Directional functional failure strength of system $[< dir > \in \{(\theta)y+, z\}]$
$f_{u,dir}$ [N] Directional ultimate strength of module $[< dir > \in \{x+, x-, y+, y-, z+\}]$
$f_{u,dir}^{sys}$ [N] Directional ultimate strength of system $[< dir > \in \{(\theta)y+, z\}]$
g $[m/s^2]$ Gravitational acceleration
M $[Nm]$ Bending moment
m_{obj} $[g]$ Mass of object to be attached
m_{obj}^{sys} $[g]$ Resting weight holding capacity of the system
q [1] Attachment quality, average fraction of modules achieving good attachment in a system upon attachment

Terminology

Device working System of the Spindel-tech technology
Fabric Fabric made up by weaving threads in to a pattern
Fibre A textile fibre, which are spun into threads (i.e., cotton, nylon, or other fibres)
Object The object to be attached to Fabric using technology
Spindel − tech Technology developed by Company-X, described in patent (Patent, 2020)
System same as 'Device'
Thread A long, thin spun strand of textile fibres used in sewing or weaving. Here it mainly refers to a woven thread in a fabric
Wire Metallic wire used for attachment by penetration of fabric
Yarn Thread

Axis system

Shear direction Directions parallel to attachment surface (Fabric), particular direciton defined by ΦY+
Tensile direction Axis going away perpendicular from attachment surface (Z+ direction of system)
$X-$ For Local axis system of Module, X- aligns with Top abutment (Origin lies on the gear rotation axis)
Z For Local axis system of Module, Z aligns with the gear rotation axis

Contents

1

Introduction

The introductory chapter explains the background of the thesis, the company and the product. It highlights the problem to be solved and defines the project goals, deliverables, and delimitations.

1.1 Background

The definition for the word ‘fasten’ is "to (cause something to) become firmly fixed together, or in position, or closed" (Cambridge, 2020). Although the word came in much later, the latent need for fastening, fixing or joining things together would have existed since the very existence of early humans (Figure 1). They were quite adept at utilizing products in nature, sticky substances such as pitches from trees to be used for adhesion, plant fibres to make ropes for tying, and sharp pin-like thorns to be used as fasteners. These products facilitated them to make valuable articles such as tools, clothes, bags and artisanal objects.

(a) A brooch from the British museum (in This Dress, 2014)

(b) Buckles from the 9th century (Flynn, 2016)

(c) Copper-allow dress hooks (Culture, 2020)

(d) Silver hook fastener from early medieval saxon period (Boutique, 2020)

Figure 1: Cloth fasteners used in the medieval period

Today there is a plethora of fasteners for various applications. For fastening in machines, the most common fasteners used are different types of nuts, bolts and rivets. For fastening clothes together, and other objects to clothes or any fabric, the most common products in the market today are buttons, pins, hooks, buckles, straps, magnets, Velcro® (Hook and loop system) and different combinations of these (Figure 2).

Company-X *(fictional name for confidentiality)* has developed a novel fastening solution, called the ‘Spindel-tech Attachment System’*(fictional name for confidentiality).* Spindel-

(a) Buckled straps (“Lätt Benfäste - 10”, 2021)

(b) Fastclips for MOLLE (“Fastclips 60mm”, 2021)

(c) Side-lock carabiner (“Sidelock carabiner”, 2020)

(d) Safety pin

(e) Magnetic button

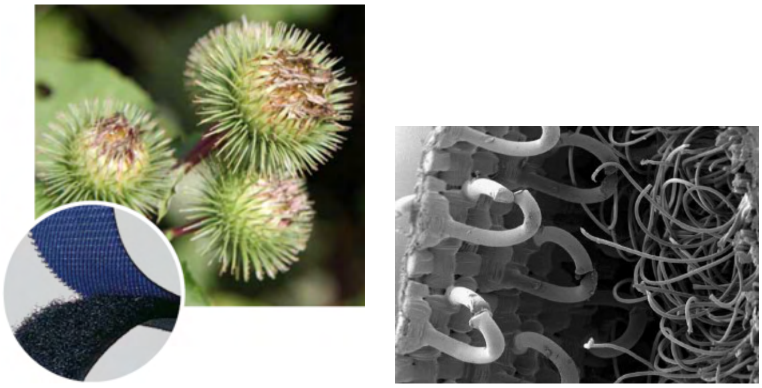
Figure 2: Modern multi-purpose fasteners

tech is a mechanical device that allows to temporarily fasten objects to clothing or any fabric. It is patented technology (Patent, 2020)*(Citation withheld due to confidentiality)*. It can be used to hold hand-held devices such as mobile phone, cardholder, wallet, activity trackers, watches, and flashlights, onto a fabric. It can be quickly attached to and later removed from the fabric using a piercing metallic wire, which is mechanically controlled. The functional mechanics of this device can be closely associated with a safety pin. It can also be visualised as a sewed thread in a fabric, where the needle itself acts as a thread. The advantage is that it can be un-sewed or detached when desired. The device is modular in nature which makes it scalable. Objects can be held on it using an external fixture or casing, fulfilling its primary function.

1.2 Fastening systems to attach objects on workwear

The common fasteners used to fasten or hold objects to the fabric are Velcro® or stitched fabric loops. Velcro® is a hook and loop system type fastener that was inspired from the *burdock* plants (Figure 3a). In 1941, a Swiss engineer de Mestral was intrigued by the burrs of the plant that kept sticking to his dog’s fur and his coat, which lead to the invention (“About the VELCRO® Brand: Velcro Companies”, 2021). Velcro® mechanics (Figure 3b) have also been observed in wood and is expected to play a fundamental role in various other hooked systems in nature, e.g., in the grip of evarcha arcuata spiders.

Stitched loops on fabric are seen in multiple forms. A robust version of this is the MOLLE (Modular Lightweight Load-carrying Equipment) (Figure 4), which is used by the armed forces, security and police personnel. There are other similar stitched loop systems used on the police duty belts and outdoor gear.



(a) Burdock seeds and a Velcro® strip

(b) Microscopic view of the Velcro® mechanics

Figure 3: Velcro® hook and loop system(“Velcro brand Woven fasteners”, 2010)

(a) An equipment vest with a MOLLE system

(b) Equipment vest in use

Figure 4: MOLLE system on a vest (“Equipment MOLLE vest”, 2020)

However, a pre-usage assembly or installation is required for these fastener to be usable. The loops need to be stitched onto the fabric, on which pouches or accessories can be attached. Velcro® needs to be stitched or bonded onto the surfaces that are to be fastened.

The fastening device by Company-X, the ‘Spindel-tech’ has leverage in this aspect. It removes the pre-usage assembly of attaching it to the fabric before being usable. Instead, it can be directly fastened to a fabric surface while holding the object with it, and removed quickly when desired. It also allows freedom of placement anywhere on the fabric. For example, a handheld music player attached to the tshirt using Spindel-tech system, as shown in Figure 5.

Figure 5: Spindel-tech attachment system (Company-X, 2021)

1.3 Spindel-tech Attachment system

The ‘Spindel-tech’ uses multiple metal wires to attach to the fabric. The metal wires make two penetrations, in and out of the fabric. For removing the device from the fabric, the wires are actuated in the reverse motion.
The device consists of three main subsystems (Figure 6):

- **The actuating system** which is actuated manually by the user when the device is to be used.
- **The module (attachment system)**, which transmits the motion and drives the metal wire along a trajectory, to cause the attachment by piercing the fabric
- **The casing (structural support)** which holds the actuating system and the modules (attachment system) together in place

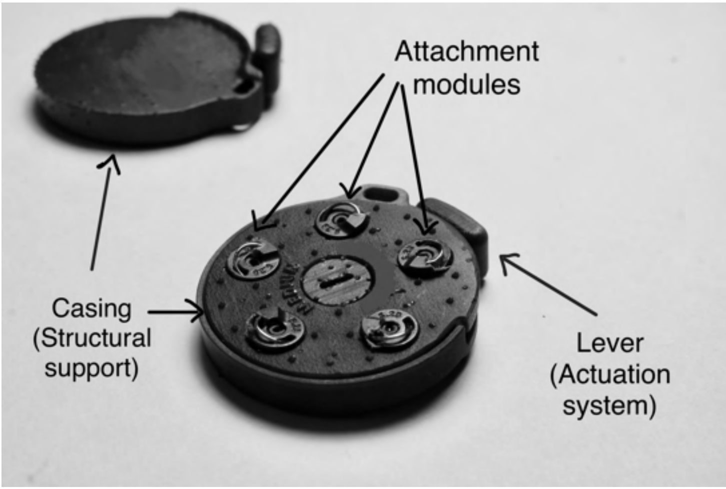
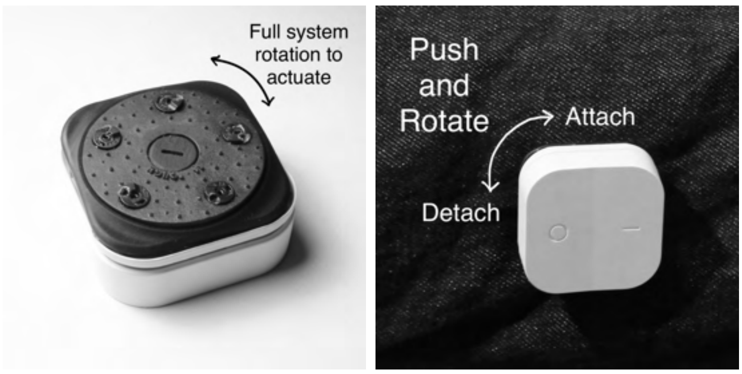


Figure 6: Spindel-tech with a lever actuation

The Spindel-tech typically has four or more modules that cause the attachment. Being a modular design, the number of modules can be increased according to the application. Diameter is another variable parameter to enable customisation. It can be actuated using a lever, or customised to be actuated by rotating the whole structure holding an object with it (See Figure 7)



(a) Spindel-Tech attached to IOT device

(b) Rotate to actuate mechanism

Figure 7: Spindel-tech used to attach an IoT product to fabric

1.4 Product Opportunity

The company has investigated a possible application of Spindel-tech for a potential user group, the first responders. These are the fire-fighters, police personnel, security guards and ambulance personnel or paramedics. First responders carry multiple objects and equipment that should be handy as well as firmly in place (Figure 8). All the equipment should be handy in an emergency, allowing quick removal and placing back with a firm and secure placement.

Figure 8: A police personnel carrying multiple equipment (“Comfort belt-13”, 2021)

Currently, MOLLE (Modular Lightweight Load-carrying Equipment) is used in various forms, like holding objects directly with straps or by attaching removable pockets that hold the items. Personal also wear bulky vests and jackets with pockets and straps to attach their equipment with carabiners and stretchable strings. According to Larsen (2018), a study on factors related to musculo-skeletal disorders in Swedish police, lower back pain is most frequently reported issue. Larsen (2018) also specifies that police duty belts, in combination with the nature of their jobs of sitting in a vehicle or walking and running, were found to have the greatest association to the pain.

Attaching items on the MOLLE is time-consuming and cumbersome. So they must keep these things attached at all times to the vests to minimise the time for reaction during emergencies. The Swedish Police Authority issued a request for information regarding an improved equipment attachment technology for police personnel (RFI, 2020)*(Citation withheld)*. They require a durable, fabric independent solution that keeps items safely attached while providing flexibility in the attachment position. Similar to police personnel, other first responders, security guards and firefighters, also carry multiple types of equipment on their body during work and have a similar need.

1.5 Problem Statement

1.5.1 Purpose

For the first responders, there are five basic requirements for a fastening system.

- Carry the weight of the hand-held object and stand strong forces when attached
- Secure and firm attachment
- Minimum damage to the fabric
- Quickness and ease of removal and placement

- Flexibility in position

The Spindel-tech needs to embody all these requirements and their combination. The Spindel-tech is limited in its strength and force carrying capacity. This limitation makes it inapplicable to some potential applications. Hence, expanding the capacity would expand the device's applicability and, therefore, its market. In other words, for this new way of attachment to succeed in the market, it needs to deliver a similar or better usability as of the existing systems like Velcro® (hook and loop), button, pins, hooks, or clips, and an added benefit of flexibility. The purpose of the study is to improve the Spindel-tech system with focus on force carrying capacity.

1.5.2 Goals

- Define performance of the Spindel-tech based on identified performance parameters
- Identify potential issues and improvement areas in Spindel-tech
- Increase the force carrying capacity of the system
- Increase other performance parameters of the system including usability

1.5.3 Deliverables

- Testing procedures to measure the performance parameters of the system
- Test results and analysis of current design based on performance evaluation
- Requirements list for development
- Details of proposed design changes and its expected performance
- Proof of concept of an improved design
- System performance prediction model, verified by experimental results

1.6 Delimitation

- Market research and business potential analysis will not be performed. Information regarding the same in the development process will be taken from Company-X when required
- The development will not be exploring usability of the device with all types of fabrics. The focus would be placed on tough fabrics of workwear (ones commonly used by first responders)
- Design for manufacturability and assembly would be considered during development, but the optimisation of final design for manufacturing will not be performed
- Effects of probabilistic variation on the performance of the system will not be studied

1.7 Report Outline

The report is divided into ten chapters and Appendices. The chapters in a chronological order are - Methodology, Technology investigation, User Study, Performance investigation, Concept development, Detailed design, Evaluation, Discussion, and Conclusions and Recommendations. Nomenclature table of variables and common terminology is included before index.

The *Methodology* chapter (2) describes the process flow and the methods used to fulfil objectives from each phase of the project.

A detailed *investigation of the 'Spindel-tech' technology* is presented in chapter 3. The chapter presents in-depth theoretical analysis of the technology. Design analysis, functional analysis, force-flow analysis are carried out along with derivation of technical models between various parameters.

The *User study* chapter (4) presents the study of first responders in order to understand the gear and equipment they use, their needs and relevant usage scenarios.

The *Performance investigation* documents experimental investigation of the product. Chapter 5 starts with defining the parameters based on which the performance is to be analysed, followed by three main types of experimental testing. The results are evaluated to derive a problem-cause map. It concludes with target requirements for development of improved design.

The target requirements and learning points from the previous chapter set a base for generating new concept ideas for an improved design. The process of concept generation, evaluation, and elimination is described in the *Concept development* chapter (6). This chapter concludes with the final concept after thorough evaluation, prototyping and elimination.

The Proposed concept is detailed out, assessed and described in the following *Detailed design* chapter (7).

The *Evaluation* chapter (8) evaluates the proposed concept for fulfilment of target requirements and compares it to the existing design. An external product comparison is presented with two external products that are widely used in the market for a similar purpose.

The *Discussion* chapter (9) reflects on the process of the study, discusses sources of error, and an outlook on the ethical, societal and environmental considerations in development. It also discusses scope for further design improvement in the design.

The final chapter, *Conclusions and Recommendations* (10), makes conclusive remarks.

The *Appendices* include additional tables, charts and figures that are referred to in the report. There are two chapters in the appendices - the first is for the experimental results, and the second is for the concept development and evaluation. Appendix A consists of a graph and data tables from the strength testing of the performance investigation phase. Appendix B consists of the morphological matrix used in the concept generation phase, material charts used in the material exploration before the final concept selection, and a pair-wise comparison matrix of criteria used in the Kesselring matrix for decision-making.

2
Methodology

This chapter explains the work process of the thesis. It describes the phases of work, their objectives, and the methodology followed in each.

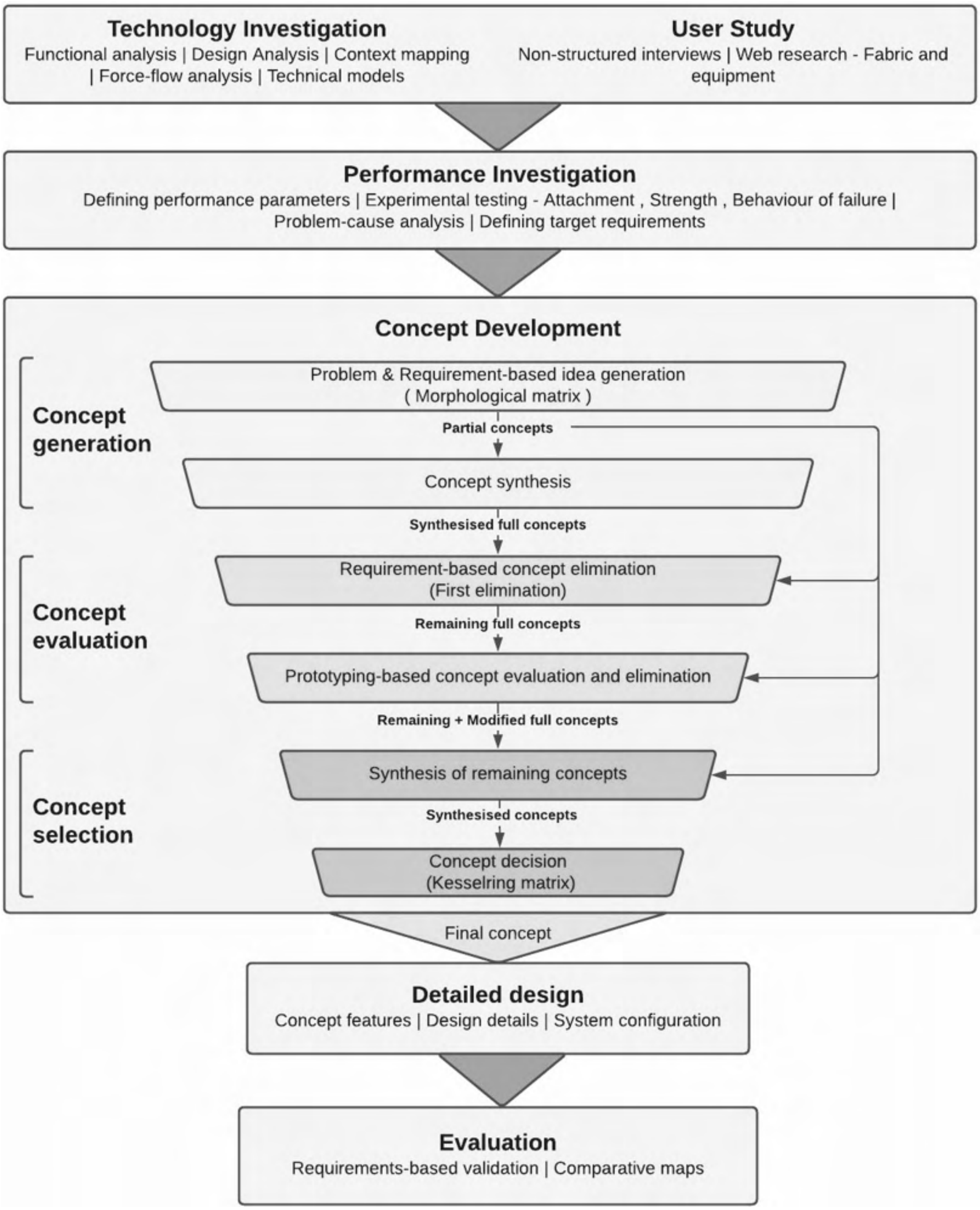


Figure 9: Project process flow

Overall methodology

Given the nature of the project, an experiment driven and lean development process was followed. Both theoretical analysis, and experimental learning is utilised as ready tools throughout the development process. Figure 9 visualises the process flow of development process.

Each phase has defined objectives to achieve the overall project goals cumulatively. The methodology followed to fulfil the objectives of each phase is explained in the following description. The phases are linearly structured, but in real nature, some are carried out concurrently and iteratively. For example, technical models were updated to predict performance specific to some new adaptation during the concept selection phase. However, the linear representation captures the essence of the development process in a structured and comprehensive way. The following subsections explain each phase and methodology used.

Technology Investigation

The technology investigation is embodied in the first phase of the project. The objective of investigation is to -

- Understand what does the device do, (the device's functions)
- Understand how does it perform these functions

To fulfil the first objective, a functional analysis of the system is done utilising black box representation and the process-flow of attachment and detachment processes. The functional analysis yields sub-system structure, which is utilised for design analysis. Design analysis thoroughly examines functionality of each component and seeks answer to how do they work together. In order to fulfil the second objective, design analysis is accompanied by context map, that explores all the other factors effecting the function of the device. Force-flow analysis deepens the understanding of 'how' to specifically create knowledge about strength, one of the goals of development. As a conclusion to technical investigation, technical models are created to predict behaviour of the system, performance of system and inter parameter relations. The technical model, along side force-flow model, theoretically captures the functioning, which supports further development process.

User study

The user study is conducted concurrently along with the technology investigation during the first phase of the project. The objectives of the study are to -

- Understand the latent needs of the first responders in attaching their equipment to their gear
- Identify types of fabrics the device need to be compatible with to hold their equipment
- Understand usage scenarios the device will be used in

A set of non-structured interviews are conducted with the users of user groups. The user interactions were conducted in the first responder's work environment, helping with observations. Observations and inputs from these are used to fulfil the first and third objective. In order to fulfil the second objective, the user observations are combined with secondary research on different fabrics used in users' workwear.

Performance Investigation

The performance investigation is the second phase of the project. and fulfils two main objectives -

- Analyse how well does the device functions and how does it fail
- Identify problems, related causes, and potential improvement areas

This phase follows an experiment driven investigation process. Defining the performance parameters to be analysed is the first step. These are based on the technical investigation of the device and the user needs. Then to analyse the performance of device, experimental testing is done on its two main functions - attachment and strength (force carrying capacity). To analyse the behaviour of device at failure, a failure testing is done in more realistic scenarios. The second objective is fulfilled by doing a problem-cause analysis based on the results from experiments. This gives a set of considerations and problem areas of the device to focus on during the concept development phase. Lastly, a target requirement list is made to guide the development of an improved concept.

Concept Development

Concept development is the third main phase and fulfils the core objective of developing a concept based on the target requirements.

The work is structured in three sub-phases. The concept generation phase is a diverging phase, while evaluation and selection are primarily converging phases with intermittent divergence. A set-based approach is followed, as multiple solutions are pursued until late in development and combined or rejected along the process.

Concept generation

Idea generation is done through various brainstorming sessions. Different methods like Scamper and excitation points like everyday objects around and in nature are utilised to facilitate brainstorming. The ideation process is done using two approaches - a bottom-up approach (functionality focused) and a top-down approach (problem-solving focused). The bottom-up approach is used to ideate all possible solutions different from the existing design focused on fulfilling the primary function of attaching to fabric. The top-down approach is used to solve issues in the current design by finding adaptations or alternatives to its sub-systems. A function-based morphological matrix is utilised to structure the generated ideas and then synthesise them into concepts. Adaptive or existing system related ideas were kept as partial concepts to be used with the current system.

Concept evaluation

First evaluation of the partial concepts and synthesised concepts is done based on criteria from requirements list, by creating elimination matrix. The concepts which fail to fulfil the demands are eliminated. The second evaluation is prototyping and testing based. The intent is to analyse the knowledge gaps of the partial and full concepts by quick prototyping and testing. This is done by making 3D-printed and hand-crafted prototypes. The process would allow for high number of partial solutions and create an evidence-based rejection.

Concept selection

The remaining partial and full concepts are then synthesised based on the essential criteria from the requirements list, that reflect wishes as well as demands for the improved design. To select the best of these synthesised concepts, they are evaluated using a Kesselring matrix. The criteria selected for the Kesselring matrix reflect the wishes from the target requirements list, and they are weighted using a pair-wise comparison matrix.

Detailed design

The detailed design is the fourth phase of the project, and fulfils the following objectives, to -

- Detail out the remaining concepts to create a proposed design
- Consider various aspects like manufacturing and assembly feasibility, modularity, scalability, and user-friendliness

Partial prototypes, sketches and virtual prototypes using CAD are utilized for the detailed development of the concept. Visual and predictive analysis of multiple variations of the chosen concept considers different aspects, like feasibility for manufacturing and assembly. System configuration is used to define and showcase modularity and to adapt to various hand-held objects and associated requirements. The rules of configuration and pros-cons are also defined to create a complete guideline. This phase concludes with the configurable proposed design.

Evaluation

This is the final phase of the project, which aims to -

- Verify fulfilment of requirements by the proposed design
- Compare the proposed design with the existing design
- Evaluate performance of the concept with external benchmarks that perform a similar function

The first two objectives are fulfilled by validating the performance values of the proposed design with target values of the criteria in requirements list. The third objective is fulfilled by comparing the proposed design, existing design, and other removable fastening products in the market using comparative maps. This comparison is primarily based on essential strength parameters and a brief discussion about where the chosen concept stands among the products, on other criteria.

3

Technology investigation

This chapter answers the following two questions: What does the technology do? How does the technology work? These questions investigate the functionality and working mechanism of the current technology, the Spindel-tech. This investigation establishes an understanding of various parameters of the technology for further design analysis.

3.1 Functional Analysis

The primary function of the Spindel-tech is to attach an object to the fabric removably. The device works such that it is fixed or assembled on to an object, and then attaches to the fabric using wire loops. It utilises the user-provided signal, energy, and haptic control, as shown in the Black-box representation in Figure 10. In other words, it acts as a connection point or attachment interface between the fabric and the object. The process is reversible, representing the removable nature of the attachment.

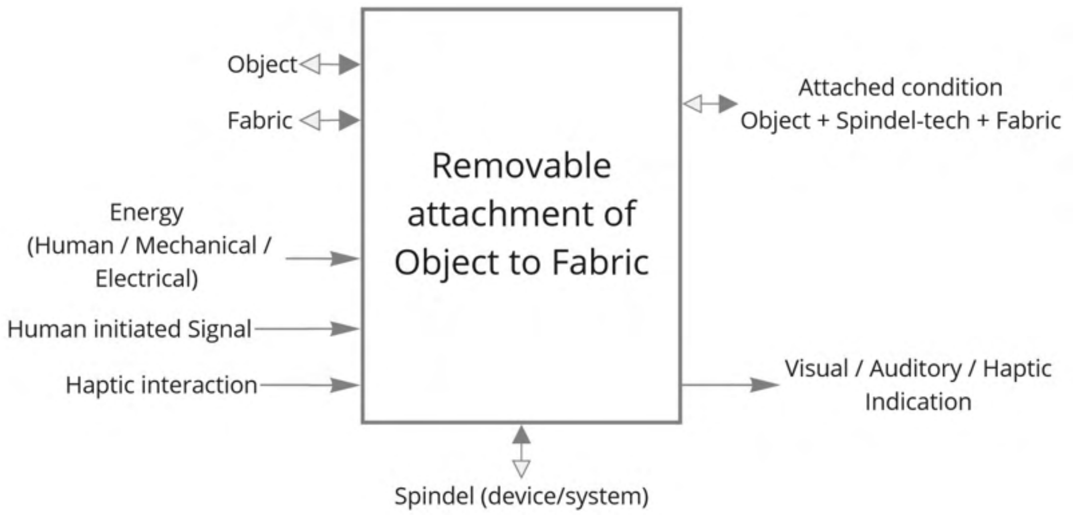


Figure 10: Black box representation

For a user, the following would be the attachment and detachment process.
1. Bring Device near to the fabric surface and flush
2. Actuate system to attach
3. Ensure that attachment is secure
4. Actuate system to detach
5. Ensure safe detachment

Figure 11 visualises these steps. Actuation is a one-step process in both attachment and detachment. This user interaction transfers both energy required for the actuation and the signal to trigger the actuation to the system. However, actuation energy can also be non-human from the internal electrical or mechanical system, depending on the design. Currently, all systems utilize the human energy provided by the user. Haptic interactions are vital for steps 1, 3, and 5. The user would understand the condition and status of the system by haptic gestures supported by visual and auditory senses.

(a) Flushing device to Fabric Surface (Step 1)

(b) Actuating system to attach/detach (Step 2/ 4)

(c) Ensuring if it is attached (Step 3)

(d) Attached state

Figure 11: User interaction steps

Figure 12 and Figure 13 show the internal process flow model of attachment and detachment process, respectively. A block represents a function, which is performed or facilitated by the device. Each function converts inputs (or initial condition) on the left into outputs (or resulting condition) on the right of the block.

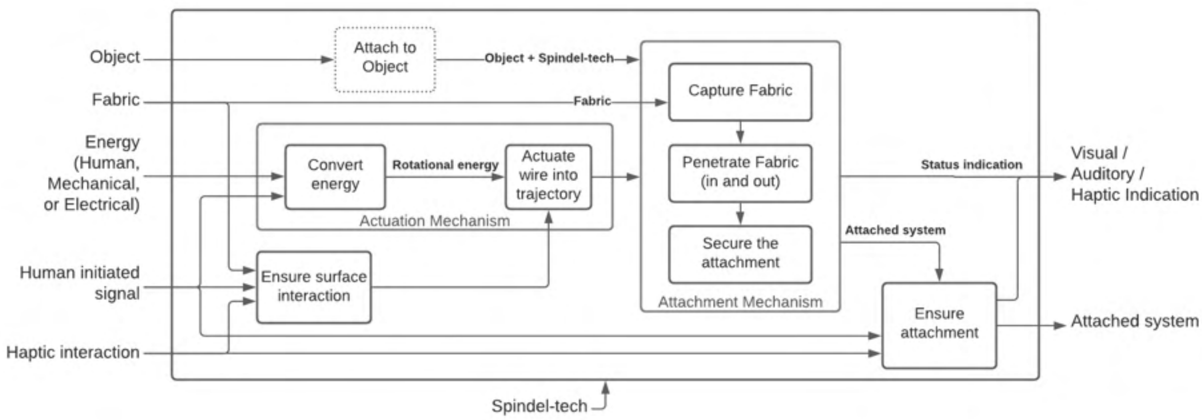


Figure 12: Attachment process of Spindel-tech

The system facilitates user functions (steps 1, 3, and 5). Hence, these are reflected in the Process flow diagrams, alongside the internal functions of the system (see Figures 12 and 13). Internal functioning is divided in three sub-systems; **Actuation mechanism, Structural support, and Attachment mechanism**.

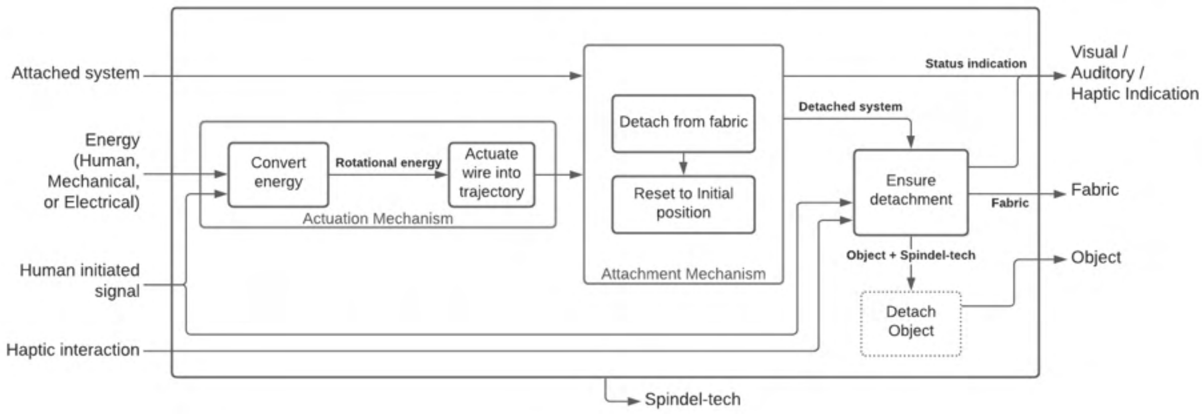


Figure 13: Detachment process of Spindel-tech

The actuation mechanism primarily provides energy in the form of the required motion to the attachment mechanism. It is also the only sub-system with which users would interact; hence it is crucial for user experience.

The structural support sub-system enables the other two sub-systems by providing physical structure and safeguarding them against external forces. ‘Attach to object,’ mainly physical, is a part of the structural support sub-system. ‘Attach to object’ is an optional function that is carried out before or after attachment to the fabric. This design decision depends on the size and shape of the object and the use case. In many cases, the system is semi-permanently attached to the object, where it is not to be detached in regular use.

The attachment mechanism realises the primary function of the Spindel-tech, i.e., ‘removable attachment.’ The primary function is facilitated by three sub-functions; fabric capture, fabric penetration, and securing the attachment. In Spindel-tech, capture and penetration are done chronologically by the wire in the same smooth motion. The sharp tip of the wire would capture some threads of the fabric and, on further movement, penetrate the fabric. The wire penetrates the fabric twice to come out of the fabric and enters a cave-like structure in the system to secure the attachment. Securing attachment has two implications. It increases the strength of the attachment, and second, it increases safety by covering the sharp end of the wire. Attached condition of modules without fabric is shown in Figure 14b. To detach, the mechanism retracts the wire fully into the system, resetting to the ‘resting state’, as shown in Figure 14a. The attachment mechanism is a modular sub-system where each module has an attaching wire. More number of modules results in more attachment points. Each module is provided with energy and motion by the actuation mechanism.

3.2 Design Analysis

3.2.1 System design and configuration

The design of Spindel-tech device can be viewed from the perspective of the sub-systems. The attachment modules are the core of Spindel-tech technology, enabling the primary function. The module design remains the same in the various application except for

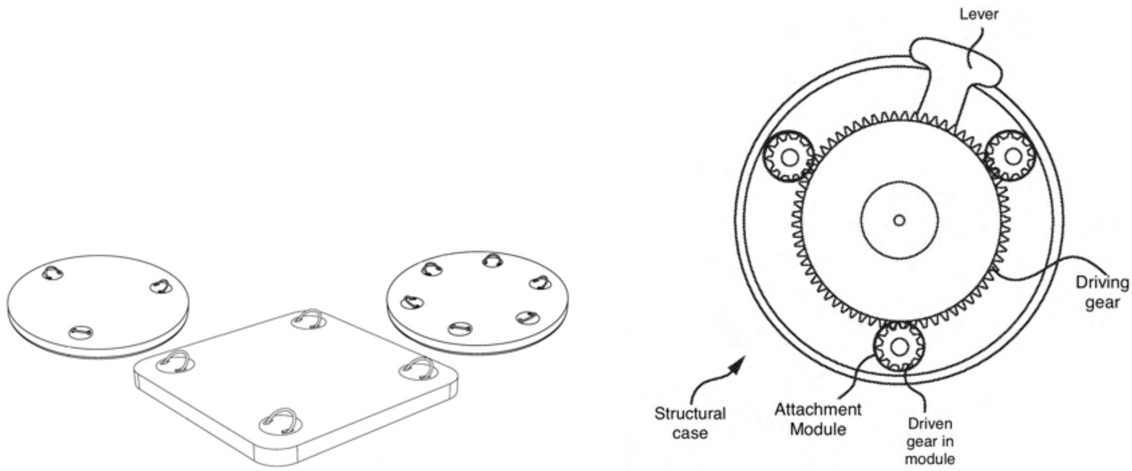
(a) Resting condition - Open loop condition

(b) Attached condition - Closed loop condition (without fabric)

Figure 14: Lever actuated 5 modules circular system

defined variation. On the other hand, the actuation and structural sub-systems adapt according to the module placement, the object to be attached, and the type of actuation input. The number of modules present in the system and their arrangement will affect how much force the system can withstand without breaking.

The form, number of modules, module placement, and actuation styles are the main variables for the system configuration (see Figure 15a). A circular form with five modules and lever based actuation is a possible system configuration, see Figure 14. This configuration is used as a reference and representative of the technology.

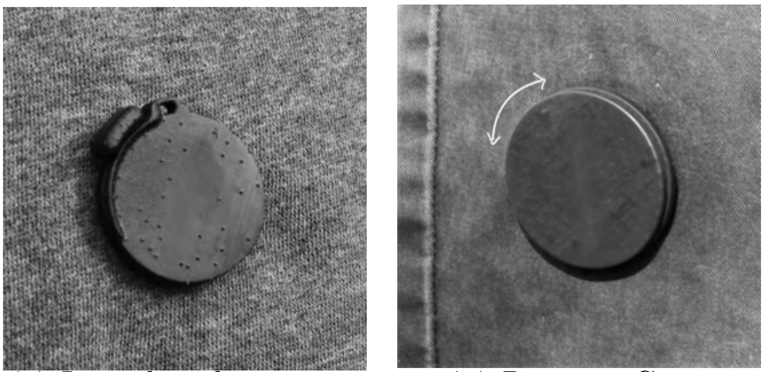


(a) Various system configurations

(b) Visualisation of internal mechanism

Figure 15: System configuration (adapted from patent (Patent,2020))

There are two types of actuation mechanism in use, lever-actuated and rotating cover (see Figure 16). In either case, the driving gear drives gears in each module of the system (see Figure 15b). In the attachment process, the driving gear has to rotate certain degrees to do the sufficient rotation of the wire. In detachment, it rotates the same amount in the opposite direction. The mechanism to rotate the driving gear varies. In lever-actuated, a lever is connected to driving gear directly, while in rotating cover, the object side cover is attached to the gear. However, other actuation mechanisms can be used, like rack & pinion, electronic motor-driven, or pulley-based systems. (Patent, 2020)

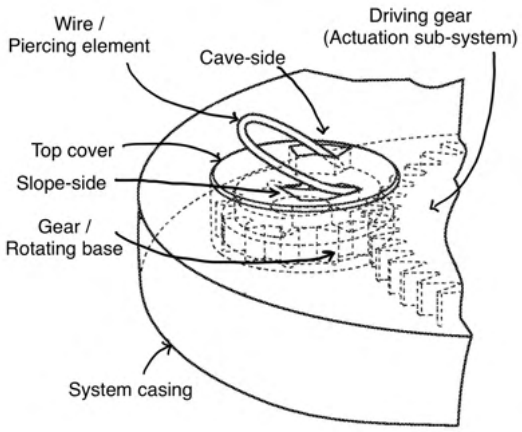


(a) Lever-based actuation **(b)** Rotating Cover actuation

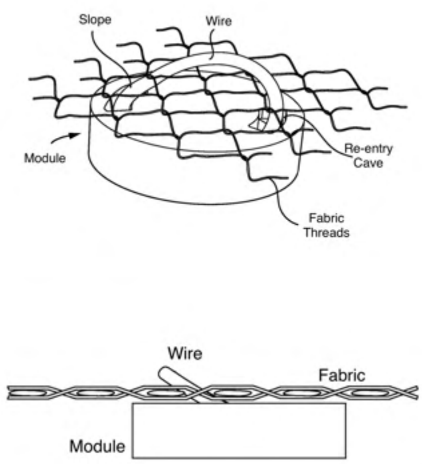
Figure 16: Systems with different actuation mechanism

3.2.2 Module design

As the patent (Patent, 2020) describes, each module has three components, a rotating base, a piercing element (the wire), and the top cover. The piercing element, the wire, pieces the fabric twice, going in and out, and attaches the module to the fabric. The rotating base provides the piercing element rotational movement, while the top cover guides the wire into its trajectory. The rotating base is often a gear that is driven by the system-level actuation sub-system mentioned above. However, there are other types of rotating bases as well, for example, screw-driver driven.



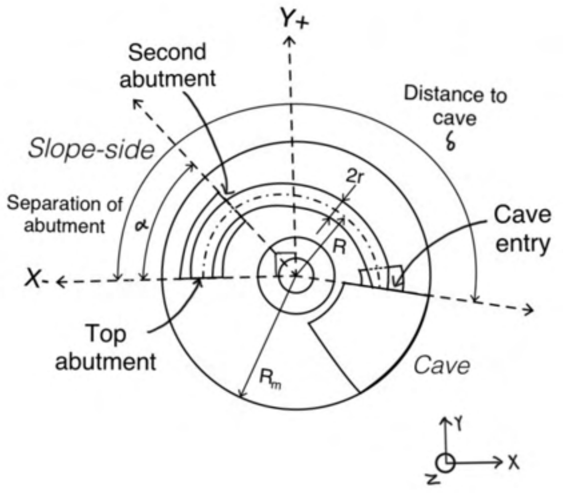
(a) A module as part of the system (without fabric)



(c) Side view with fabric)

Figure 17: Visualisations of a module in closed-loop state [adapted from patent (Patent, 2020)]

The wire is a circularly bent Stainless steel (AISI 304) circular cross-section wire. One end of the 270 degrees arc is a pointed tip, while another end is connected to the rotating base (see Figure 17a). The piercing element has the same central axis as the rotation axis of the base. In order to approach the fabric, the wire's trajectory is changed by tilting its rotation axis while in motion. The top cover facilitates the bending of the wire to achieve the tilt. Wire bending consists of two bending types: spring-like bending and another is 3-point bending. The circular shape of the wire enables spring-like bending. Two abutments, the top and the second abutment, and the contact point on the rotating base create the arrangement for the three-point bending.



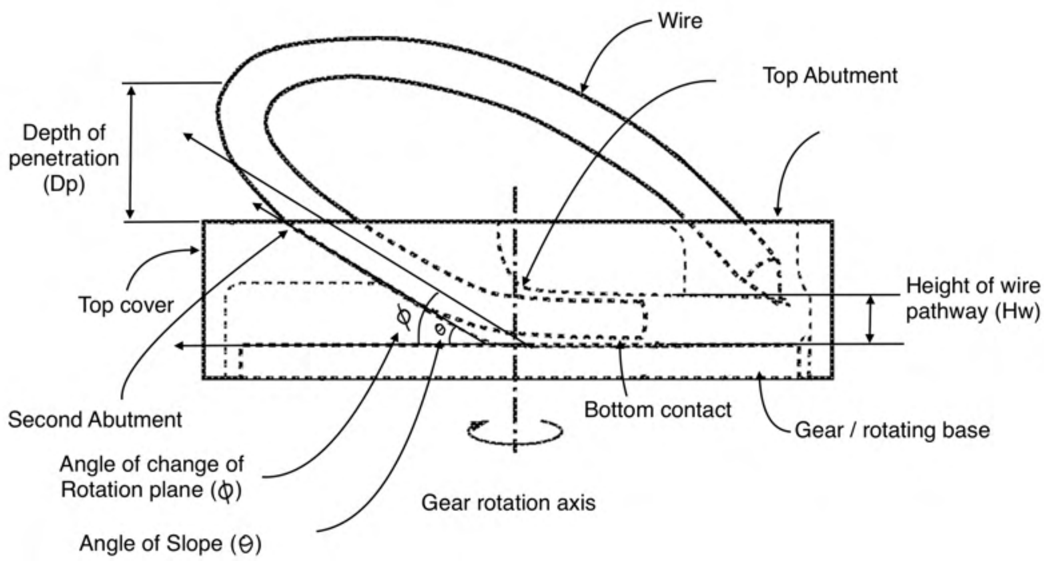
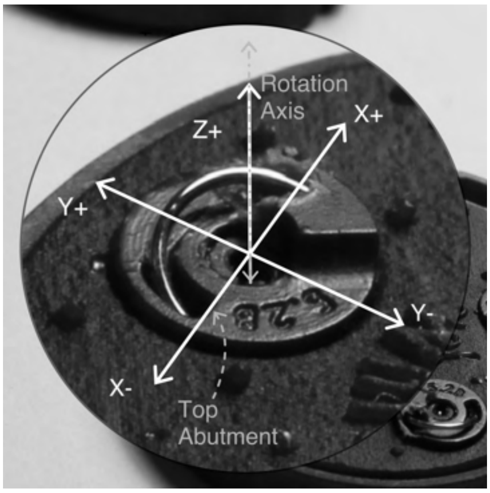
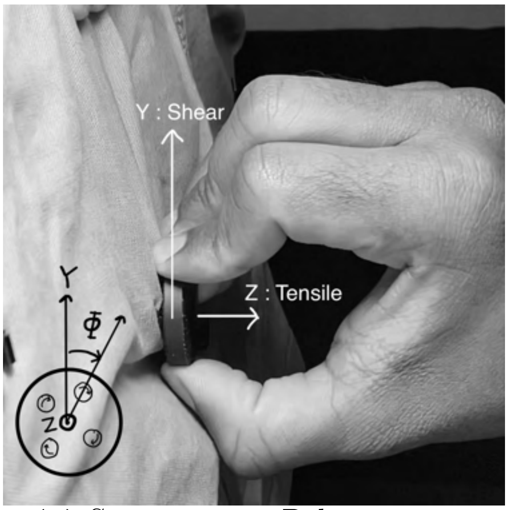


Figure 19: side view of a module in a attached condition

The bending allows the wire to approach the fabric with some penetration angle. The penetration angle (β_1)is dependent on the separation between abutments (α), wire thickness ($2r_w$), height of wire pathway H_w and the radius of the wire R_w (See Figure 18 and 19). Between two abutments on the modules, the diagonal plane, where the wire comes out, is referred to as 'slope'. The wire would be in rotational motion while being bent in the process of attachment. As shown in Figure 17, the wire bends at the slope, and travels in a tilted, almost circular trajectory and re-enters into the top cover. The wire penetrates the fabric once out along the slope. Due to the circular shape and motion, the wire again penetrates the fabric in the opposite direction, eventually entering the top cover. This re-entry structure in the top cover is referred to as a 'cave'. The cave helps safeguard the tip of the wire (Figure 14) and enhance strength. The top cover's and rotating base's material is Polyoxymethylene (known as POM and acetal), a thermoplastic. Axis system used in the study is presented in Figure 20.



(a) Module's local axis system



(b) System axis - Polar system

Figure 20: Axis system for module and System

3.2.3 Variants

Module variants

In order to attach to varied thickness of fabrics, the modules have three variants; A, B, and C (See Figure 21). A is for applications with thin fabrics, and C is for the thick and tough fabrics, while B is positioned between A and C. The first angle of penetration (β_1) and depth of penetration (D_p) increases from A to C. The higher the angle of penetration, the easier it is to penetrate with less force. Moreover, the higher the depth of attachment, the more fabric is captured. Manipulation of the angle of change in the rotation axis (γ) changes D_p and β_1, increasing with increment γ. Table 1 defines each variant using design parameters.

Figure 21: Module variants (Left to right - A, B, C)

Table 1: Variants - Design parameters

Parameter	A		B		C
Slope angle θ	30°	$<$	45°	$<$	50°
Slope opening α	25°	$>$	15°	$>$	5°
Distance to Cave δ	155-165°	$<$	175°	$=$	175°
Height of wire pathway H_w		$=$		$=$	
Depth of Attachment D_p		$<$		$<$	
Angle of penetration β_1		$<$		$<$	
Wire bending (ϕ)		$<$		$<$	

System variant

As described in the subsection 3.2.1, the full system is configurable with multiple variations. System configuration are named as follows

$$< \#modules >< Variant >< Wire\ thickness >< Actuation >< Other\ variations >$$

Table 2 tabulates configuration options and few examples. The configuration naming system is used further in the work. B variant, 0.4mm wire and Lever are the most common and hence used as default. So, 5mB4tLstd and 4mB4ttwisted would be referred to as 5mStd and 4mTwisted respectively. The twisted module variant features different module position where the slope side is radially outwards such that X- direction is radial (see Figure 22). This is in contrast with the standard variant where the Y+ direction is radial. Module's axis system is visualised in Figure 20a.

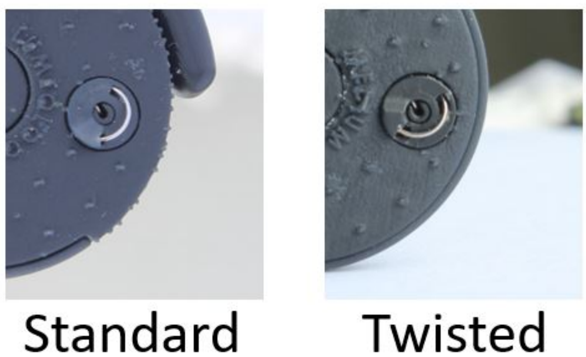


Figure 22: Twisted module orientation compared with standard orientation

Table 2: System Configuration

Name	#modules	Variant	Wire thickness	Actuation	Other variations
-	Number	A	4t=0.4mm	L:Lever-based	Standard
-		B	5t=0.5mm	R:Rotating-cover	Twisted modules
-		C	6t, 7t, ...	Other	Similar descriptions
5mB4tLstd	5	B	0.4mm	Lever-based	Standard
4mC5tRtwisted	4	C	0.5mm	Rotating-cover	Twisted module

3.3 Context mapping

A product functions in a complex environment interacting with numerous external factors. These may affect the systems' functioning, while the system affecting some factors in return. These interactions of a product are captured by a Context map presented in the Figure 23. The parameters on the left side of the figure primarily affect the functionality. They create a context (a working environment) in which the product would function. The parameters on the right-hand side of the map are affected by the function or are the function's result. These are to be considered when designing for the function. Together both types of factors create constrain on the product function. Left-side factors create constraints on which product should work in or work with, while the right-hand side parameter creates constraints on the product's impact, both desirable and unintentional.

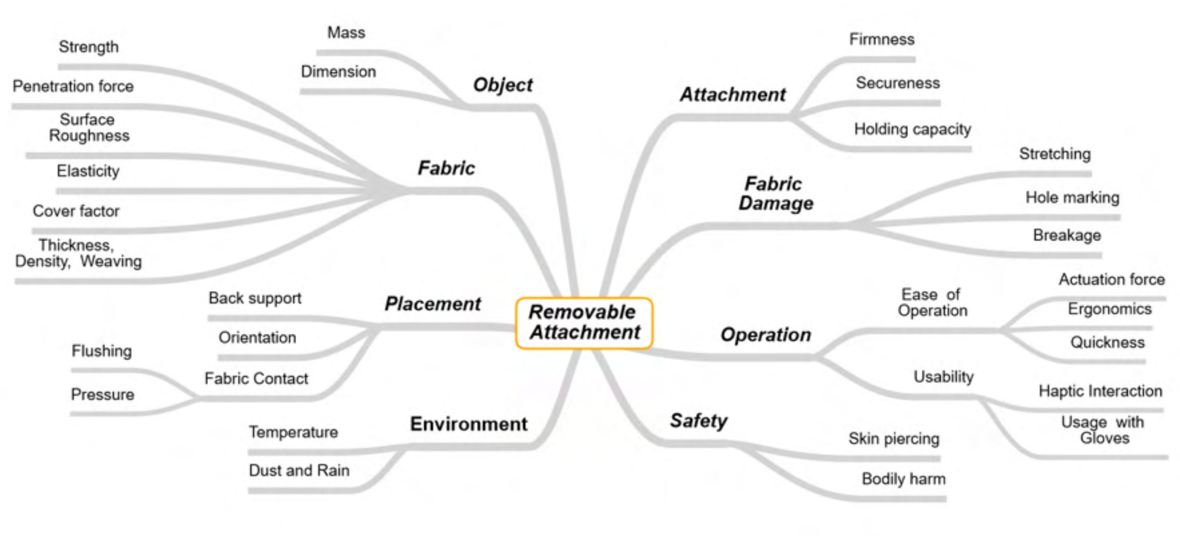


Figure 23: Context map - What parameters affect the function and what aspects are affected

Influencing factors

Object

As operand, the object and fabric are two of the crucial factors. The object's shape constraints how it can be attached to the system and how much area is available for attachment with fabric. It also has considerations for ergonomic design for holding and actuation. The mass and mass distribution of the object directly links to the resting force on the system. The mass also puts a higher requirement on strength in other conditions, like oscillation forces when running. Though object parameters are non-controllable, it is possible to optimise other design parameters to meet the constraints posed by the object.

Fabric

The target operand, fabric, has the most critical effect. Unlike the object, having a less compatible or incompatible fabric can directly result in no attachment, leaving no room to improve using other factors like flushing or pressure. Also, the fabric is a non-controllable factor. Once a user tries to use the system with some fabric, the system will either fail or function, with very little room for influence with other parameters like pressure. For better usability, technology sought broad fabric compatibility. A fraction of fabrics can be selected using parametric screening based on suitability with technology. Another approach would be to study likely fabrics for the target user group and adapt the system for those fabrics. As chapter 4 describes, the second approach is taken for the current study as the target user is defined, and the fabric compatibility study is out of scope. Nevertheless, a basic understanding of fabric is required.

Surface roughness, strength, fabric penetration force, pores (size and amount) and tightness, and the fabric's elasticity are the relevant parameters for technical functioning. These relate to the fabric design parameters, like yarn material, cover factor, weaving pattern, fabric thickness, thread count, density, elasticity, and yarn strength. (The cover factor is the fraction of the area of the fabric covered by its threads; it captures the pores between threads and the tightness of weaving (Galuszynski, 1987).

For initial fabric capture, high surface roughness helps the wire to capture. Loose fibres on the surface also contribute to better fabric capture. Thread type, thread count, fabric thickness and cover factor, among others, affect the surface roughness of the fabric (Akgun, 2014). Various coatings on the fabric surface, like water-resistant and oil-repellant, alter the surface roughness (Wan and Stylios, 2017).

The strength of the fabric can be a weak point in the force flow from the object to the fabric (described in Section 3.4). Both tensile and tear strength indicates the strength concerning attachment by wire.

Penetration force and elasticity directly affect the wire actuation force. If highly elastic, the fabric would stretch and move. This behaviour would make it difficult to penetrate the fabric, as fabric would move with wire and potentially reduce the amount of fabric captured.

Environment

The external environmental factors are another non-controllable factors. These are considered as requirements, especially for material selection.

Back support

The placement of the device on the fabric has four factors that would affect the attachment. The back support is the support behind the fabric. When attaching the device to a shirt, the body acts as back support. If it is on the jacket, the support would be softer and different from the bodily support. If the system were to attach to a hanging cloth, like a curtain, there is no back support.

Flushing

Flushing is achieved when the fabric and attachment surface of the system is in narrow proximity, preferably touching. If the fabric is far from the system, the wire will fail to capture the fabric. Moreover, the wire's depth of penetration is defined, so the farther the fabric, the less amount of fabric will be captured, if at all it captures. Good Flushing would result in better penetration and more fabric being captured. A higher amount of fabric capture would distribute force, reducing stress concentration in fabric. It would differ due to the type of back support.

Pressure

Flushing can be achieved with some mechanism inside the system or by adding pressure at the attachment points. Pressure is typically added by pressing the system against the back support. However, pressure may have adverse effects. It can create concave curvature in back support and hence the fabric, affecting the flushing. High pressure may also affect the trajectory of the wire and can restrict the motion of the fabric. The user applies pressure. Hence, the application can vary based on the situation, even by a single user. Ergonomic considerations would dictate pressure level, the way of application. If the functionality is sensitive to pressure variation, it will reduce usability. The back support, flushing and pressure together control the performance of the system.

Affected factors

Four aspects relate to the function during or after it is performed. These define the context of the outcome.

Safety

Usage of pointed metallic wire poses a risk of skin piercing. Avoidance of skin piercing especially becomes vital in the context of healthcare. Moreover, attaching an object to the body can lead to other bodily harm in specific scenarios like falling. Hence, safety is essential to be considered in the design.

Attachment firmness and secureness

Attachment, the primary outcome, has three main parameters which require attention — firmness, secureness and holding capacity. These are user-oriented parameters, which would decide the system's applicability with various users and objects. Secureness is the measure of attachment quality. The object is safely attached to the fabric and should not fall off in regular use. The firmness is a measure of the robustness of the attachment or wobbliness of the attachment. High wobbliness also increases failure possibility because of fatigue loading. However, firmness does not consider the inherent flexibility and elasticity of the fabric, as this would exist irrespective of the attachment method, quality and robustness.

Holding capacity

Holding capacity is a quantification of the strength of the system. The strength of the system is directional because the modules are unsymmetrical. There are two limits, functional failure limit and ultimate failure limit. Functional failure strength is the maximum force system can withstand without having any lasting effect on the system's functions. On the other hand, ultimate failure strength is the maximum force a system can withstand before forcefully detaching from the fabric. Both these limits decide the system's applicability for various objects and conditions. The higher the limits, the heavier objects can be used, and higher forces can be applied.

Fabric damage

Fabric damage is a worry of a user when using such a system. Such damage is divided into two types based on when it occurs. One is attachment damage, and the second is Failure damage. The damage due to attachment can vary from visible marks and holes to a pill (or similar pulled fabric). However, the damage at failure can be anywhere from small holes, pills to torn threads and stretched threads or fabric. The extent of damage depends on fabric parameters, like cover factor and elasticity. It certainly depends on the type and quality of attachment, for example, the amount of fabric capture. Lastly, it depends on the direction and amount of force. However, the applied force acts on the user's body transferring via fabric; hence it is vital to consider the safety aspect of bodily hurt when looking at fabric damage.

Operation and Usability

The user interacts with the product. A user would actuate the system while flushing it with fabric and applying pressure. Easing this operation process by making it ergonomic and quick would be vital for a good design. The actuation force, the force required to actuate the system, is a crucial parameter for Spindel-tech technology (see Section 3.4).

3.4 Force flow analysis

The system has three distinct force condition. These are forces in actuation, forces in attached state, and Handling forces. The analysis identifies how the forces transfer in the device, and identifies weak points and relationships between forces and design parameters. Handling forces refer to accidental forces and impact forces exerted on the system when not in use (i.e, device is dropped when not in use). Handling force analysis is relevant to design a robust structural casing. As the focus of the development is on functional strength, handling forces analysis is not carried out. However, it is acknowledged that a robust structural case design would safeguard the device against accidental force.

3.4.1 Actuation force analysis

The actuation system transfers the user applied force on the lever to the modules by gear rotation, refereed as F_w^{sys}. The lever ratio and gear ratio between module gear and lever gear converts F_w^{sys} to F_w, the required actuation force for each module using equation 1. Gear mechanism is shown in figure 15b. This F_w rotates the wire about the rotation axis of module gear (see Figure 24).

$$F_w = \frac{F_w^{sys}}{n}\left(\frac{L_{lever}}{R_{base}}\right)\left(\frac{R_g}{R_w}\right) \tag{1}$$

At the start of the actuation rotation, the tip of the wire hits the slope. Due to the slope angle (θ) and shape of the tip, the wire starts to slide upwards on the slope. The effect of the slope (θ) is limited to this initial gradual upward push. Once the wire touches the top abutment, it starts to generate the Normal forces shown in the Figure 24. The three-point bending condition arises with these contact reaction forces. The design geometry engenders and dictates the forces by physical restriction.

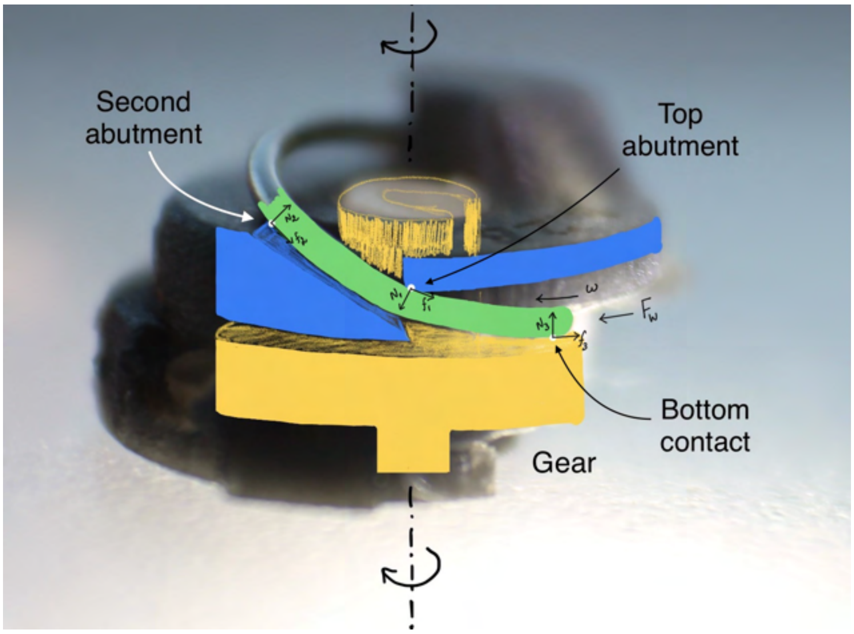


Figure 24: Bending in actuation - Free-body diagram of wire

The F_w keeps rotating the wire, due to which wire undergoes three-point bending at the abutments, as shown in Figure 24. The moving wire leaves the top cover, moving towards the cave in a tilted rotation plane. Friction forces at each contact point apply on wire opposing its motion. The bending is the result of the bending moment M created by the reaction and friction forces as a response to the F_w.

Force and moment balance for wire would give a direct relationship between M and F_w. Because of that, there is a inverse relation between F_w and Bending radius ρ. The lower the bending radius ρ, the larger the bending angle. The change of angle of rotation plane (ϕ) includes effects of spring bending and three-point bending. The ϕ increases as bending angle increases. Bending radius (ρ) reduces with smaller separation of abutments (α) and smaller height of wire pathway (H_w). Higher H_w allows for spring-like bending and reduces three-point bending. The bending radius ρ is for three-point bending. Spring-like bending requires far less bending force compared to three-point bending because of less stiffness and torsion based deformation. Being part of actuation function, the bending radius ρ (and bending angle ϕ) is fixed by design. Hence, the force to achieve required bending would be proportional to bending stiffness (S) of the wire (of the section where actuation bending is takes place)(Popov, 1990).

$$F_w \propto \frac{1}{\rho} \propto \frac{1}{H_w \alpha} \tag{2}$$

$$F_w \propto S \propto EI \propto E\ r_w^4 \tag{3}$$

F_w increases with friction resistance, which depends on friction co-efficient (μ) between materials. In addition, Fabric poses further resistance. Fabric penetration force is applied using F_w, which increases F_w. After penetration, friction resistance is also applied on the wire when rubbing against the fabric threads.

The normal reaction forces at the two abutments and the contact point on gear apply opposite force in the top cover and the gear, respectively. On the top cover, these forces create flexing at the top abutment by applying an upward force on top abutment and downward force on the second abutment. Similarly, the gear also tilts slightly as a reaction to the normal force. These deformations and adjustments depend on tolerances between surfaces and the amount of force. The actuation bending deformation is designed to be elastic deformation. In the force-flow from the lever to the wire, the potential week points are the gear teeth and the top abutment.

Once the wire is rotated by γ_o (fully actuated) rotation is stopped, and the F_w would stop to apply. However, a portion of the wire remains in a bent position in the attached condition. The bent section of the wire continues to apply normal forces at the contact points, trying to un-bend. These forces lock the wire in place. The gear meshing further refrains the wire from rotating back to the open-state without user applied force. Table 3 shows the measured actuation force for two types of systems.

Table 3: Measured Actuation force f_w^{sys} and f_w

System tested	f_w^{sys} [N] (Measured)	Module-Wire	f_w [N] (eq. 1)
4mB4T	7-8	B - 0.4mm	3
4mC5T	20-22	C - 0.5mm	9
	Adjusted for B (eq. 3)	B - 0.5mm	7.5

3.4.2 Attached-state: Holding force analysis

In the attached state, there is a force interaction between the device (the system) and fabric, and also between the device and the object. Force (F_{ext}) applied on object transfers through the device to the fabric. Applied force (F_{ext}) includes the gravitational force on the object, oscillatory forces of movement due to walking, running, impact forces, or hand-applied forces. These forces act on the object's attachment point with the device and then are transferred to the device's top cover via the central assembly screw. The top cover houses all the modules in a circular locus. The force is then transferred to the fabric via attachment wires in each module.

F_{ext}<- Object - [Attachment point- Connecting screw - Modules - Wire] - Fabric threads - User body

The applied force (F_{ext}) is combination of the aforementioned forces. Hence, for each condition the details of force flow would vary. However, the presented force-flow holds true for each condition. As there is no acceleration of the device, the force applied on the fabric is same as that applied on the Object (F_{ext}). The fabric exerts an opposite force (-F_{ext}) on the wires cumulatively. As n number of modules are attached, each module supports a part of F_{ext}. The variation of force supported depends on the moment balance and the fabric condition at the attachment. If fabric can not take load, in spite of good attachment, module can not transfer any load. The variation of force on each module indicates possible stress concentration, and subsequently higher fatigue load on some modules compared to others. The moment generated by the gravitational force contributes largely to the unequal force distribution among modules. The flexible and elastic nature of the fabric also contributes.

For each module, let, force F = (F_x, F_y, F_z) be the force applied on the wire by the fabric (See figure 26). In reality, the force F is applied over a area on the wire (as a distributed force, pressure) where the fabric threads are looped around the wire. However, to simplify, an equivalent point force F can be assumed. Force F is applied at an equivalent point on wire with a position vector D_f, from the top abutment as shown in the Figure 25. θ_f is a angular representation of D_f w.r.t. the rotation axis (see Figure 26).

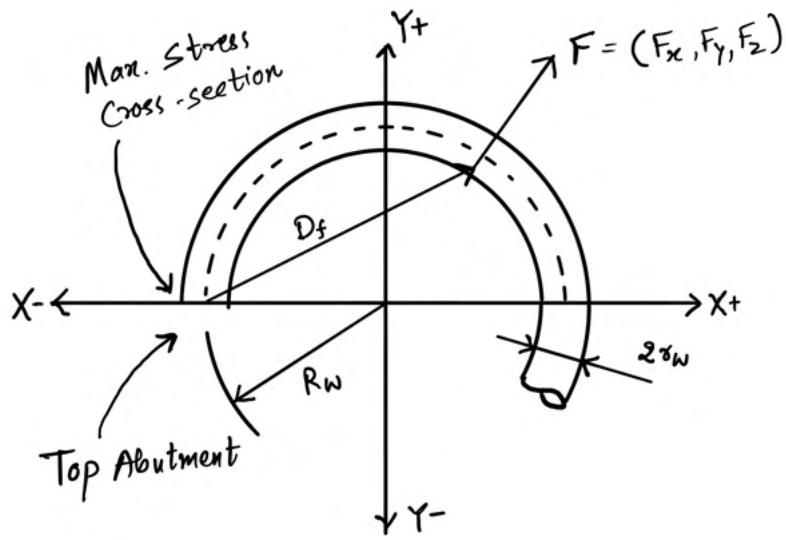


Figure 25: Representation of Equivalent force F and D_f in a an equivalent model of wire

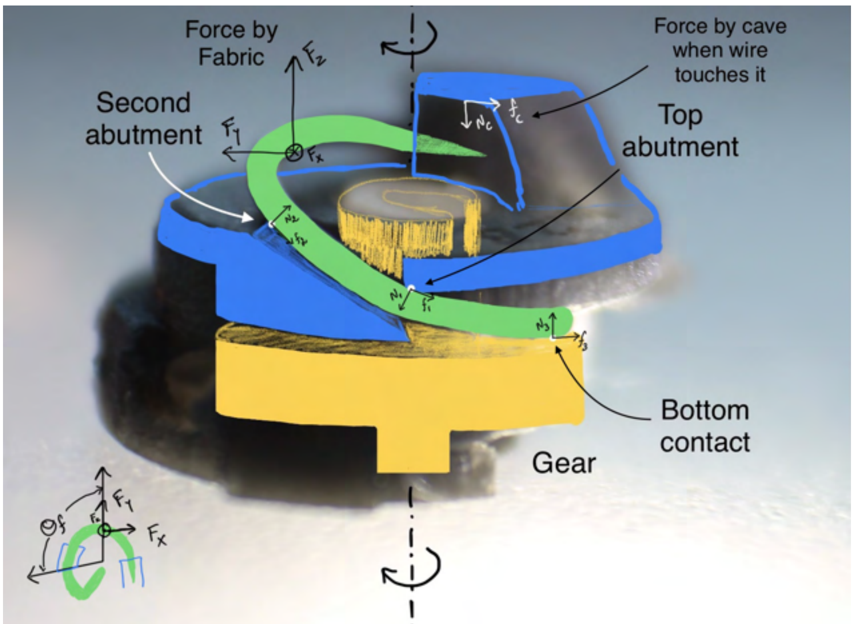


Figure 26: Force interaction with fabric - Free body diagram of wire within module

As shown in Figure 26, the force F would create reaction forces at the contact points of wire with the top cover and the gear. If the wire deforms in Z direction and touches the cave wall, a reaction force would be applied by the cave also. Each point would apply friction force as reaction. Depending on deformation of the wire, the contact points would change. For example, in case of $F_x < 0$, referred as F_{x-}, the second abutment slides in negative x direction to touch outer wall of the slope, which becomes a contact point and provides reaction forces.

In the force flow, there are three weak points, fabric threads, wire and the screw. Only a few fabric threads are captured by the wire, hence the force bearable by those thread is a limiting factor. If fabric is the limiting factor, the fabric damage would be high, as it is the vulnerable link. Due to this contradiction, for each fabric, the system would have a limit on the rated capacity to avoid excessive fabric damage. However, the focus of the current development is focused on tough fabrics in order to design and realise high-capacity systems.

The wire is the most vulnerable component in the system. It would undergo maximum deformation and fails first, making it a limiting factor. Since the top abutment and other contact points support the wire, the top cover is also a vulnerable component. The screw, being the only contact between the module plate and the object, is a critical link in the force flow. It can fail after being exposed to extreme force conditions for few times due to fatigue, if not right away. Other features, such as the snap-fit grooves of the modules, do transfer forces; however, they are supported by the structure to prevent breakage.

3.4.3 Fatigue force analysis

In every actuation, attachment or detachment, the wire undergoes a fatigue loading cycle. Points on wire bend and then relax each time it is actuated. Hence, in each full actuation cycle, attachment and then detachment, wire undergoes double load cycle. Similarly, the top cover also is loaded in attached condition and relaxed in open condition. F_{ext} can also be cyclic, for instance, when running with the device attached to a shirt. Hence, over time, fatigue failure can arise in these components if the stress level crosses the fatigue limit. Fatigue failure can decide the lifetime of the system. However, the weak points on the systems like wire are more likely to fail in use, limiting the lifetime.

3.5 Technical Models

Technical models represents the relationships between various design and functional parameters. A model captures which parameters affects certain aspect, and how do they affect. Equations 1, 2, and 3 and other relations defined in section 3.4 are example of technical models, defining relationships between parameters. Figure 27 visualises relationships between design and functional parameters. Long-dashed line blocks are functional parameters, small-dashed line blocks are derived parameters and solid line blocks are design parameters.

3.5.1 Depth of Penetration D_p

Depth of Penetration (D_p) and penetration angle (β_1) have direct proportionality with angle of change of rotation plane (ϕ). Depth of penetration (D_p) reduces with thickness of wire (r_w), as thicker wire allows for less open-space for fabric threads. So, even though

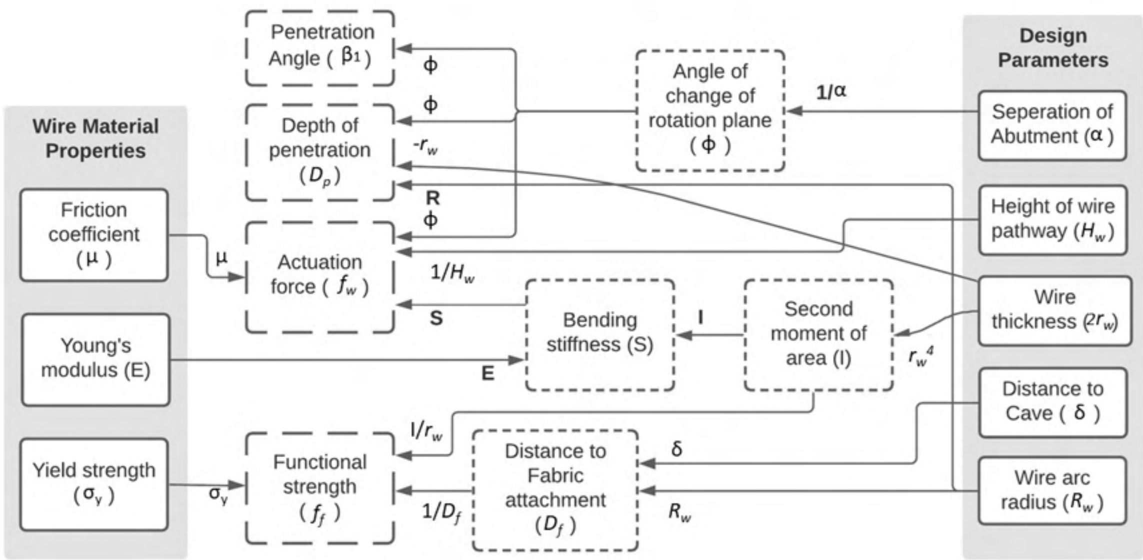


Figure 27: Relationship of design parameters to functional parameters

the depth at which wire penetrates is same, effective depth of penetration (D_p) for fabric capture would be less for thicker wires.

3.5.2 Angle of penetration β_1 & β_2

The penetration angles (β_1 and β_2) are angles between a linear object (wire) and a planar surface (fabric). Though angles are converted to planar angles, the 3D angles are sensitive to minor changes in geometry. A minor change in shape of the wire tip or tilt in fabric surface causes the angle to change. Two of the main parameters for β_1 are the fabric surface position (flushing) and angle of change of rotational plane (ϕ). Better flushing, or higher ϕ increases β_1. However, except the flushing, β_1 is defined fairly well by design parameters because fabric is stationary. Expected value for β_1 for B variant would be 30° to 40°.

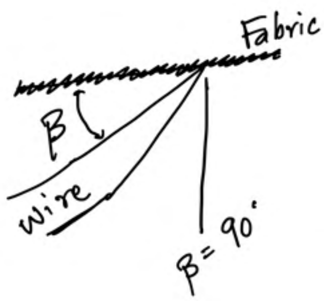


Figure 28: Angle of penetration

The second penetration angle (β_2) is result of the arc shape of wire. Unlike β_1, β_2 is sensitive to multiple factors. These are, second penetration point on fabric, fabric movement and elasticity, and possibility of wire deformation. In the current module design, β_2 has very low values as the wire has near parallel trajectory at the point of second penetration (just before cave). The shape of the wire (grounded from bottom-inward direction) pushes tip further from fabric, further reducing β_2. Values for β_2 can be expected to be between $0°$ to $20°$. However, as the fabric moves and stretches with the tip of the wire, the angle is not well defined. The cave would also alter the angle by partially restricting the fabric motion, and in some cases providing a opposite support against the wire motion.

3.5.3 Functional strength f_f and f_u

Functional failure is defined as the force (F_{ext}) at which the system, or part of the system, can no longer perform desired function. For wire, functional failure (f_f) is defined as a force (F) which generates permanent deformation which would stop the wire from actuating and attaching as designed. For a single module system (n=1), $F = F_{ext}$ and $f_f = f_f^{sys}$.

The wire outside of the module, starting from the top abutment till the tip, do not have any in-built stress when in attached condition without fabric. This is because material in this section is bent in actuation and then allowed to return to the relaxed state. This section of wire is identical to a semi-circular wire (of same length). The force (F) is transferred to the top cover through contact points (as shown in Figure 26), among which top abutment being the primary point. Under force (F), the wire section at the top abutment experience maximum bending and torsional stress.

As described in section 3.4, F applying at D_f on the semi-circular wire would give a limit of the force F. This simplification ignores effect of cave (reaction at cave shown in figure 26). The force interaction at the cave is driven by normal and friction force, until the wire deforms to pop out of the cave. Once the wire pops out, the abutments are the only support for the wire. Though the cave may increase force bearing limit (f_f) marginally, it primarily restricts deformation of wire, that delays fabric slipping off the wire. The limit calculated without effect of the cave would be less than actual limit, allowing for factor of safety.

In the wire cross-section at the top abutment, the force F creates M moment (equation 4). The stress developed by the force F and moment M are shown in equations 6, 7, 8, and 9 (Popov, 1990). The stresses presented are stress components because of each component of F or M. Using superposition principle, stress would add up. The stress distribution due to bending is directional, for example equation 7 applies to each point at distance +r in z direction, from the central axis of the wire. Equating total stress to yield stress (σ_y), would give functional failure limit f_f. For estimation of directional functional failure limit, compare stress induced by only F_z with σ_y.

$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} F_z D_{fy} \\ -F_z D_{fx} \\ F_y D_{fx} - F_x D_{fy} \end{bmatrix} \tag{4}$$

$$I = \frac{\pi r_w^4}{4} \qquad \& \qquad J = \frac{\pi r_w^4}{2} \tag{5}$$

$$\sigma(F_y) = \frac{F_y}{A} \tag{6}$$

$$\sigma(r, M_x) = \frac{-M_x r}{I} \qquad ; \ -r_w \leq r \leq r_w \ ; \ \text{in Z direction} \tag{7}$$

$$\sigma(R(r), M_z) = \frac{-M_z(R_b - R)}{RA(R_w - R_b)} \tag{8}$$

$$\text{where } R_w - r_w \leq R(r) \leq R_w + r_w \ ; \ \text{in X direction}$$
$$\text{and } R_b = \frac{R_w + \sqrt{R_w^2 - r_w^2}}{2}$$

$$\tau(r, M_y) = \frac{M_y r}{J} \qquad ; \ 0 \leq r \leq r_w \tag{9}$$

The stress do not represent deformation or deflection of the wire. Bending stiffness (S) is the force required per unit deflection. Bending stiffness is proportional to E, young modulus and I, second moment of inertia. As equation 3 shows, lower stiffness would reduce actuation force (F_w). On the other hand, f_f is proportional to I (equation 7, other directions also have similar r_w^4 or equivalent dependency). Hence, there is a trade-off between f_f and f_w. Alternatively, having higher young's modulus (E) would increase stiffness, and having higher yield strength (σ_y) would increase f_f. Reducing distance to the fabric attachment point (D_f) would reduce bending stress (σ) and increase f_f.

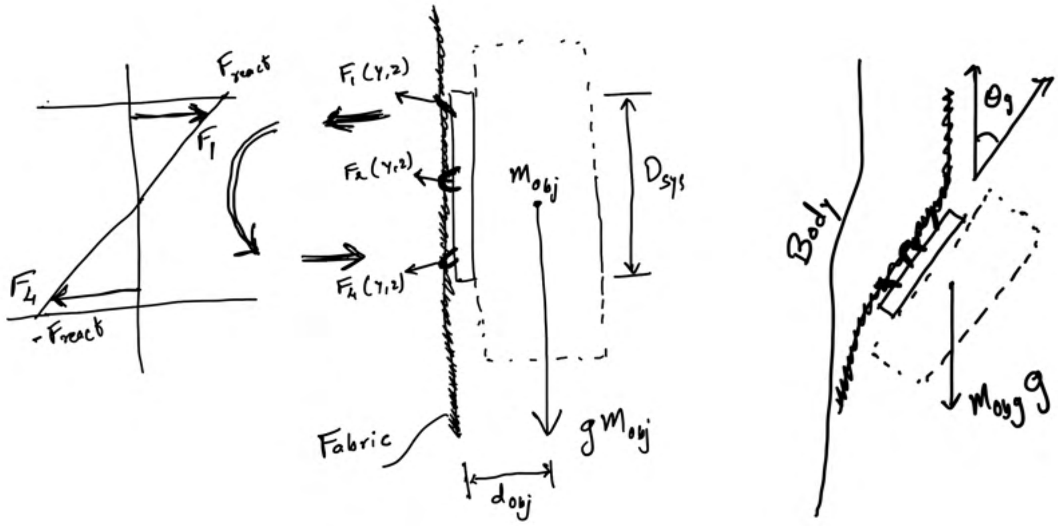
Ultimate strength (f_u) is the strength when the system (or module) detaches from the fabric under force F. Under force F, wire starts to deform elastically, leaves the cave, and eventually undergoes plastic deformation. In the process fabric slips on wire in direction of the force, and sometime breaks. Lesser the wire deforms under certain force, higher would be f_u, because fabric slipping is delayed. As multiple mechanisms are in place, it is not possible to predict ultimate strength theoretically.

3.5.4 Attachment quality and repeatability

Functioning under many influencing parameters, not all modules would attach with good attachment quality. The condition of attachment would affect other parameters. on the other hand the repeatability of the attachment can be defined as expected value. One factor, q, can be defined as expected fraction of modules attaining good attachment condition upon attachment. This is a probabilistic parameter, averaged over multiple observations. As probabilistic study is out of scope, this parameter is not studied. However, as it reduces the system performance, it needs to be considered in the predictive theoretical calculations.

3.5.5 Resting weight m_{obj}^{sys}

Resting weight capacity of the system m_{obj}^{sys} is defined as maximum weight of object m_{obj} which can be used with the system without failing. It can be predicted based on analysis of forces in resting condition. Figure 29a shows forces on the system in resting condition. In real condition, fabric would stretch out and create a angular hanging position for the system as shown in Figure 29b. The angular condition transfers a fraction of gravitational force in a tensile direction, which is unevenly distributed among various modules. If the angle is 0° as shown in Figure 29a, the attachment experiences a pure moment, which puts certain modules under compression and certain under tension, as shown. In this condition, There is a high force concentration on the top module, with a little help from nearby. Modules in the centre and bottom are relaxed, or in compression. This creates an extreme condition.



(a) Extreme Resting condition

(b) Normal Resting condition

Figure 29: Forces in Resting condition - Prediction of Resting weight capacity

Using moment balance at bottom module, following equation can be written where $F_1(x, y, z)$ is force on top module, and d_{obj} is distance to centre of mass of object

$$F_1(z)\ D_{sys} = m_{obj}\ \ g\ \ d_{obj} \tag{10}$$

Bending effect is analogous to stresses in beam bending but in this case stress is accumulated as force at few points. For simplification a near-zero force on central modules is considered as zero. However, it is possible to include this modules with summation of moment created by each. Force $F_1(z)$ is force on top module, or equivalent force supported by nearby placed modules which creates same moment. This force $F_1(z)$ should be less than $f_{f,z}$ of a module, or nearby modules supporting it, which yields equation for resting capacity.

$$m_{obj}^{sys} = \frac{f_{f,z} D_{sys}}{g\ d_{obj}} \tag{11}$$

The dimension of the object and weight distribution would change the the d_{obj}, and which changes resting capacity. However, to compare different systems, $D_{sys} = d_{obj}$, can be used as definition of resting weight. For a 4 module system only one module on top supports the force. For a 30 mm diameter 6 module system, two nearby modules would do so, hence capacity would be twice the functional limit of a module. However, for a 50mm diameter 6 module system, same can not be said as the modules would be far away.

4

User study

This chapter focuses on the target user group of this project. It describes the user groups, the gear they wear, their equipment, and how it is fastened to their gear. It also reflects on their needs for attaching the equipment, which helps us understand the potential usability improvement of the Spindel-tech. The chapter results in narrowing down the fabrics to use in product testing, understanding various usage scenarios the device would be subjected to.

4.1 Nature of the study

User study for a product is usually done to understand its need from a user's perspective, to define the requirements for which the product is then developed. User research plays a key role in the design of a product. In this project, it is done more to understand the change or improvement needed in the product, whereas the use case has not been explored in depth. The targeted user group, i.e, the first responders are studied in brief to identify and understand the areas of improvement for Spindel-tech design. There are some factors which directly relate to the strength and reliability of the attachment. For example, the activity of the user and usage scenarios dictate the forces which will act on the attachment. Understanding these force conditions would create the basis for design requirements. The clothing and gear of the user is used to identify the fabrics, to analyse the product's performance on similar fabrics.

From the company's investigation of a possible application of Spindel-tech for the first responders, and the Swedish Police Authority's issued request for information regarding an improved carrying device for police personnel, the focus of this study is on three main user groups. The police personnel, but also the security guards and the fire-fighters who carry multiple equipment on their body during work, and have a similar need.

4.2 User groups

- **Security guards (Ordningsvakt)** : They are responsible for security in public places in the city. Their responsibilities include - conducting security checks over a specified area, monitoring alarms and CCTV cameras in buildings and public places, preventing illegal activities and vandalism, and detaining criminal violators. They are appointed at various places like parks, bus/tram/train stations, shopping malls, commercial buildings, banks etc.

- **Police personnel** : They are law enforcement personnel responsible for several duties - responding to emergency and non-emergency calls from the public; patrolling areas by vehicle, horse, or foot; direct traffic during special events and traffic accidents; assisting investigators and detectives in processing crime scenes, obtaining warrants and arresting offenders. Police personnel's work may vary with the type of department they are appointed. For example, personnel working for the bomb diffusion squad may have a different nature of work than one patrolling an area in the city.

- **Fire fighters** : Their primary responsibilities and duties are - putting out fires, rescuing and caring for the sick and injured, preventing future fires and investigating the sources of fires, especially in the case of potential arson. If the need comes, for example, during a natural or man-made disaster, they are also responsible for evacuating people and animals from public places and buildings safely.

4.2.1 Personas

Three personas were created based on the different user groups with an aim to represent the nature of their work, the gear and equipment they use.

- **Billy Jean**
  Billy is 28 years old and works as a security guard. He is from Göteborg, is half Swedish and half Greek. He has a cheerful personality and believes ensuring safety and security for the public is a good way to serve society. He follows soccer and has been a loyal fan of IFK Göteborg. He has also been a professional swimmer in school. His usual working hours vary from 8-9 hours a day, and he likes his job more on days when it is a mix of indoors and outdoors.

Figure 30: Billy Jean (Mock picture (Källdén, 2020))

- **Nature of work**: Most days he conducts security checks at Nordstan (shopping mall), monitors alarms and CCTV cameras, and prevents illegal activities in the mall and the retail stores inside the mall.
- **Clothes and gear**: Light jacket with breast pockets and shoulder loop; Cargo pants with four pockets on each leg; Equipment belt (also known as Duty belt)
- **Equipment and placement**: Panic alarm on the belt; Two handcuffs on the belt (one in closed pocket, one in open pocket); A Remote Speaker Microphone on shoulder loop and receiver on the belt; Keys on the belt with hook or carabiner; Baton on the belt; Flashlight on the belt; Gloves on belt held with a buttoned loop or Velcro loop; Paramedic equipment in a pants pocket
- **Issues with gear and equipment**
  - Occasional backache from tight duty belt and standing or walking during most of the work time
  - Velcro on the glove holding strap goes bad after frequent use

- **James Water**
  James is 36 years old and is a firefighter. His office and the fire station is in Göteborg, but the department is responsible for a large part of Västra Götaland County in Sweden. He is a highly energetic person and can fluently speak four different languages. Usual working hours for him are 7-8 hours, but shifts can occasionally extend, depending on the emergency they have to respond to. He recalls one of the most challenging experiences from his job was when his teammates and he spent 22 hours trying to put off a forest fire. He is an avid reader of science fiction and claims to have witnessed a UFO when travelling in Chile.

Figure 31: James Water (Mock picture (“Swedish fire-fighter”, 2020))

- **Nature of work** : Spends a lot of time at the office or fire station but has to be well prepared to respond to emergencies, for which daily checks of equipment and vehicles have to be conducted. When responding, for example, putting down fire in a building and safely evacuating the public, the conditions can be extreme, with high temperatures and risk of falling debris. The response team has 90 seconds between the emergency call, sitting in the vehicle, and leaving the fire station. Most of the equipment is in the vehicle so they can equip themselves during the travel time.

- **Clothes and gear** (in responding situations): Helmet with a visor; Inner shirt; Fire resistant jacket with two loops on the shoulders, two pockets below the shoulder, two breast pockets, one loop with carabiner and two more pockets on the lower torso; Fire resistant pants with four pockets on each leg; Reflective vest with shoulder loops and side pockets; Thick fire resistant gloves
- **Equipment and placement** (in responding situations):Gas mask on the face; Extinguishing cylinders on the back; Infrared camera attached on a shoulder loop with carabiner; Headlamp on the helmet; Hand-held flashlight attached to a loop with a flexible string; A Remote Speaker Microphone on shoulder loop; Receiver in the jacket pocket; Smoke and radiation sensing devices in the jacket pockets
- **Issues with gear and equipment**
  * The hand held flashlight and IR camera are held with a carabiner, which makes the attachment wobbly and can be problematic in some situations
  * Small devices can be tricky to operate with thick gloves but he says adapted to it

- **Robert Copper**
Robert is 49 years old and is a police officer in Göteborg. His hometown is Mora, in the beautiful Dalarna County of Sweden. He is a father of two and loves spending his free time outdoors with his children and husband. He has a tenth-degree black belt in Taekwondo. The usual working hours for him are 7-8 hours a day but may vary if he has to respond to an emergency or a special event on the weekend. He says that he wishes for a peaceful and happy world for everyone equally and tries to do his duties well to maintain law and order.

Figure 32: Robert Copper (Mock picture (police Authority, 2020))

  - **Nature of work** : He is mostly patrolling different areas in the city by car and responding to emergency calls and situations when required. There are also regular changes in his duties. For instance, one day, he would work at the office to do some paperwork and intervene in a violent domestic dispute the next day.

- **Clothes and gear**: Jacket with torso pockets on each side and shoulder loops; Cargo pants with 4 pockets on each leg; Police duty belt
- **Equipment and placement**: A Remote Speaker Microphone on jacket's left shoulder loop; Receiver on duty belt; Body cam on jacket's right shoulder loop; One pair of handcuffs in an accessory attached to the duty belt; Baton in an accessory attached to the duty belt; Hand gun in a holster attached to the duty belt; Flashlight in an accessory attached to the duty belt; Gloves held on the duty belt with a buttoned loop
- **Issues with gear and equipment**
  - Back ache due to the pressure on the waist area from the duty belt, specifically when driving or sitting in the vehicle wearing the belt
  - Most of the equipment attached to the duty belt, making it heavy

4.3 User understandings and reflections

The personas discussed in the above section have some things in common for the fact they are all first responders, but their nature of work is different from each other. The issues police personnel (Robert) and security guard (Billy) have with the current equipment are not directly related to attachment to their gear. But more to the lack of freedom of its placement. On the other hand, the wobbliness of a specific attachment was an issue for James (firefighter).

There is a potential use-case of the Spindel-tech for all these user groups, which can overcome their current gear and equipment issues. For Robert and Billy, most of their equipment is on the belt, which leads to all the weight distribution along the waist and lower back when standing, and pressure on the lower abdomen and lower back when sitting in the vehicle. The Spindel-tech can solve this issue by placing individual equipment anywhere on the worn gear. So the weight of the equipment is not focused around the waist. For James, the wobbly attachment of the hand-held devices on the gear can be solved by having these devices attached to the gear with the Spindel-tech over a more distributed area. At the same time, it could easily be removed and attached when required. However, for all these use-cases of the Spindel-tech, it has to hold strong forces when attached. Robert and Billy may get into situations where the equipment might be pulled by another person, for example, while trying to take an offender under control. The Spindel-tech must also be easy and quick to remove when actuated by the user. James' work would include getting into narrow spaces, for example, trying to rescue a person from under a fallen ceiling. He should be able to quickly remove it if the equipment gets stuck somewhere. These requirements are the driving factors for improving the design of the Spindel-tech, and hence its performance.

4.3.1 List of user needs

From the user study, a set of basic needs were identified from the three user categories, for a good attachment system. They are as listed below :

- **Easy and quick assembly of a hand-held object to the device**: The equipment user wants to attach to their gear, must assembled with the attachment device quickly and with ease

- **Easy to attach and detach from the gear**: The whole attachment system (device and the hand-held object it holds) must be quick and easy to attach to the fabric, and the same to detach when required
- **Secure attachment of the system to the fabric (gear)** : The attachment system must be securely attached to the fabric every time, so it is reliable to use
- **Able to take excessive forces from sudden pulls** : The system must be able to take strong external forces when pulled intentionally or unintentionally in an attached state
- **Able to firmly hold most of the hand-sized equipment they use**: The device must be able to carry the weight of a hand-held object (m_{obj}) while being firmly attached to the gear(fabric)
- **Harmless to the user, when in use and also when not in use**: The system should not harm the user when being attached, when attached, while removing and when not in use
- **Usable with gloves**: As most of the first responders use gloves when working on field (responding to emergencies), the attachment system must be usable with gloves
- **High longevity of attachment system without decrease in functionality**: The system would be used on a daily basis during work by the users, so it needs to have a good lifetime

4.3.2 Fabrics

In order to test the performance of Spindel-tech, fabrics used by these user groups for their gear is of importance. These fabrics are very similar to each other, as it has to be tough, yet flexible and comfortable. To narrow down the scope of testing the device, four types of fabrics were chosen :

- **Delinova® 150** : This material (Figure 34a) is widely used in carrying systems, backpacks, protective clothing, ballistic vests, holster and other clothing applications. It is chosen for testing the device, as it provides a condition of relatively stiff and less flexible fabric, with its toughness and high tensile strength, which makes it tear-resistant up to 85 N in the warp, and 100 N force in weft (*62256-xxx/501 Delinova® 150 specification*, 2021). Tear resistance is the most common and essential aspect of fabrics used in first responders' clothes. It composes of Polyamide 6.6 Cordura® in the warp as well as in weft (Figure 33). It is coated on the backside with polyurethane for waterproofing and impregnated with fluorocarbon for oil and dirt resistance. The waterproof coating also provides stiffness to this fabric.

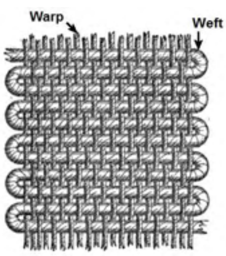
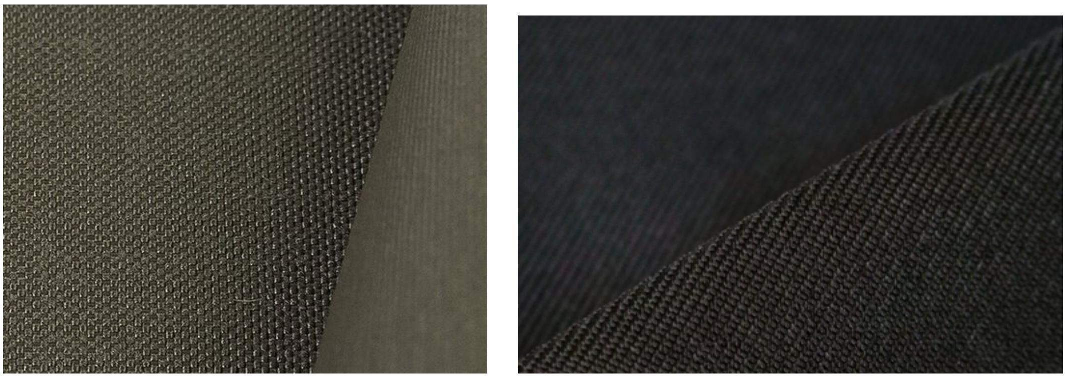


Figure 33: Warp and Weft in plain weaving

- **Delinova® 150 Stretch** : This material (Figure 34b) has applications in tactical gear and military clothing. It is chosen for the testing for its combination of high



(a) Delinova® 150 fabric **(b)** Delinova® 150 Stretch fabric

Figure 34: Delinova® fabrics

tear resistance and elasticity. It provides a flexible fabric condition to test the Spindel-tech. The tear force this fabric can resist is 320 N in the warp and 260 N in weft (*62007/323 Delinova Stretch 150 technical data*, 2020). The composition is Polyamide 6.6 Cordura® in warp and comination of Lycra and Polyamide 6.6 Cordura® in weft. It is not water-proof but has fluorocarbon impregnation for oil and dirt resistance.

- **Tightly-woven Cotton** : Cotton is a material combined with either nylon or polyester in many clothing applications for the first responders. However, to test the device for its usability on complete cotton fabrics, this material was used. A tightly-woven cotton apparel (Figure 35a) was used for testing to provide a rugged cotton fabric condition.

(a) Cotton pant fabric **(b)** Light wool sweater fabric

Figure 35: Cotton and Wool fabrics used

- **Wool** : Wool is mostly used in sweaters, which is worn under the outerwear by the security guards and the police personnel. However, in some conditions they may not wear an outerwear and to test the device on a loosely woven fabric like wool, this material (Figure 35b) was chosen.

4.3.3 Usage scenarios

The work of the first responder categories mentioned in the above sections is subjected to all weather conditions. For various use-cases of the Spindel-tech, it has to perform well in multiple usage scenarios. Below are the main usage scenarios the device would be subjected to when attached -

- **Resting position (Carrying the weight of attached object)**
  This is the basic condition, where the object is attached to the clothing of the user. The Spindel-tech needs to withstand the object's weight without failing and allowing it to tip or fall. As the object's size can be bigger than the Spindel-tech, the centre of mass allows tipping of the object, which would make the attachment wobbly, and also have a force concentration due to moment on one or two modules. This condition behaves two ways if the object is attached length-wise to gravity; one while the user is standing (Figure 36g), and another while user is walking or running. In the walking or running condition, it would have an oscillatory motion, leading to bigger holes in the fabric and making the attachment loose and wobbly.
- **Twisting of object**
  This scenario (Figure 36h) would occur in the resting position of the object, or when it is being pushed, pulled in a twisting motion, or even when trying to remove the attachment. This would cause a twisting motion of the device on the cloth, causing a moment to act on the attachment.
- **Pulled perpendicularly to the attached surface**
  This scenario (Figure 36a is when the object is being pulled away from the fabric, without actuating the detachment of the Spindel-tech. It would happen when the user like a police personnel or a security guard would be engaging in physically controlling an offender, and the offender tries to pull the object off their gear.
- **Pulled along (parallel) the attached surface**
  This scenario is similar to pulling the object away from the fabric, but instead, the pull happens parallel to the attached surface. This would happen when the user tries to pull the object sideways (Figure 36c) or upwards (Figure 36d) along the cloth without actuating the detachment of the Spindel-tech.
- **Object lifted from the bottom** This scenario can occur accidentally (Figure 36e) when hitting an obstacle or intentionally (Figure 36f) while trying to detach the object. It concentrates the force on a single module of the Spindel-tech more instead of distributing it to all the modules.
- **Object bumping into an obstacle**
  The user might bump into any obstacle while walking, running or doing any task that includes motion. As the object is attached to the outside of the user's gear, it is vulnerable to hit any such obstacle. This scenario (Figure 36b) could act similar to the lifting from the bottom scenario where the force is not distributed to all the modules f the Spindel-tech.

(a) Object being pulled away in attached

(b) Object hitting obstacle sideways (shear

(c) Object being pulled sideways (shear force)

(d) Object being pulled upw

(e) Object hitting an obstacle from under

(f) Object being pulled upwards (unsymmetrical)

(g) Resting position - object weight

(h) Object twisting

Figure 36: Usage conditions

5

Performance Investigation

This chapter looks into the performance of the Spindel-tech. It is done through a set of experiments on the device's attachment, force bearing capacity and the behaviour of failure. The chapter starts with highlighting the performance parameters, followed by the description of experiments and the results for each category of testing. Finally, the performance investigation results are analysed and used for formulating the target requirements for improved design.

5.1 Performance parameters

Performance parameters give a basis for analysing the system's design and functions based on the experiment results. Table 4 shows the parameters considered in each domain and how they are quantified. The domains here are strength, attachment, user-friendliness, fabric damage and development. These particular parameters are chosen as they reflect the main performance attributes from each domain. *Fabric Damage* and *Actuation complexity* are kept as subjective parameters. However, it is a hypothesis that the fabric damage would have a relation with the wire thickness (r_w).

Given the usage condition, both shear and tensile strengths are to be analysed. Hence, a minimum of all directional strengths is taken as defining the performance of a module or complete system. By doing so, the weakest direction is captured and highlighted, from where the system would likely fail. Similar to a material's yield strength, the directional functional limit and ultimate directional strength are essential to define the system's performance.

5.2 Testing

There are three main types of testing required to analyse the performance of the device. These are attachment testing, strength testing, and failure testing. The Spindel-tech modules have three design variants, and the number of modules in a device can be varied depending on the application. The variants are tested individually for some tests but also tested as different combinations during the testing. Below is a description of each type of testing, the objective, parameters involved and the experimental setup.

5.3 Attachment testing

The testing is done using a 5m device with all module variants and on different fabric types.

Table 4: Performance parameters

Strength	Functional limit ($f_f$andf_f^{sys})	N force applied before wire starts to bend
Strength	Directional ultimate strength ($f_u$andf_u^{sys})	N force applied before failure
Attachment	Attachment Quality	% No. of securely attached modules of total in the system
Attachment	Attachment Repeatability	% No. of times attachment quality is good
User-friendliness	Actuation force (F_w^{sys})	N force applied to completely attach the device to fabric
User-friendliness	Actuation complexity	Subjective (Ease of holding actuating lever and device while attaching)
Development	Manufacturing complexity	No. of unique components in the system
Fabric Damage	Damage during attachment and breakage	Subjective

Objective

The main objective is to analyse how well does the device attach to the fabric when actuated. It is also to know the difference in attachment quality between the module variants with different fabrics and other influencing parameters like pressure and back support.

Parameters to study

- Quality of attachment of the device, using all the module variants
- Equality of attachment among all modules of the device
- Attachment repeatability of the device

Observable

- Capability of first penetration into the fabric, for each module
- Capability of second penetration into the fabric, for each module
- Secureness of attachment (if the wire in each module has gone well into the cave)
- Differences in pressure and back support required for good attachment, among different module variants and fabric types

5.3.1 Variables in testing

There are five variables in this testing, using which the attachment is analysed. These variables and their respective types are :

- **Fabric** : Four fabrics are used in the testing as discussed earlier, these are, Delinova 150, Delinova 150-Stretch, Cotton (pants), and Wool

- **Back support** : This is the support or pressure from the back of the attachment surface of the fabric, during the attachment. Two types of back supports used during the tests are, cushion support, and firm body support
- **Module type** : All three variants of modules, i.e, A, B, and C are used in a 5m device for attachment testing. The wire used in all the module types is the 4t (0.4mm cross-sectional diameter) wire. Type A module is tested first on all fabrics, following that the B, and the C are tested
- **Pressure** : This is the pressure applied on the device while actuating it for attachment. Three types of pressure levels, i.e, low, medium and high, are applied during the attachment. All the different types of tests are performed by applying each of the pressure levels on the device
- **Wire** : The two types of wires used vary in the diameter of the cross-section. The 4t wire is used for most of the tests. Whereas 5t wire is used in one particular testing combination, based on observations from 4t wire testing.

5.3.2 Setup

In order to cover all the performance parameters for attachment, and to mimic real usage conditions, the tests are performed with two types of back support. The setup for achieving these supports for the attachment is as below :

- **Cushion setup** : The fabric being tested is placed on a cushioned base, in this case, a hard mattress (Figure 37a). Then the device is tested on the fabric, by applying low, medium, and high pressure during the actuation. This is done for all three module variants (A,B and C).
- **Firm setup** : The firm support is mimicked by the body of user, wearing a single layer (non-cushioned) clothing (Figure 37b). The fabric being tested is placed on the body, with a single layer of clothing behind. Then the device is tested by applying low, medium, and high pressure during actuation. This is also done for all three module variants.

(a) Cushion support - Jacket like support, imitated by hard mattress

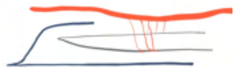
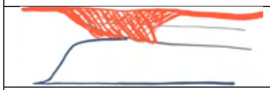
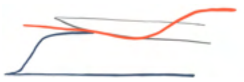
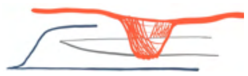
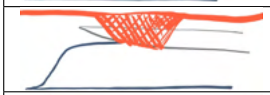
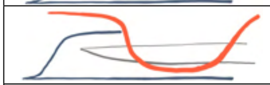
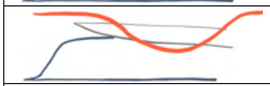
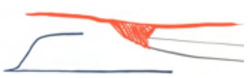
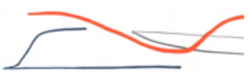
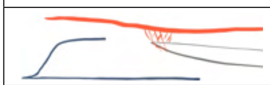
(b) Firm support - Bodily support on Chest

Figure 37: Attachment testing setup

5.3.3 Results and Observations

The primary function of the Spindel-tech being attachment; the device needs to attach to fabric securely. As discussed earlier, various parameters affect the quality of attachment. Table 5 shows different types of attachment conditions observed during the testing. These conditions are the effects of different combinations of variables in the testing. The effects of these variables are explained in detail after.

Table 5: Observed attachment conditions

Condition	Name	Description
	Zero penetration (ZeroP)	No penetration of fabric
	Fibre	Only few fibres are captured by the wire
	1p-partial	Wire does 1st penetration and captures partial t
	1p-full	Wire does 1st penetration through full t, fails to enter the cave and do the 2nd penetration
	1p-stuck-partial-secured	Wire penetrates through partial t, fails to do 2nd penetration and fabric gets stuck at the cave entrance
	1p-stuck-full-secured	Wire penetrates through full t, fails to do 2nd penetration and fabric gets stuck at the cave entrance
	2p-partial-secured	Wire does 2 penetrations and enters the cave, but only through partial t
	2p-partial-loose	Wire does 2 penetrations through partial t and goes over the cave
	2p-full-secured	Wire does 2 penetrations through full t and enters the cave
	2p-full-loose	Wire does 2 penetrations through full t and goes over the cave
	1p-partial-not-reached	Wire penetrates through partial t, fails to do 2nd penetration and fails to reach the cave entrance
	1p-full-not-reached	Wire penetrates through full t, fails to do 2nd penetration and fails to reach the cave entrance
	fibre-not-reached	Wire captures only few fibres of the fabric and fails to reach the cave

Effect of fabrics on attachment quality

Different fabrics effect attachment in different ways, below is a description of how each of the four fabrics effect the performance of the device :

Delinova 150 : This is a tightly woven, tough fabric. It also has a coating on the backside for water-proofing, making it difficult for the wire from the device to pierce into the fabric. The most common attachment condition observed in the testing with this fabric is Zero-P, which means no penetration happens. This condition is observed most with the type A module device, under all pressure levels and back support types. This is due to the lower angle of first penetration (β_1) in type A modules.

The best attachment on this fabric happens when using the type C module, firm support and high pressure. The steep gradient of the wire due to low α in this module allows a higher (β_1) in the fabric. The combination of firm support and high pressure is beneficial here as it restricts the slipping of this fabric during attachment.

When using type B module, under high pressure and firm back support, the wires in the device can do the first penetration, but only through the partial thickness of the fabric (t) and also fail to reach the cave. The reason for partial penetration is the insufficient (β_1). The reason for not reaching the cave is that the pressure applied on the device during attachment is relatively higher, and the back support is firm. Due to this, the wire gets enough external resistance and slips internally over the gear and fails to complete the desired amount of rotation.

Delinova 150-Stretch : This fabric composes the same material as the Delinova-150 but includes the elastic material - Lycra. It also differs in texture as it does not have a water-proof coating, making it more permeable and flexible. This characteristic of the fabric allows suitable attachment with the device. It is observed that with the change in types of modules, i.e., from type A to type C, as the (β_1) increases, the attachment with this fabric gets better. However, the pressure conditions and back support play a significant role in the quality of attachment with this fabric.

The best attachment is with the type B module, under high pressure and firm back support. This is the 2p full-secured attachment, where the wire does two full penetrations, captures the full thickness of the fabric (t) and enters the cave. The possible reason for this is that high pressure and firm support facilitate adequate flushing of this fabric with the device surface, yet does not restrict the wire movement as the fabric allows the wire to penetrate through it easily and complete its rotation.

In the scenarios where the combination of pressure and back support is not adequate, the attachment condition is either 2p partial-secured or 1p stuck partial-secured. 2p partial-secured is because the fabric is not adequately flushing, and so the wire captures partial-thickness (of total t) and enters the cave. 1p-stuck partial-secured is again because the pressure on the fabric for flushing is not enough on the cave side to resist its movement; hence, it does not allow second penetration. Due to flexibility, it moves along with the wire and gets stuck on the cave entrance.

Another notable attachment condition observed with this fabric is 2p full-loose and is most observed in the type C module. A possible reason is that as the wire has a larger β_1, it does the second penetration, but as the wire tends to take a higher trajectory than in the type B module, the fabric being flexible deviates the wire to the top of the cave.

Cotton : The cotton fabric used in attachment testing is from outdoor-wear pants. The fabric is relatively tightly woven than a cotton t-shirt or shirt, making the wire difficult to pierce through. For that reason, it behaves similar to the Delinova 150, but allows more penetration under specific scenarios.

Two significant attachment conditions occur with this fabric, which are not observed often with the other fabrics. These are 1p stuck full-secured, observed in type B and type C modules, and 1p partial-not reached, observed in only type B module. 1p stuck full-secured happens here because the wire does the first penetration through the full thickness of the fabric (t) due to a combination of adequate pressure, back support and adequate β_1, but fails to do the second penetration as the β_2 decreases. The fabric is also tightly woven, allowing the wire to slip on it during its rotation. The 1p partial-not reached condition occurs because the first angle of penetration (β_1) is not as steep in type B module as in type C module, and fabric being tightly woven, the wire fails to penetrate through the entire thickness (t). The reason for not reaching the cave is that the fabric does not allow easy penetration; it pushes the wire under pressure and firm support and restricts it from doing a full rotation, causing the wire to slip internally on the gear.

Wool : Wool is the lightest and most permeable fabric used in attachment testing. This makes the attachment highly dependant on the gradient of the wire for its first penetration. Similar to Delinova 150-Stretch, the quality with wool increases as the gradient of the wire and β_1 increases, i.e., highest in type C module and lowest in type A module. However, wool's toughness is much lesser than Delinova 150, which makes it light. The effect of back support in attachment is lesser in wool than in other fabrics, and the attachment quality increases as the pressure applied on the device during attachment increases. The best condition, i.e, 2p full-secured condition is observed in the type C module with a combination of high pressure, in both cushion support and firm body support.

Effect of module type on attachment quality

The primary differences in the variants of the modules is their seperation between abutmentsα, angle of slopeθ and hence penetration angleβ_1. The observations from attachment testing in three different module types is discussed below :

Type A : The best attachment condition observed in type A module is with wool fabric, under medium and high pressure application. This condition is the 2p partial-secured, which is not the best attachment condition in general as it does not capture full thickness of the fabric (t), which makes the attachment loose over time and the fibres from fabric vulnerable to easy breakage. Moreover, the best observed condition is in wool, because it is a light and loosely woven, which allows easy penetration of the wire. The primary reason for this module not being able to attach well to fabrics is that it has small α, which gives the wire a very small β_1.

Type B : The α is shorter and θ is higher in type B module than in type A, which allows the wire to have a higher β_1. Hence, it is observed that attachment quality using type B module is better than using type A, and the gradient is neither to less nor too much, to allow good penetration of the wire. The best attachment condition observed using type B module is with Delinova 150-Stretch, under high pressure and firm support. This is possibly because the combination of adequate angle of first penetration, pressure, back support and fabric's characteristics allow the wire to penetrate through the full thickness

(t) easily and complete the full rotation entering the cave. Due to the medium gradient of the wire, it is possible to use type B module for attachment on thin and single layer of clothing, as it avoids the risk of piercing the skin of the user, while attaching to the fabric securely.

Type C : The attachment with type C module is fairly good and almost better than in type B module, as it has the shortest α, allowing the best α. Although the attachment is good, a notable attachment condition, 2p full-loose, is commonly observed in this module. The primary reason for this is that as the wire has a steeper angle of first penetration, even a slight force from the fabric during attachment may deviate the wire from it's natural rotational trajectory. This makes the wire slip over the cave after doing the second penetration. For the same reason, it is observed that type C module attached perfectly in wool, where the weight of fabric is negligible and does not put any force to deviate the fabric from entering the cave.

Effect of pressure on attachment quality

The pressure applied on the device during attachment and the back support, together facilitate flushing of the fabric and the device surface. Hence, the combination of both significantly effect the quality of attachment. It is repetitively observed that as the pressure on the device is increased form low to high ,the quality of attachment gets better. In most scenarios, the best attachment is observed under high pressure. However, when the fabric is tough and tightly-woven, like Delinova 150 and cotton pants, medium pressure works fairly better. This is because in these fabrics, as the wire is not easily penetrating, it can push the wire against the surface of the module and restrict it from completing the full rotation and entering the cave. This allows the wire to slip out of the gear inside the module, and hence high pressure application may have a negative effect on the attachment.

Effect of back support on attachment quality

The back support on the fabric is essential in facilitating the attachment effectively. It aids in flushing of the fabric with the attaching surface of the device. The type of back support also determines the equality of pressure on all modules of the device during actuation of the device. It is constantly observed that the **firm body support** performed better or equally good in all scenarios than the **cushion support**.

Effect of wire cross-section diameter on attachment quality

The 5t wire is tested for attachment, using type C module, and on Delinova 150-Stretch and firm body support. The test is to compare it against the 4t wire's performance in the same scenario. It is observed that using the 5t wire, the deviation caused by the fabric to the wire is lesser, hence, the condition of 2p full-loose is not seen here. Overall, the attachment quality is good, but not significantly better than in 4t wire, and seen to be increasing with increase in applied pressure during attachment. This is possibly because it is harder for a thicker wire to penetrate the fabric, and the movement of fabric during attachment would adversely effect it.

Conclusions from attachment testing

Some general and significant observations from the attachment testing of the Spindel-tech are :

- The angle of change of rotational plane ϕ in the Type A modules is very less, due to larger seperation between abutments (α), making the first penetration angle (β_1) less. This restricts the device to attach well on tough fabrics commonly used by the first responders. The α in Type B module is most adequate out of the three types of wires, as it facilitates good penetration into the fabric, and does not allow the wire to get deviated over the cave easily as in type C module. Type B module is also suitable for usage when the user is wearing a single thin layer of clothing, due to just enough depth of penetration (D_p).
- Pressure distribution and back support distribution is not equal throughout all the modules on the device. This is commonly observed as when the user actuates the device for attachment, some part of the circular surface of the device remains more flushed with the fabric surface, than the other. This makes some modules act differently than others even when all the other variables (back support, pressure, module type, fabric) are same.
- The device attaches best to fabrics that are not very tightly woven, slightly flexible, and not coated for waterproofing. It is observed that the best attachment of the device happens on Wool and Delinova 150-Stretch, which have these characteristics.
- The main effect of the pressure and back support on the module is to restrain the fabric from moving on the surface of the device during the attachment, facilitating an ideal condition for the wire to make both penetrations and enter in to the cave. Even though firm bodily back support on the fabric is better than cushion support, the most ideal condition needs to have some softness in the support. This is to prevent the pressure getting transferred on the wire, which may result in restricting its rotation and allowing it to slip internally on the gear.
- The fabric tends to remain towards the cave during the attached state. However, during general movement of system, for example, when walking or during any external force on the attached system, the fabric could possible move anywhere on the wire along δ.

5.4 Strength test

The testing of strength is done on one type of fabric. This is to ensure repeatability of testing. The fabric chosen is the Delinova 150 Stretch for its combination of high tear resistance and elasticity. This provides a more accurate analysis of the device without damaging the fabric easily.

Objective

The primary objective is to analyse the force bearing capacity of each module, and hence the device, in its attached condition. The force is to be analysed in different directions, to know the weakest and strongest components of a module and the device as a whole.

Parameters to study

- Directional ultimate strength per module (f_u) and of the system (f_u^{sys})
- Functional limit per module (f_f) and of the system (f_f^{sys})

Observable

- Directional forces on individual modules of type A,B and C in Z-axis, positive Y and X axes, and negative Y and X axes (based on the local coordinated of the device)
- Directional forces on a 4m device, in Z-axis, and in direction parallel to the surface of attachment
- The behaviour of failure in different types of modules in different directions, to observe the weakest points on the modules with respect to the directional force applied
- The directional forces for which a module resists the weakest and the strongest

5.4.1 Variables and combinations in testing

The detailed list of experiments is as shown in Appendix A.2. The main variables in the strength test are:

- **Direction of force** : As discussed earlier in the technology investigation of the Spindel-tech, a local coordinate system (Figure 20a) is used for the device, to ease the directional orientation. Based on that, the directions for force application during the tests are in Z-axis, positive Y and X axes , and negative Y and X axes.
- **Module type** : All three variants of modules, i.e, type A, type B, and type C are tested individually. For the 4m device testing, only type B is used. The 4m device is used as the orientation of each module in such a device is at right angles to each other. This gives a clearer analysis of force bearing behaviour of individual modules, and their effect on each other when placed in combination as in the device
- **Wire type** : Two types of wires are tested in the modules. These vary in the diameter of their cross-section, one is 4t (0.4 mm) and the other with 5t (0.5 mm)

In order to understand the strength and force bearing capacity of the device, it is important to analyse the same for a single module in the device, as that is the component holding the wire attached to the fabric. Hence, along with the 4m device, 1m device is tested in various combinations of the different variables. The Table 6 shows combinations in which the different modules and the device is tested.

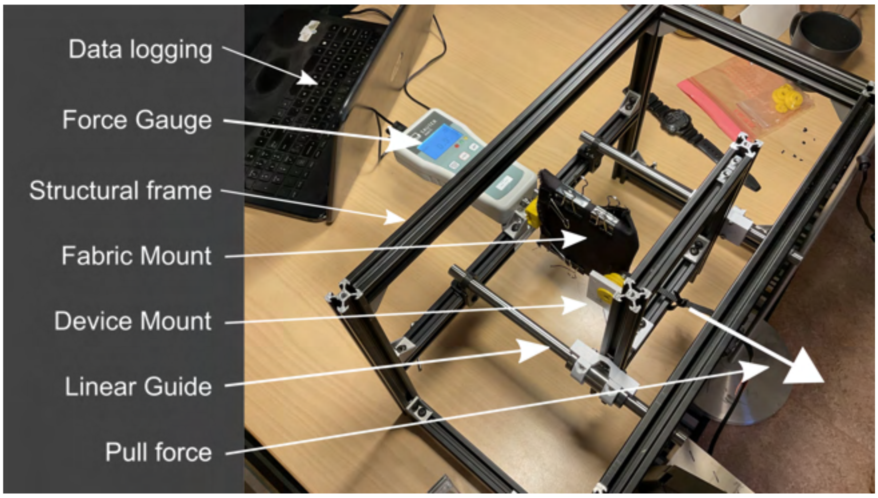
5.4.2 Setup

The real usage conditions would be such that the forces on the device would not be completely unidirectional. This is because of the nature of the fabric, when the device would be pulled away from the attached surface along with the object. However, to observe the unique forces in individual directions, the setup is made so the force can be applied unidirectional on the device. The setup (Figure 38) includes :

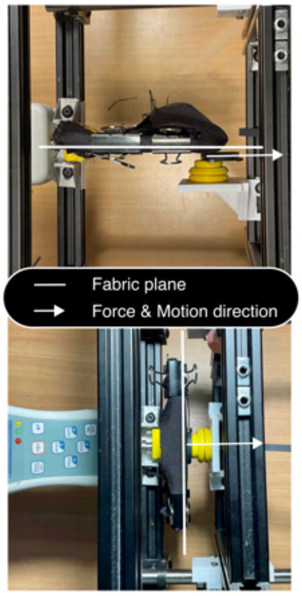
- **Main frame** : The cuboid frame structure is made of 20 mm aluminium sections, held together with corner flanges, screws and locking nuts. This gives structural rigidity to the setup when the forces are applied.
- **Device mount** : This is a square frame made of the 20 mm aluminium sections, and rests on two guide rods with linear bearings, to allow linear movement across

Table 6: Strength test combinations

Combination	Reason
Type B module using 4t wire in Y-, Y+, X-, X+, Z	Type B module attaches best to Delinova 150-Stretch
Type B module's injection moulded variant using 4t wire in Y- and X-	To analyse performance difference between 3D printed Type B module and injection moulded variant in directions needing maximum force
Type A and Type C using 4t wire in Y+, X-, Z	To analyse performance difference from Type B module on directional forces along one axis each
4m device using 4t wire in Y+, 45°Y+, Z	These directional forces mimic forces in real usage scenarios (perpendicular and parallel to surface)
Type C module using 5t wire in X-, Y+, Y-, Z	To analyse difference in force bearing capacity between 4t and 5t wire, in all the axes
Type B module's injection moulded variant using 5t wire in Y- and X-	To analyse difference in force bearing capacity between different 5t and 5t wire in injection moulded variant, in strongest directions
Type B module with a removed cave using 5t mm wire in Z	To analyse the effect of cave under Z directional force



(a) Experiment rig - components and placement



(b) Two orientation of setup

Figure 38: Strength experimental setup

the bigger cuboid frame. The device is mounted on a 3D-printed plastic mount in the centre of the frame. There are two types of these plastic mounts (Figure 38b)-

– **Perpendicular device mount** has the attaching surface of the device perpendicular to the axis of movement of the device holding frame. This is used to analyse the Z-axis forces on the device (both 4m and 1m)

- **Parallel device mount** has the attaching surface of the device parallel to the axis of the device holding frame. This is used to analyse the forces in Y and X-axes on the device (both 4m and 1m)

- **Force gauge** : A digital hand-held force gauge is used to measure the force, and is connected to a computer for logging the read data during the tests. The force gauge used has a measuring capacity up to 250 N, resolution of 0.1 N and maximum error of 0.2%. It is mounted on top of a straight beam of 20 mm aluminium section. This beam is mounted perpendicular to the middle beam of the main frame, in the centre, in the same axis as the movement of the device holding frame.
- **Fabric mount** : The fabric is clipped tightly at the edges of a square, 3D-printed plastic frame. The frame is attached to the fixture on the force gauge. There are two fabric mount orientations (Figure 38b) -
  - **Perpendicular fabric mount** keeps the fabric surface perpendicular to the axis of movement of the device holding frame. This is used in combination with the perpendicular device mount
  - **Parallel fabric mount** keeps the fabric surface parallel to the axis of movement of the device holding frame. It is used in combination with the parallel device mount
- **Force application** : A pull force is applied along the axis of linear guide. A rope is connected to device mount, pulling which exerts force on the connection between device and fabric. The application is a gradual force, in reaction to the resistance given by the attachment. In other words, it is displacement driven force application, similar to how tensile testing is carried out for materials on Universal tensile machine. In the setup, constant force can be applied by hanging desired weight to the rope, supported by a pulley.

Procedure : The setup is placed on a table and the force gauge connected to a computer. For testing of the 4m device, the device is placed on the perpendicular or parallel mount, depending on the direction it has to be tested in. For testing the 1m device, the module is placed in one module slot of the device. Testing in Y and X axes, a module is placed in a slot of a device in parallel mount, and the desired direction is set by rotating the device at certain angles. The rotation angles are marked on the device mount. The module is then attached to the fabric which is placed on the fabric mount. For testing in Z, same procedure is followed in Perpendicular mount.

In this type of setup, the back support needed for attachment is applied by hand using a soft surface between the fabric and the hand. To start force application, the device holding mount is pulled using a firm string gradually (see Figure 38). The force gauge measures and logs the reading to the computer at 50 milliseconds interval. The frequency was found to be sufficient for the reasonably measure quick changes in Force. During the testing, a slow motion video of the module-Fabric attachment is captured. A rough measure of travel of the device is also estimated from travel of the rope using a measure tape. The travel speed is a measurement of rate of deformation, variation in which may affect test results. After a test is done, the modules are removed and replaced by removing the top cover of the casing. The modules are photographed and observations are documented. This is repeated for the different types of tests.

5.4.3 Results and Observations

A series of experiments, as mentioned in Table 6 and Appendix A.2, generated data for ultimate failure strength in each condition. In addition to the controlled parameters, uncontrolled parameters like attachment condition were also part of the observation. Analysing the data of ultimate strength, variables, end condition and deformation of wire, the results are presented as follows.

Directional ultimate strength $f_{u,dir}$

Directional ultimate strength ($f_{u,dir}$) values for a single B type module with 4t wire is presented in Figure 39. Each experiment is carried out with displacement driven force application and repeated 3 times. Some experiments are repeated 5 times, if high variation is observed. The diamond markers show individual observations, while the error bars shows one standard deviation on each side of average value. In this subsection, strength is used to refer to directional ultimate strength of modules ($f_{u,dir}$).

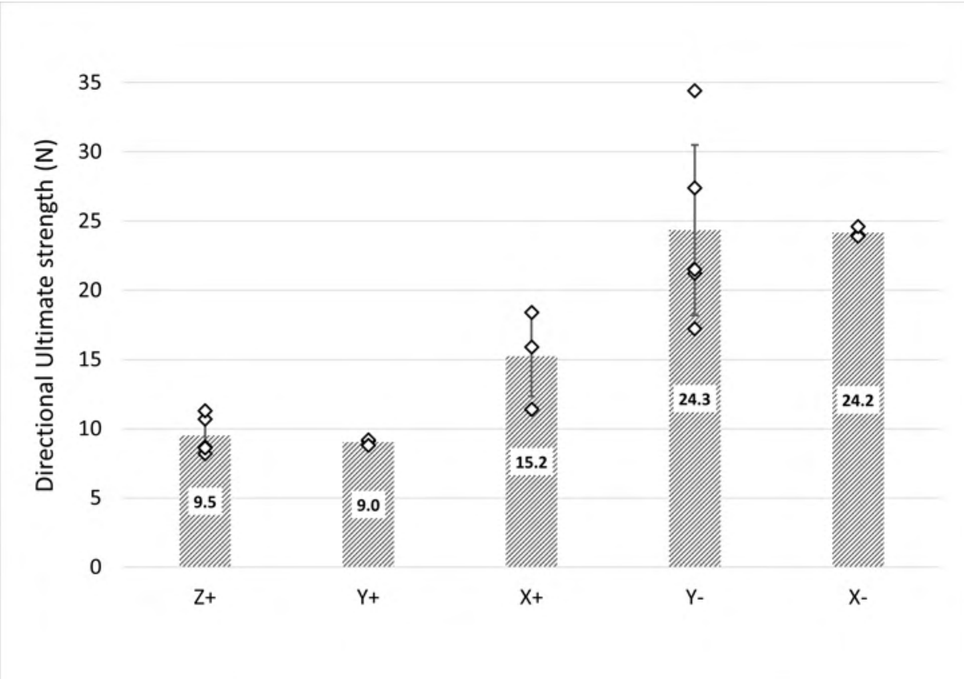


Figure 39: Directional Ultimate Strength $f_{u,dir}$ for one B type module with 4t wire

It is evident from Figure 39 that the minimum strength, 9N, is seen in Y+ and Z+ directions. The high strength of 24N is observed in Y- and X-.

X+ and Y- strengths have high variation compared to Y+ and X-. Z+ also has higher deviation in strength compared to Y+ and X-. It is observed that, in both Y+ and X- both wire solely supports the force. Hence, the stress in wire and deformation of wire determines the ultimate strength in these directions. However, in other three directions, the wire is partially supported by the cave initially. Once wire deforms sufficiently to pop-out of the cave, it then supports the force on its own. This two phase deformation causes uncertainty. Secondly, during pop-out from cave, the wire undergoes an uncontrolled transitions from one state of boundary condition to another. Having a non-changing boundary condition is a likely explanation for low variation in strength in Y+ and X-.

Fabric tends to slip off the wire whenever under force. In any direction, fabric slipping is an active mechanism. The cave gives some resistance to fabric slipping when motion is against it. Another factor which affects the strength, especially in Y-, is the length of wire inside the cave. This length can change because of faulty manufacturing of wire, or issues in gear (discussed in Section 5.6). The maximum observation at 34N is example of such condition. This effect is further experienced in Y- testing of moulded modules.

Producing repeatable results, these directions can be designed to take load reliably in a system configuration. Moreover, measuring strength in three directions Z+, X- and Y+ would be sufficient to reliably define strength of a module, it shows. These three direction includes high and low strength directions and all orthogonal directions, hence sufficient to define performance of a module. Only testing three directions, reduces the experiments while capturing still gaining required information.

Effect of module variants on $f_{u,dir}$

Figure 40 represents strengths for module variants. As expected, low error is observed in X- and Y+ directions in all variants. For Z+ direction A is stronger, while in X- C is stronger. Notably, there is no , universal trend in strength between module variants. For the trend in Z+, it can be argued that because of low ϕ more deformation is required

in Z direction in order for fabric to slip. And as ϕ increases, the deformation required is less, hence C has lower value. However, it should be noted that the measurement error is $\pm 0.5N$. The strength values are not far apart to assume trend's significance. In Y+, strength values are also nearby.

In X-, wire bends at the second abutment. However 3D-printed modules were breaking at the strength point. in 3D-printed less wire deformation is observed because the force is transferred to the plastic top cover which breaks. But, in case of moulded modules, the material of top cover do not break and wire bends. Coincidentally, the strength values are not different between 3D printed and injection moulded modules, later having marginally less value.

Effect of wire thickness on $f_{u,dir}$

A simplified model discussed in Section 3.4 predicts that in y+ and Z, the f_f would be proportional to r_w^3. Unlike in X-, plastic deformation under F_{y+} and F_z are relatively low. The low plastic deformation suggests that the Ultimate failure happens soon after functional failure. Because of this observation, f_u should also be proportional to r_w^3. This proportionality is predictive rather than exact. Change of wire thickness r_w from 4t to 5t would approximately increase f_f by 1.95 times, and hence f_u, in Z and Y+.

Figure 41 visualises $f_{u,dir}$ for wire thickness variants tested using C type module. The ratio of $f_{u,dir}(5t)/f_{u,dir}(4t)$ is 1.98 and 1.62 for Z and Y+ respectively. The reduced value in Y+ is expected to be because of higher fabric slipping, and changing force application point. Both of which would be relatively low under F_z. This observation validates the simplified theoretical model for relational understanding and approximate predictions. Based on the model, 6t wire would have 3.37 times strength while, 8t wire would give 8 times strength. However, actuation force would also increase as discussed in section 3.5.

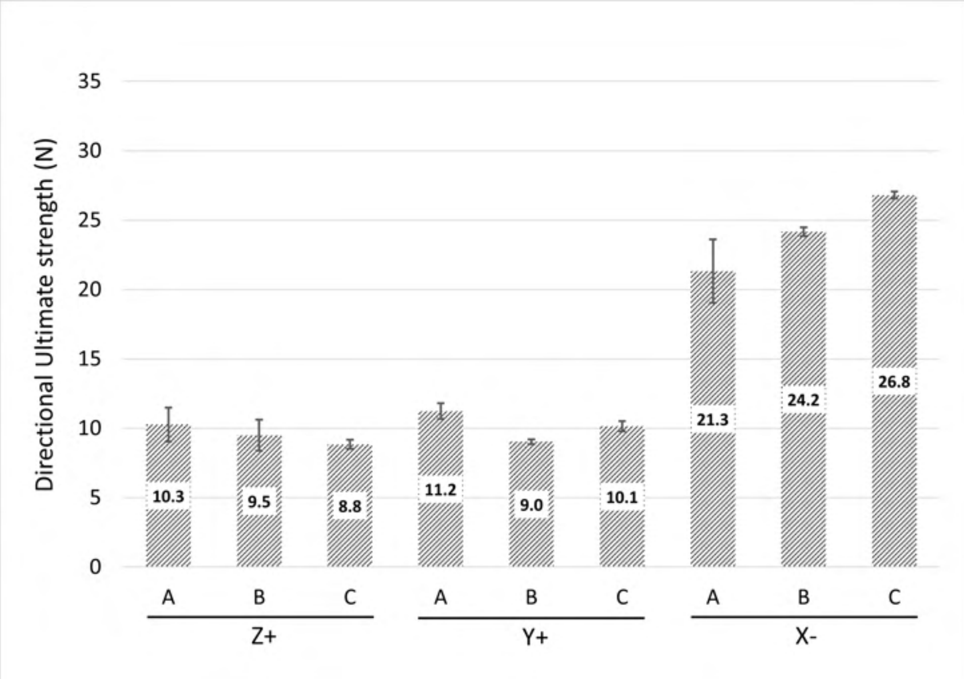


Figure 40: Comparison of Directional Ultimate Strength $f_{u,dir}$ between module variants (single module, 4t wire)

Due to Very high plastic deformation it is not possible to predict $f_{u,x-}$. 5t wire has 1.31 times high $f_{u,x-}$ compared to 4t thick wire. Based on one test, $f_{u,y-}$ also has similar increase.

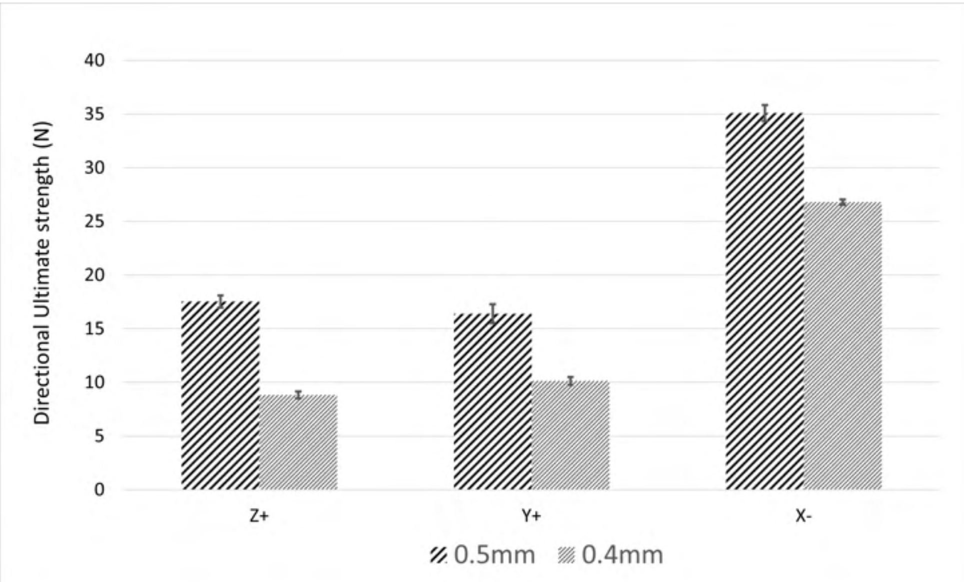


Figure 41: Comparison of Directional Ultimate Strength $f_{u,dir}$ between wire variants (single C module)

Effect of Cave on $f_{u,dir}$

The comparison of $f_{u,dir}$ of modules with and without cave gives insight in to the contribution of the cave in strength. Table 7 documents which performance parameter is affected by the various walls of the cave. The table is based on motion understanding of wire observed from with cave modules and strength understanding gained from no-cave experiments. No-cave experiments used C variant of module and 4t wire thickness.

In Z direction, $f_{u,z}$ retains 90% (7.9N) of its strength with cave, if penetration is 2p. If only 1 penetration is achieved, the strength drops to 55% (4.8N). In Y- direction, $f_{u,y-}$ has 85% (20.6N) value of module with cave. There is no affect on strength in Y+ and X-. As Table 7 shows, the attachment is positively enhanced by the cave acting as opposite support. However, cave height negatively affects first penetration as the fabric can not flush.

Table 7: Effect of cave walls on strength and attachment

Cave wall	Attachment	Z+	Y+	Y-	X+	X-
Top wall	$\sim$	$+$	$\sim$	$+$	$+$	$\otimes$
Outer wall	$+$	$\otimes$	$\sim$	$\otimes$	$+$	$\otimes$
Inner wall	$+$	$\otimes$	$\otimes$	$\sim$	$\otimes$	$\otimes$

$\sim$: minor effect $+$: Contributes positively $\otimes$: Do not affect

System's Directional ultimate strength $f_{u,dir}^{sys}$

Hypothesis: As all modules are subjected to same directional force, a system with n modules should follow equation 12 (see Figure 42a for force direction visualisation).

$$f_{u,z}^{sys} = nf_{u,z} \tag{12}$$

For parallel forces (shear force), i.e. Φ°Y+, The ultimate strength is summation of directional limits of each module according to its orientation.

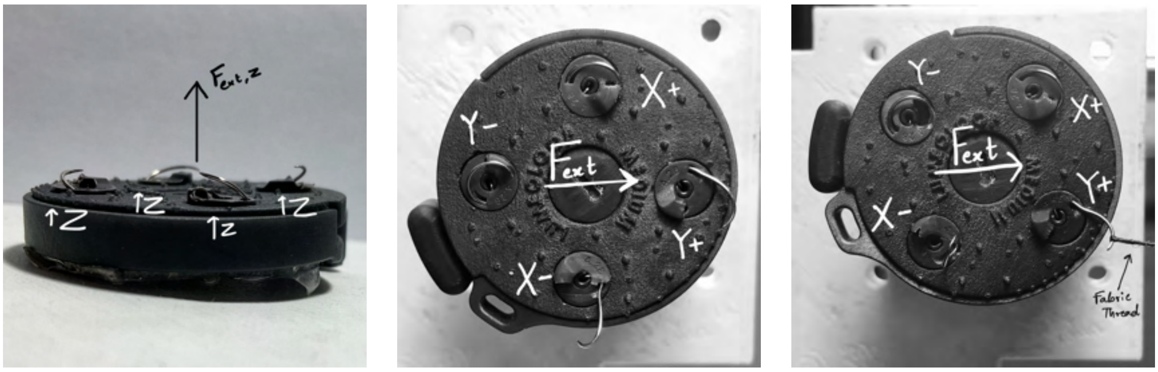
$$f_{u,\phi y+}^{sys} = \sum^{n} f_{u,dir} \tag{13}$$

For 0°Y+ condition in Figure 42b, $f_{u,0y+}^{sys} = f_{u,y+} + f_{u,y-} + f_{u,x+} + f_{u,x-}$

Figure 43 plots measured values of $f_{u,dir}^{sys}$ for a 4 module system. As per equation 12, a 4 module system (4mB4t) should have $f_{u,z+}^{sys} = 38$N . However, it is observed to be 23.2N. The reduction is attributed to attachment conditions. They were observed to be partial fabric capture or loose. Based on multiple testing, it can be concluded that on average only a fraction of modules would attain good attachment condition in the system, called as attachment quality (see Table 4). When sizing a system, this fraction measuring attachment quality needs to be considered and equation 12 should be updated with a factor q to capture attachment quality ($0 < q \leq 1$).

$$f_{u,z}^{sys} = qnf_{u,z} \tag{14}$$

A 4 module system using 5t wire and moulded B modules had 58N $f_{u,z}^{sys}$. This observation also follows q factored equation 14.



(a) Z **(b)** 0°Y+ **(c)** 45°Y+

Figure 42: Deformed state of 4m system in various force condition (B, 4t). (Direction label near module represents local force direction on each module)

Strength for parallel forces also do not meet the requirement. According to equation 13, the strength should be 72N, while observed value is around 63N. Effect of factor q can also be applied here. However, given that each orientation has different contribution, which module is not applied would change the result. In the lowest value observed in the Y+ direction in Figure 43, the module oriented in Y- had loose attachment where fabric slipped, and the module contributed less.

Nevertheless, a Heuristic approach is to not count any contribution of the modules oriented in y+ direction. As the F_y is supported by wire deformation, if deformation is not possible, wire can not support the force. Other orientations, X-, Y- and X+, do not deform in initial stage. This would make Y+module to have very minor or no force applied on it. This is the rational behind the heuristic approach. Based on the heuristic the system strength should be 63N, which is what is observed. The heuristic will provide a maximum ultimate strength of system.

$$f^{sys}_{u,\phi y+} = \sum^{n} f_{u,dir} \qquad ; dir \neq y+ \tag{15}$$

5.5 Failure test

The failure testing is done on a 4m device, using only the type B modules. It is performed on the four different fabrics, i.e, Delinova 150 , Delinova 150 Stretch, Cotton and Wool.

- **Objective** The primary objective of the failure testing is to analyse the behaviour of failure of the modules in attached condition, under different types of force applications. These forces are not completely uni-directional, but are mimicking the real usage force application scenarios.
- **Parameters to study**
  - Damage to fabric after device failure
  - Behaviour of device failure
- **Observable**
  - Type of breakage in modules and damage to the fabric after the device gets detached due to force application

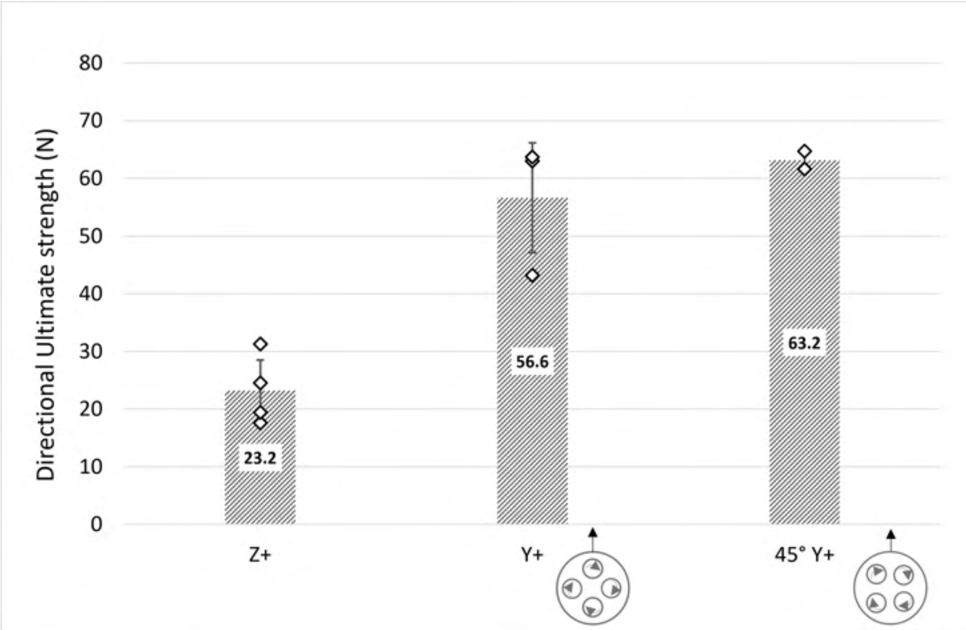


Figure 43: Directional Ultimate Strength for 4 module system (B type, 4t wire)

- Effect of type of attachment on the failure of the device and type of breakage in the modules
- Effect of type of directional force application on the device and the fabric
- Behaviour of different fabrics under different types of force applications on the attachment

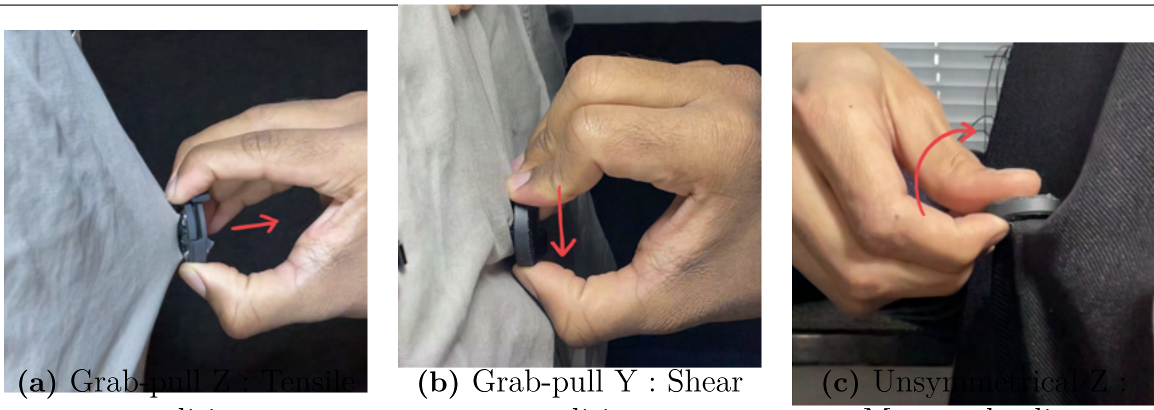
5.5.1 Variables in testing

The tests are performed using the type B module with a 4t (0.4mm cross-sectional diameter) wire. There are two main variables in these tests, the different fabrics and the type of force applied. The materials used in the testing are Delinova 150, Delinova 150-Stretch, Cotton and Wool. The different types of forces applied are from the usage conditions:

- **Grab-pull Z** : This is the force condition when the device is grabbed and pulled, in its attached condition, perpendicular to the surface of attachment (Figure 44a)
- **Grab-pull Y** : This is the force condition when the device is grabbed and pulled parallel to the surface of the attachment (Figure 44b). Y+ and 45°Y+ are two variations for a 4m system.
- **Unsymmetrical Z** : This is the force condition when the device is grabbed from one of the sides (for e.g, under-side) and pulled perpendicular to the surface of attachment (Figure 44c)

5.5.2 Setup

The failure testing was carried on four different fabrics. A rectangular piece of cardboard is used as the support structure, that holds the fabric stretched and tight. The 4m device is attached to the fabric while on a firm bodily support. Then, the fabric is clipped on the edges of the cardboard piece. For the testing, failure of device is caused by pulling it in a certain direction. Slow-motion video is captured with focus on the attachment point. After failure, detailed documentation of fabric damage and end condition of wires and



(a) Grab-pull Z : Tensile condition

(b) Grab-pull Y : Shear condition

(c) Unsymmetrical Z : Moment loading

Figure 44: Realistic Failure testing conditions

modules is carried out including photo-documentation. The test is repeated by changing the damaged modules to test on different combinations of fabrics and force conditions.

5.5.3 Results and Observations

While strength experiment observes behaviour under uni-axial force, the failure testing observes in near-real force condition. The overall behaviour would differ because of complex and adjusting loading in failure testing. However, the mechanism of failure for modules remain same. Some conclusive observations are mentioned.

(a) Wire inside the cave

(b) Wire popped out of cave

(c) Further deformation

Figure 45: Process of Wire deformation (Unsymmetrical Z force)

(a) Modules on verge of failure

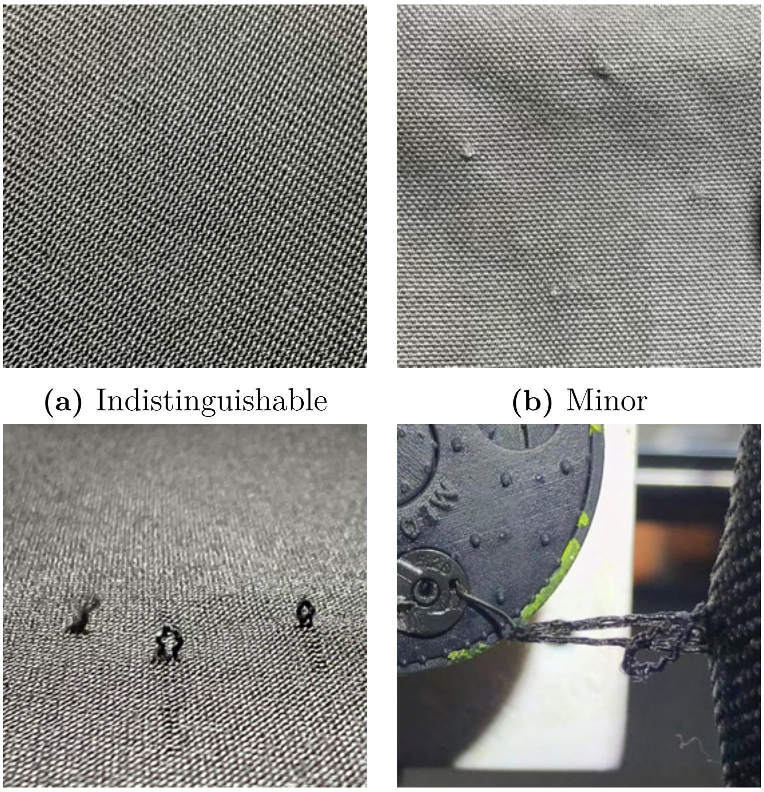
(b) One module fails - Frame 2

(c) Fully detached - Frame 3

Figure 46: instantaneous Ultimate failure of system

Conclusive observations

- Force concentrates on modules in Y direction loading (shear loading) because of non-rigid nature of fabric.
- Unsymmetrical force is observed to create very high force concentration on single module (or two if applied along edge). The module opposite of the load is seemingly unaffected, while the nearest module fails.
- Once a module fails, it starts a quick chain reaction of system failure. The failure of module suddenly load other modules with that force. This sudden force transfer, pushes other modules to their failure limit. Figure 46 illustrates how fast is this failure chain reaction. Figure shows three consecutive frames in 240 frames/second video. The failure happens instantly. This indicates that in a uniform loading condition, no module can fail, if not the whole system will fail.
- It is observed and verified that the screw is a weakness point in the force-flow. This observation is also supported by breakage of screw during strength testing. Having only a central holding element (the screw), the top plates bends and tends to come out of the casing when under load.
- In Z direction loading, the deformation is a two-stage process. First the load is supported by the cave, and the deformation is seen as increase in ϕ. Once the deformation is enough, the wire pops out of the cave and starts to deform as bending. (See Figure 45)



(a) Indistinguishable **(b)** Minor

(c) Pills **(d)** Stretched

Figure 47: Fabric Damage

Fabric damage

- Tensile forces in a loose attachment condition have almost indistinguishable fabric damage (Figure 47a and 47b). This indicates prominence of fabric slipping and low wire bending stiffness (S).
- Delinova 150 stretch shows most failure of all fabrics tested. This is also observed in the strength test. (see Figure 47c and 47d)
- In strength testing, more fabric damage is observed compared to failure testing. This is likely because of controlled motion in strength testing, which does restrict the fabric slipping due to minor change in direction (as in failure testing). Multiple times, a thread was stuck to one of the wires, elongating for over 2 cm (see Figure 47d).

5.6 Problem-cause analysis

There are multiple problems observed during the three types of testing. The problem-cause diagram (Figure 48) highlights on the main functional problems in the device and the different factors causing them. The problems are highlighted in orange boxes, the pink boxes show the factors which lead to these problems, and the grey boxes highlight on the domain of the attachment system these factors belong to. The causal effect of each factor leading to a problem or another factor, or vice-versa is stated on the leading arrows.

Functional problems

Wire unable to enter the cave smoothly

This means that when the wire is actuated, even in absence of fabric, it either hits the cave (Figure 49a) , or rubs the side or top wall of the cave before entering or slipping over the cave (Figure 49b). The two main reasons are - (1) the tip of wire having an upward or inward bent as a manufacturing defect, and (2) the deviated trajectory of the wire due to vertical gap between top cover and gear of the module. The second condition occurs when the wire gets high resistance from bending at the slope (less distance between two abutments) and flexes the top cover (Figure 49c) to create enough space to come out and upwards from the groove in the gear.

Wire slipping off the gear

This means the straight part of the wire, which is placed in a groove on the gear, rises up and slips out from the groove. This makes the gear loose control on the wire rotation (Figure 50a, and also damages the gear (Figure 50b).

Wire unable to reach the cave

This means that the wire tip failed to reach a desirable amount inside the cave as it should naturally do. Two main causes associated to this problem are - (1) the tip of the wire is grind more, so the length of the wire becomes less, and (2) the wire is unable to do the amount of rotation it should (Figure 51b), because of it slipping off the gear.

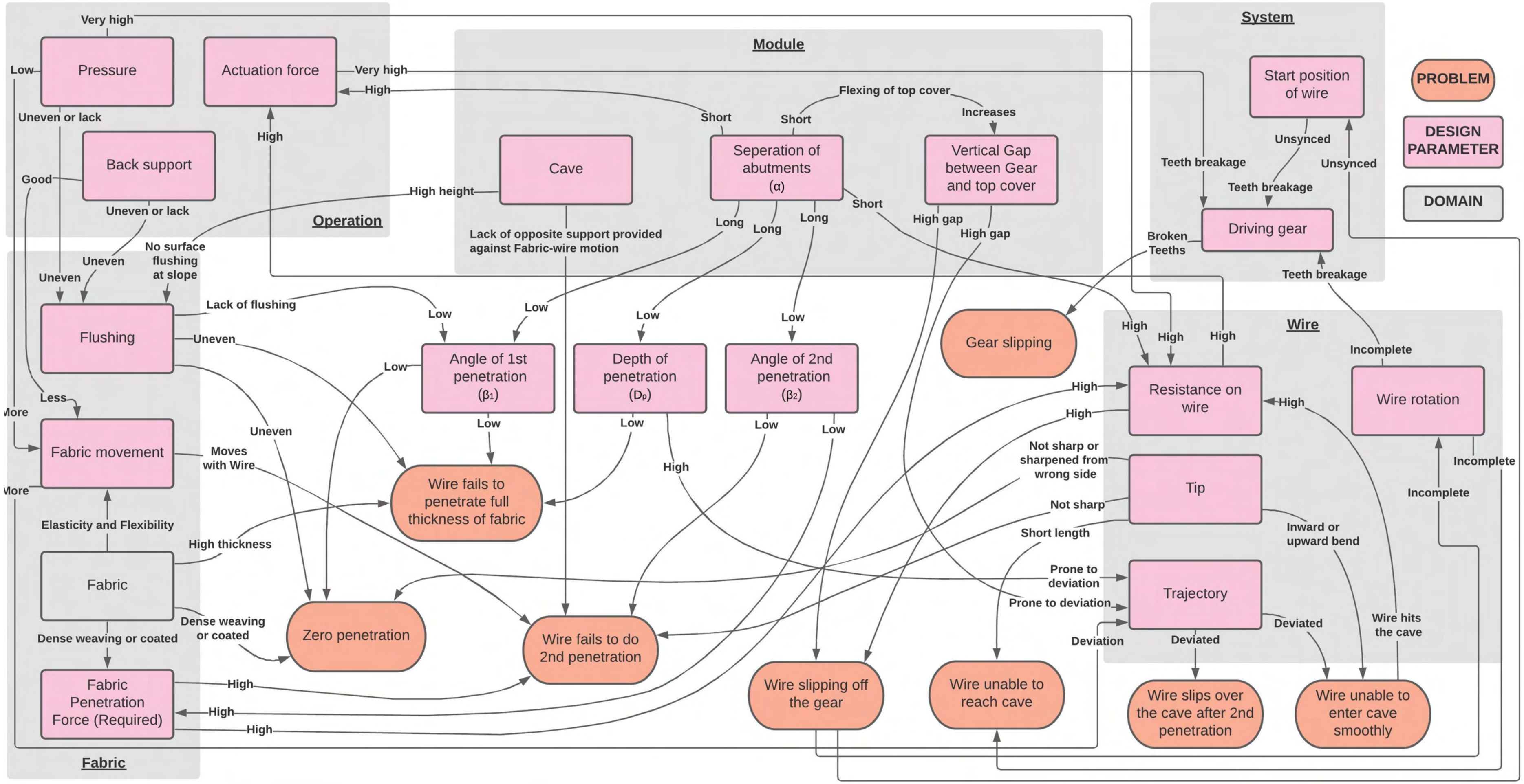


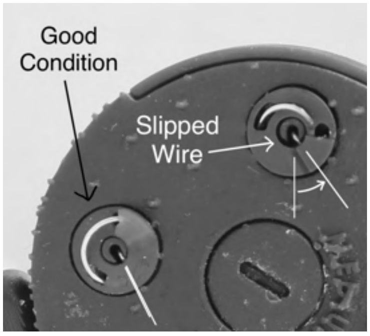
Figure 48: Problem-cause diagram

(a) Wire hitting top wall of cave entrance

(b) Wire slipped over the cave

(c) Flexing of module due to reaction force from wire bending at Top abutment

Figure 49: Causes for wire not entering the cave smoothly



(a) Gear losing control on slipped wire

(b) Damaged gear due to wire slipping off the groove on right, compared to original gear on left

Figure 50: Wire slipping off the gear

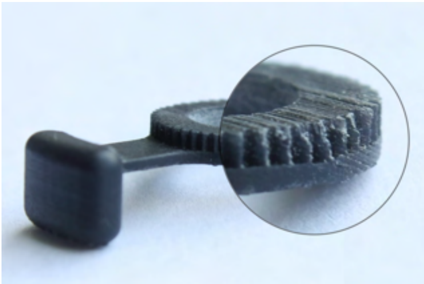
Gear slipping

This means the driving and driven gears slip, leading to loss of rotation on the wire/wires in the respective module/modules where the slipping happens. The main reason for this is teeth breakage in either of the gears (Figure 51a). The teeth breakage occurs when - (1) the lever (driving gear) is actuated under very high actuation resistance, which is either due to the slope of the module, or from an externally induced resistance on the wire. (2) The initial position of wire in all modules goes out of sync (Figure 51b) because of the wire slipping on gear, which makes wire hitting the end of rotation faster in some modules and resisting the driving gear.

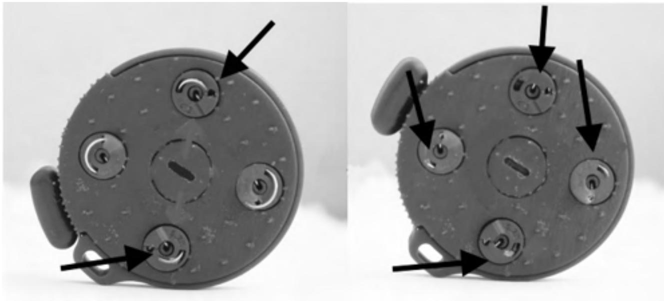
Attachment problems

Zero penetration

This is an attachment condition where wire completely fails to capture the fabric. There are multiple causes for this condition - (1) lack of back support and pressure, which leads to uneven flushing with fabric surface, (2) Dense and tightly woven fabrics, (3) Low β_1, due to the larger α, (4) Wire not grind properly on the tip (Figure 53). Flushing of the fabric with the device's top surface is not evenly distributed. The cave restricts some part of the fabric. The Figure 52a depicts the flushing of the device surface with fabric. It is seen that the roof of the four caves has a prominent mark on the fabric.

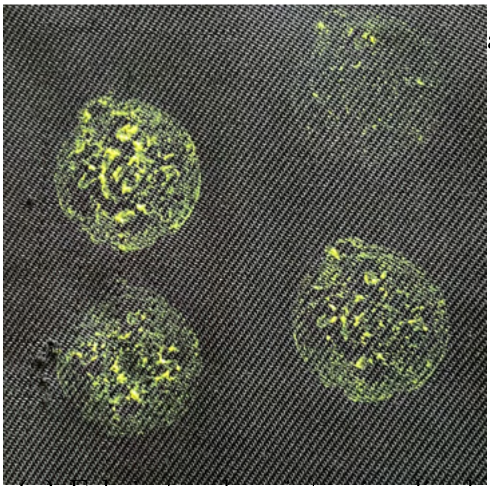


(a) Broken teeth of driving gear (lever)

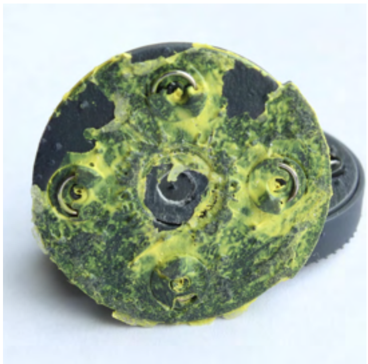


(b) Wires in modules gone out of sync (Left - Wire do not reach the cave, Right - Different positions of wire in resting)

and out of sync wires



(a) Fabric touch points visualised with colour



(b) Colour removed from system

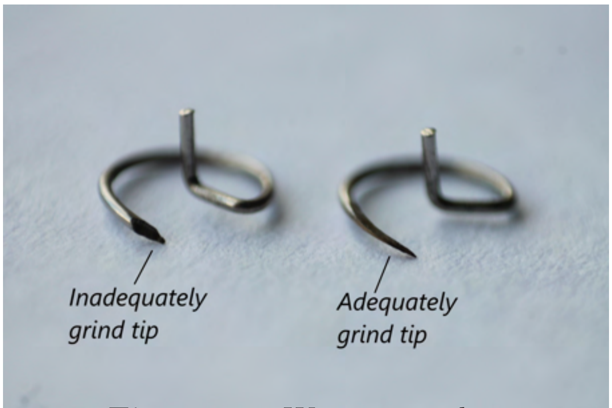


Figure 53: Wire tip quality

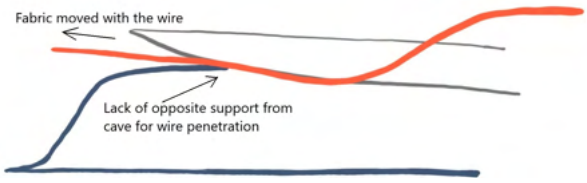


Figure 54: Illustration of lack of cave support on fabric due to fabric movement

Wire fails to penetrate full thickness of fabric(t)

This problem is caused by (1) smaller angle of the wire due to a larger α, which further leads to low β_1 and lower D_p (Most observed in Type A modules and least in Type C)

(See figure 21) . (2) Uneven or lack of back support and pressure, which leads to uneven flushing with the fabric surface. (3) High thickness of fabric (t) with respect to D_p of the wire would also lead to this problem.

Wire fails to do second penetration

This is an attachment condition where the wire does the first penetration but not the second one. The main reasons are - (1) Uneven or lack of pressure and back support allowing fabric to move during attachment, this makes the fabric move with the wire instead of allowing it to penetrate. This further leads to lack of opposite back pressure from the cave on the fabric to facilitate second penetration (Figure 54). (2) Dense and tightly woven fabrics need a higher force of penetration, and as they do not spread on the contours of the device surface, the force required can get increased due to low β_2 (3) Tip of the wire not grind sharp enough, or grind incorrectly.

Wire slips over the cave after second penetration

This means that the wire does two penetrations through the fabric, capturing it completely, but fails to enter the cave, instead goes over the cave. The main reason for this change in trajectory of the wire is due to fabric movement. This problem gets alleviated when the α on module is short (steep slope), leading to high depth of penetration (D_p), and slight deviation by fabric would allow the wire to go over the cave.

5.7 Target requirements for Improved Design

Understanding technology and user needs, following Target requirement list is developed. Requirements are created based on performance demand, user needs, cost, environment and sustainability aspects. Included user needs are common needs of the users described in the chapter 4. However, a particular user group, i.e. Police personal, would have additional specific needs. Such specific needs of particular user groups are not included in the list and current development.

The requirements are structured as 'Demand' or 'Wish'. Demand has to be met by the concept, while wish's target value is a desired value to approach. For critical performance parameter, both demand and wish values are incorporated as requirement to guide the design process. The requirement are defined for the technology in a general context. Some of these requirements are not applicable for the current development which are mentioned in the following discussion.

The demand for resting weight capacity is based on the weight of common equipment user would use. Body CAM has potential use of the technology, as it is attached to torso of police person (of certain places). Taking it as reference, the demand value for resting weight is set at 200g, higher than 174g of a reference body-cam (Axis W100 camera by Axis Communications AB). The demand is also higher than weight of smartphones, if considered for general use. Wish for resting weight capacity is kept at optimistic value of 1kg.

It is targeted to reach 200N f_u^{sys} based on the most functionally comparable competitor, Velcro® and Dual lock fastener. With attachment area of 40mm diameter, restricted by

Table 8: Requirement list (D:Demand, W: Wish)

ID	Requirement	d/w	Value	Unit	How to measure
	Strength				
1	Support minimum resting weight m_{obj}^{sys}	D	200	g	Experimental
2	Maximise resting weight capacity m_{obj}^{sys}	W	1000	g	Experimental
3	Minimum combined directional ultimate strength f_u^{sys}	D	100	N	Experimental
4	Maximise minimum directional ultimate strength f_u^{sys}	W	200	N	Experimental
5	Minimum functional failure strength f_f^{sys}	D	10	N	Theoretical
6	Maximise minimum functional failure strength f_f^{sys}	W	50	N	Theoretical
	Cost and Lifetime				
7	Maximum Manufacturing cost per device	D	150	SEK	Cost calculation
8	Lifetime - Number of cyclic operations (Min. of all components)	W	1500	#cycles	Lifetime assessment
	Attachment				
9	Allow flexible placement on the body	D	-	-	Experimental
10	Allow secure attachment - independent of Bodily or cushion-like back-support, and orientation	D	-	-	Experimental
11	Firmness of attachment - Minimise wobble	W	-	-	Experimental
12	Wide Fabric compatibility	W	-	-	Experimental
	Safety				
13	Should not harm the user when in use	D	2	%cycles	Experimental
14	Should not harm the user when actuating without fabric or holding	W	10	%cycles	Experimental
	User-friendliness				
15	Allow usage with gloves	D	-	-	Experimental
16	Ergonomic design for holding and actuation	W	-	-	Experimental
17	Maximum force of actuation	D	20	N	Experimental
18	Minimise force of actuation	W	2	N	Experimental
19	Maximum number of steps involved	D	6	#of steps	Experimental
20	Minimise number of steps involved	W	3	#of steps	Experimental
	Design and Assembly complexity				
21	Minimise number of unique components in the system	W	7	#	Experimental
22	Maximum Number of components in the module	W	3	#	Experimental
23	Minimise Number of assembly interaction steps	W	30	#	DFA
	Working environment				
24	Maximise 'Maximum operating temperature'	D	35	°C	Material Properties
25	Minimise 'Minimum operating temperature'	D	-30	°C	Material Properties
26	Should be operational in mild rain	D	-	-	Material Properties
	Size				
27	Maximum Width	W	40	mm	CAD
28	Maximum Length (Height)	W	40	mm	CAD
29	Maximum thickness outward from the fabric	W	10	mm	CAD
	Other				
30	Must be able to disassemble to a degree that the materials can be recycled or remanufactured	D	80	%mass	DFA
31	Allow for easy and quick replacement of Vulnerable components	W	-	-	DFA
32	Allow usage by differently abled users	W	-	-	Ergonomics study

size requirement, shear and tensile strength for Velcro® is 151N and 88N respectively. Same for Dual lock fasteners would be 145N and 176N. (Zhang et al., 2019) Given this performance, if the technology achieves minimum directional strength of 100N at least, it would be comparable. If 200N is achieved, the technology would surpass the performance of Velcro® and dual lock fasteners in strength aspect. With this reference, 100N and 200N are kept as Demand and wish for ultimate strength f_f^{sys}. Values for functional strength f_f^{sys} is kept as 5 times that of holding capacity. For current system of 5mStd, f_f^{sys} is 15N as per calculation, which is in range.

Cost is an unavoidable aspect of any development. For current system, cost of manufacturing and development is approximately 10 SEK/module including cost of system components for a batch size of 5000 modules. So cost of a 5 module system would be approximately 50 SEK. Cost approximations are derived from company's current processes. However, due to confidentiality, only approximate values are presented. The cost of novel solution should not be more than 150 SEK. Demand of strong and versatile system allows for higher price. The cost is kept as a demand to remove unrealistically high cost concepts in the development. Cost can be driven down later by further development and refinement of novel ideas. Moreover, the number of unique components and assembly steps captures aspect of cost, both development and manufacturing. As a wish, the values are taken from current system with an intention to minimise.

Lifetime is another vital aspect of a product. Lifetime is defined as number of cycles of operation before system seize to work under normal usage. It is possible to derive a lifetime by assessing all weak points of the systems for fatigue, wear or creep etc. The company do not have any data on lifetime, and experimental analysis is out of scope of project. However, as the focus of the project is on robustness under extreme conditions, the life is not quantified.

Attachment criterion are subjective as they primarily reflect functionality. Though subjective, these are considered in various ways. Similarly, safety would be considered in development. As the context development, attachment to thick/tough fabric worn as outer layer in work wear, it is not possible to pierce skin. For this reason, safety is not quantified as the requirement defines.

Actuation force F_w^{sys} should be maximum of 20N and should be as low as 2N. During measurement of actuation force, as tabulated in 3, 20-22N force while actuating 4mC5T was perceived to be high. As mentioned in chapter 3, there are five actuation steps. The best would be to have 3 actuation steps, bring near fabric, actuate to attach, actuate to detach. To not reject ideas with slightly complex actuation, 7 steps is kept as demand.

Size of the system is kept as a wish. For requirement 27, 28 and 29, the values indicate maximum desirable value. However, being a wish, bigger system would not be rejected. As size is dictated by objects, there is no particular desirable values. However, if a system is smaller, it would be more compatible. Usage with gloves, consideration for ergonomic use and inclusive design are user oriented requirements. Requirement 30, about end-of-life, pushes for sustainable product design. Easy maintenance and end-of-life disassembly both relate to design for assembly. Many values for demands and wish are derived from current system, or based on current system. The current system's performance on requirements is mentioned later in Table 15 along with evaluation of new concept in chapter 8.

6

Concept development

This chapter explains the iterative concept generation phase of the project. It starts with generating partial solutions for the main problem areas in the system. The solutions for each area are presented in a morphological matrix. Some solutions are then synthesised to full concepts, and some kept as partial concepts to be evaluated using three evaluations. The first two evaluations are based on the requirements list, and the third evaluation based on prototyping and testing the remaining concepts. The remaining concepts are then eliminated or combined based on detailed evaluation in the final section. The chapter results in a final chosen concept.

6.1 Concept generation

Based on the requirements list and the performance investigation of the current design of the Spindel-tech, five major areas for improvement are identified in the system. These are

- Fabric capture (surface flushing)
- Fabric penetration
- Locking the attachment
- Actuation
- Module orientation

The ideation process for generating solutions to these problem areas followed two main approaches - firstly, a **Bottom-up approach**, where the motive was to come up with all possible concept ideas different to the current system, which fulfil the primary function of attaching to the fabric. This approach helped in broadening the perspective during idea generation, exploring everything outside the Spindel-tech. The second approach was a **Top-down approach**, where the aim was to break down the current system and find alternative concepts or adaptive changes to its sub-systems. This approach facilitated parametric and adaptive alterations to the existing design of Spindel-tech. The idea generation is done by sketching ideas inspired by various everyday objects, technical systems in other domains, insects, animals, plants and other fastening products. A morphological matrix used to segment ideas in each problem area is presented in the Appendix B.3 and B.4. A descriptions of these ideas are presented with a reference number to the sketches in the matrix.

Fabric capture

- A rubber coating on the attachment surface, to increase capture by friction (FC2)
- A temporary adhesive on the attachment surface, like a *Gecko tape* (FC1)
- Micro hook-like fibres on the attachment surface (FC7)

- *Devil's jaw* (FC9): It has a notch like structure, where the driving end has angled pins to capture fabric and carry the fabric to the slot. This idea is also for the **fabric penetration** area.
- *Camera shutter* (FC10): As the name suggests, it captures fabric using pins on the edge of each shutter blade
- *Straight pinch* (FC11): Pinching the fabric using two cubical components, and shooting a pin through the fabric. This also works for **fabric penetration**
- *Twisted earring hooks* (FC12): Inspired by an earring hook, these hooks capture the fabric by manual actuation, and every alternate hook twists inside the fabric which facilitates **locking**
- Attaching surface of the device is concave, and the modules placed at angles. This would fabric to fall towards the centre of device when pressure applied during attachment (FC3)
- *Raised walls* (FC4): The periphery of the device has raised walls to push fabric towards the top surface when pressure applied during attachment. These are of two types, fixed walls and active walls (actuated with push actuation)
- *Tsunami island* (FC8): This has components on the periphery which are actuated to push towards the centre of the device during attachment

Fabric penetration

- *Pin-to-umbrella* (FH2): This has multiple micro metal fibres, initially bound together in a pin shape, and when actuated, they penetrate the fabric and open inside like an inverted umbrella
- *Magnetic pin* (FH3): Two opposite magnets, one carries a pin, and the other has an eye where the pin goes in
- *Magno-hook dance* (FH6): A magnet below the attachment surface drives the hooks to penetrate the fabric and twists them alternately inside for **locking**
- *Gripper* (FH7): Inspired by insects, it uses curved pins to grip onto the fabric
- Two wires going criss-cross over each other, penetrating the fabric and strengthening the attachment by making a deadlock
- *Static dance* (FH11): Same as magno-hook, but the wires could possibly be driven by static charge
- *Helical wires* (FH12): Spring like wires pierce into the fabric. Only one penetration point and the spring formed behind the fabric holds the attachment securely
- *Helping cave* (FH1): This concept adds extended side walls at the entrance of the cave, to provide extra back support on fabric for second penetration
- *Mini cave*: The height of the cave is reduced
- *Cave-to-cave* (FH10): The slope where the wire comes out has a cave on top. This is to increase angle of first penetration. There are two variations of this, one with the slope like in the existing design, and the other where the wire sits raised on the gear, so it does not bend into upward trajectory
- *Head-on collision* (FH14): In this concept, the cave also moves in an opposite rotation to the wire and both meet in the middle. This would allow the fabric to be pushed from both the cave and the wire and cause a pinch penetration
- *Pot-hole*: The area below the wire path, where it attached to the fabric has a small concavity to allow more space for fabric
- The wire is angular (for e.g pentagonal) instead of circular. The idea is to decrease fabric slipping out of the wire as it would get stuck at angles (FH5)

Locking the attachment

- *Active or hinged cover safety pin* (L6, L7): Like a safety pin, but the cover which holds the needle is actuated transversely or as a hinge to lock the wire in
- *No cave just hook* (L9): This uses penetrating wires, with trajectory opposite to each other. After penetration they behave as two opposite hooks which makes the fabric difficult to slip out
- *Notch snap-fit* (L1): The wire has a slot behind the tip, and the cave has a hollow cylindrical inner cross-section of diameter equal to the wire, and a notch inside. The wire then snap fits with the notch in the cave. There are two variations to this, one with a fixed notch, and the other where the notch is actuated manually when the wire goes in the cave
- *Sewing wire* (L8): The piercing wire carries a fabric thread along on the tip and makes a temporary removable stitch. The wire has a small hole near the tip like a sewing needle.
- *Magnetic restrict* (L3): A small magnet is placed in the bottom of the cave, so when the wire enters the cave, it gets activated and pushes the wire against the top of the cave
- *Plate pressure fit* (L4): A flexible angled plate (metal or plastic) blocks the open back of the cave, so when the wire enters the cave, it hits the plate creating a gap between the wall of the cave and the plate, where it gets held pressed
- *Long wire (deep lock)* (L5): An increased length of wire which allows it to go deeper into the cave and back into the module, making a partial double rotation and harder to be pulled out easily
- *Wire snap* (L11): With force wire slides into a a groove in the inner corner of he cave and gets pressure fit. This would happen during Y+ and Z directional forces
- Have an external covering over the wire, to restrict it from bending with fabric

Module Orientation

- *Full twisted modules* (M1): All modules oriented such that wires are towards the centre of the device, instead towards the periphery of the device
- *Clusters*: Modules are not equally spaced but oriented in clusters with their wires facing each other. The rotation of wires in cluster would be opposite to each other facilitating better fabric capture and penetration
- *Flat stacking* (M3): Modules are placed co-linearly such that the axis of rotation of wires is parallel to the attaching surface of device. Four stacks of these placed at right angles to each other. The change of wire rotation axis would also increase **fabric capture** and **fabric penetration**
- *Spaceship* (M5): The attaching surface of the device is angled at the edges and the modules are pushed help in better **fabric capture and penetration** as the fabric falls on the angled edges during attachment
- *Tilted modules* (M4): The modules are tilted such that the axis of rotation of wire is at an angle to the top surface of the device

Actuation

- *Bevel gears* (A1): This concept is for angled modules and flat stack orientation. The existing spur gear transmission is changed to bevel gears
- *Cam-push* (A2): This concept uses a spring loaded button or similar component on the back of the device, to rotate the angled or flat stacked module wires using a cam type transmission.

- *Push Rotation* (A3): This can be used as an alternative to the existing lever gear design. A component having helical slot drives the middle gear, and in turn, the middle gear drives the module gears
- *Alternate actuation* (A4): Every alternate gear gets actuated at a time. The driving gear has meshing teeth corresponding to every alternate driven gear

6.2 Concept synthesis

The ideas generated for each problem area using the two different approaches include some 'new concepts', ones that significantly differ from the existing design, and some 'improved solutions', which are changes to components or sub-components of the existing design. Based on these, the concept synthesis was carried out in two parts. The first is to create 'Partial concepts', which are improvements over the spindel-tech. And the second part consists of 'Complete concepts', which are new ideas of performing the functionality of attachment.

6.2.1 Partial concepts

Individual concepts based on the spindel-tech were included as Partial concepts. Some of the improved solutionswere *Thick wire, Long wire, alternative wire material, Small-diameter wire, metallic module, cave protrusions, Pot-hole*. The *alternative wire material* was taken as a sub-concept which would affect other ideas like *thick wire* and *small arc diameter wire* identified during the technical investigation of the system. If the material of the wire is changed to one with higher yield strength (σ_y) , increasing the thickness of the wire ($2r_w$) and decreasing the wire arc radius (R_w) would result in a higher strength (Both f_u and f_f) (see Figure 27).

Various cave designs and changes to the current design are also included in the partial solution. Partial solutions also include concepts for **actuation** and **module-orientation**. Ideas that are additions to the system, like having an adhesive material or a remote moving cover, are also built upon the current system and hence kept as the partial solution.

In a synthesis of partial ideas, all ideas are included which are perceived to improve the performance except once which are apparent not to work. Ideas are kept separate to evaluate their merits on an individual basis in subsequent steps so that better-performing ideas can be integrated with the system in a later stage of development.

6.2.2 Complete concepts

Other new concepts are synthesised as entire concepts. The process of generation was to start from ideas of fabric penetration. Then compatible ideas for capture, locking, and actuation are synthesised together. Choice of these second functions is primarily based on the weakness of the attachment idea. For example, the Fat-boy cluster concept started from strengthened modules and then merged with a cluster like attachment to improve fabric capture. In the synthesis process, most ideas of fabric penetration were used. Multiple concepts of the same penetration ideas were synthesised to incorporate most ideas of other concepts. One of these multi-synthesised concepts would become superior in evaluation. Only non-functional or incompatible ideas were rejected during synthesis.

Some Spindel-tech improvement concepts detailed in the synthesis step are also presented here as a complete concept. However, the consisting sub-concepts were evaluated as partial concepts. An example of this is the remote cover-up. The full synthesised concepts are listed below.

Fat-boy cluster

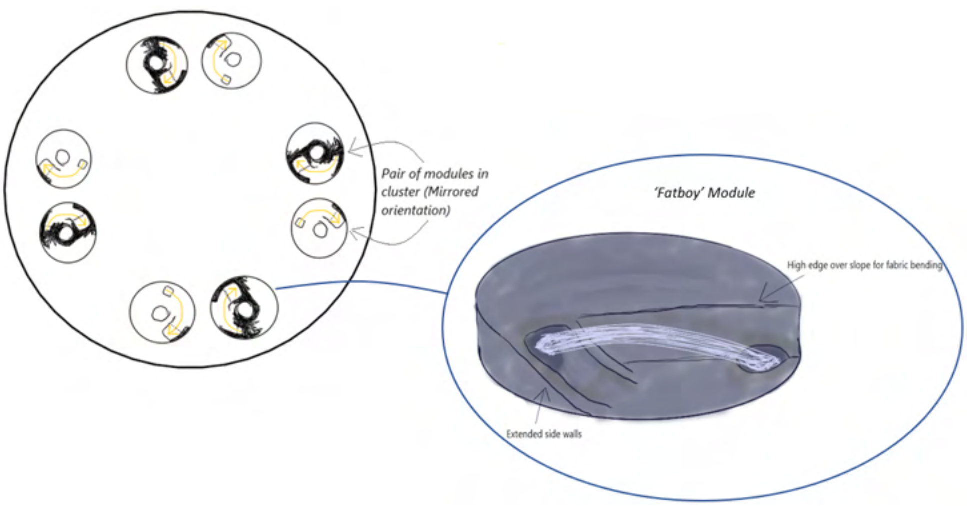


Figure 55: Fat-boy cluster

The concept is derived from the *cluster* orientation of the modules (Figure 55). The wires in the modules face each other and rotate in opposite directions to each other, facilitating better **fabric capture and penetration**. The modules used in this concept are derived from the *cave to cave* idea of having a cave on top of the slope where the wire comes out which would increase **fabric penetration** by increasing the angle of first penetration. Thickness of the top surface of module is increased in the non-attaching area, and hence the module is termed 'fat boy'. The cave also has extended side walls derived from the *helping cave* idea.

Magnetic camera shutter

This concept is derived from a combination of *camera shutter*, *straight pinch* and *magnetic pins* ideas which facilitate better **fabric capture and penetration**. It consists a top module, which has triangular blades, holding a magnet and straight pins, and a bottom module having cuboid bosses holding a magnet inside and holes where the straight pins go in (Figure 56). Both the triangular blades and the cuboid bosses are shelled from inside to place the magnet. The top module is the surface flushed with the fabric. The bottom module is driven with a lever and the fabric gets pinched between the triangular blades and cuboid bosses, and the pins pierce the fabric and go into the holes. The magnet is used to hold the attachment, but to increase the locking, both modules can have an active snap fit. Another variation of this concept would include the *devil's jaw idea* where the pins on the triangular blades would be on its upper edge, and the rectangular bosses would have a notch-like face.

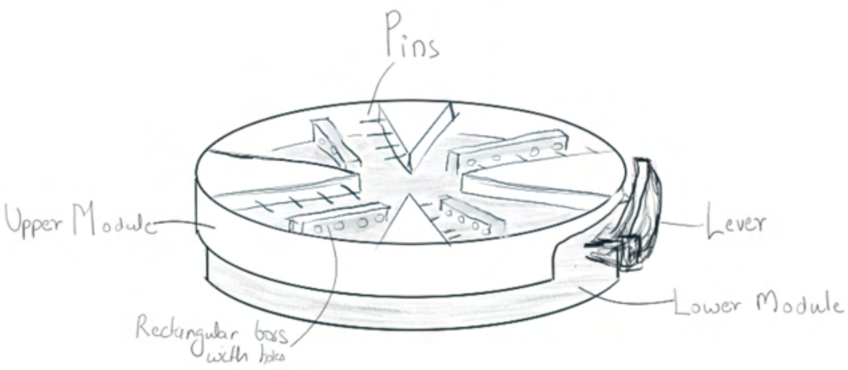


Figure 56: Magnetic camera shutter

Figure 57: Direct dish

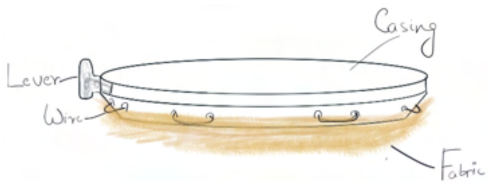


Figure 58: The spaceship

Direct dish

The concept is derived from an idea of removing the modules from existing Spindel-tech design, having curved wires driven directly without a gear. The name 'dish' is termed because of the *concave top surface* idea which would facilitate better **fabric capture**. This surface has caves similar to Spindel-tech modules, corresponding to each sloped holes. The bottom component is driven directly with a lever, and has curved wires mounted. These wires come out of the sloped holes on the top surface and go into the caves, when the bottom component is rotated with the lever (Figure 57).

Spaceship

This concept is derived from the idea of having the device angled at the edges of the attaching surface (Figure 58). This can use the same modules as in the flat stack or the existing design of modules as in the Spindel-tech. For the flat stack type modules the *bevel gear* actuation can be used. It can also include the idea of a *long wire*, which would allow a deep self-locking and facilitate better **locking of attachment**. The aim of the concept is to achieve better **fabric capture and penetration** as it is observed that the fabric falls better over the edges.

Flat stack

This is derived from *flat stacking* of modules where they are arranged linearly instead of in a circular pattern on the device (Figure 59). These linear stacks can be placed at right angles to each other on a circular device, or parallel in a rectangular or square shaped

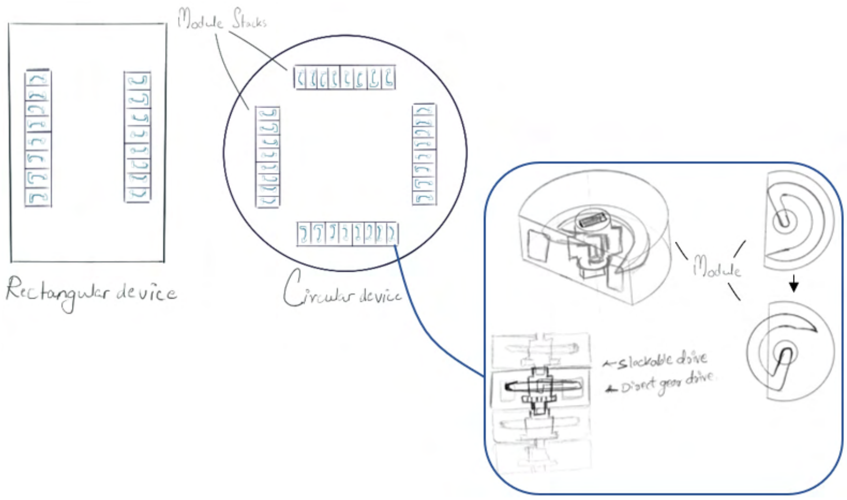


Figure 59: Flat stack

device. The modules used in this concept would have wires with rotational axis parallel to the attaching surface of the device, unlike in the existing design. This orientation of the modules would improve both **fabric capture and penetration** due to the increased angle at which the wires come out, and also facilitate **locking the attachment** as wires are placed closely in stacks. The **actuation** is done using the *cam-push* idea.

Tilted gear device

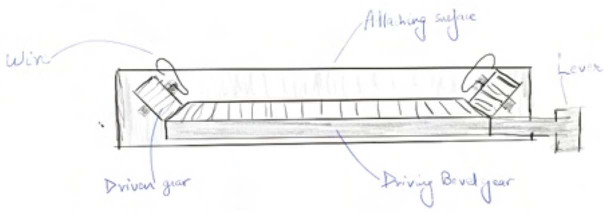


Figure 60: Cross-section of the tilted gear device concept

The concept is derived from the idea of changing the rotational axis of the wire. So it combines *tilted modules* orientation with *bevel gear* actuation type (Figure 60). In the existing design, the wire goes out by bending at the slope on the module, but the tilted driven gear, allows reduction or removal of bending as the angle of rotation of the wire is as much desired for the wire to come out without the slope. This would facilitate similar or better **fabric penetration** with a decreased actuation force, as there is no resistance on wire from bending. It would also open the possibility of having a *thicker wire* and stiffer *alternative wire material*, increasing the load carrying capacity.

Helical wire device

The concept uses modules which have spring like longer *helical wires*. These wires penetrate the fabric from one point and then form helix behind the fabric to **lock the attachment** (Figure 61). The main idea is to increase the penetration angle and depth, for good **fabric penetration** and increased load carrying capacity as the fabric would not slip out or flex the wire easily.

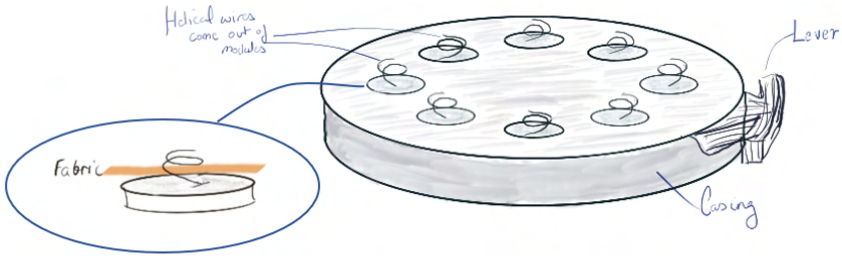


Figure 61: Helical wire device

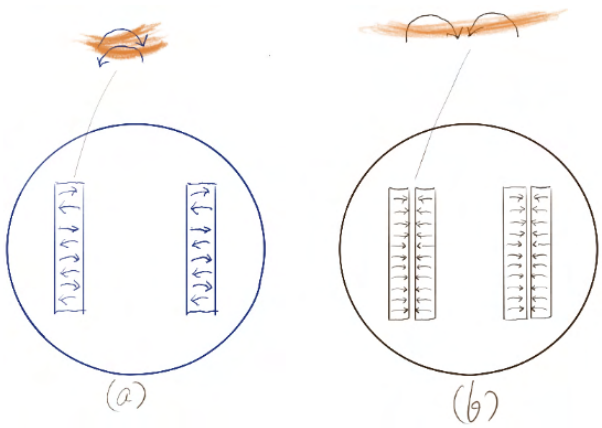


Figure 62: Crab hook - two variations

Crab hook

The concept is inspired from the *gripper* idea, which would give better **fabric penetration**. It would also facilitate **locking** by having two opposite facing hooks, like in the *No cave-just hook* idea not allowing the wire to slip out easily. The material of the wire can be hardened or changed as all the load bearing is done by the hook (wire) here. The concept has two variants, one is the *uni-axis* variant where the modules are placed *flat stacked*, but the wires rotate oppositely in every second module (Figure 62a). Another variant is where two flat stacks of modules are placed parallel and mirrored but close to each other (Figure 62b), for the opposite hooks effect.

Remote cover-up

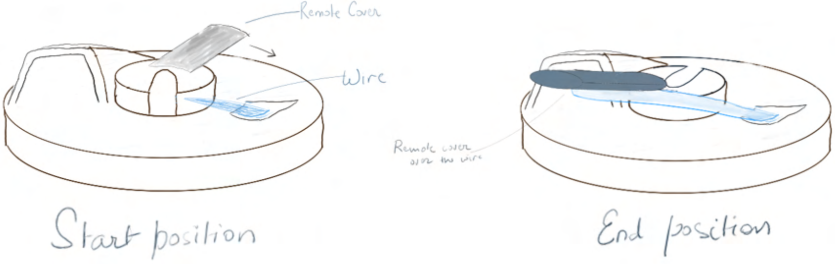


Figure 63: Remote cover-up on Spindel-tech module

This concept is an altered version of the *moving cave cover*. The aim is to have an extra cover on the wire in the current Spindel-tech design, but from the slope side of the module, instead from the cave side. This cover is an extended feature on the gear hub in the module and rotates with the gear (Figure 63). It is placed at an angle such that it reaches over the wire just before the wire completes the rotation and enters the cave after piercing the fabric. It would provide increased resistance to the wire against bending from external loads when attached to the fabric, facilitating secure **locking of the attachment** and also increasing the load carrying capacity of the system.

6.3 Concept Evaluation

6.3.1 First elimination

After synthesis, an evaluation is carried out. This step filters out ideas that do not perform to the mark in the requirements list, have some significant flaw or failure possibility, or have a very high knowledge gap. Filtering criteria are selected to create this elimination filter. These criteria reflect demands from the list and some general criteria like design realizability, knowledge gap, and failure possibility.

Table 9 shows the elimination matrix. The demands for cost, usage with gloves, working environment and afterlife, are not considered for the first evaluation. The design details at this stage are not enough to evaluate these criteria. Also, some demands, like usage with gloves or afterlife impact, are possible to fulfil by detailed design later. This applies to the strength criterion as well. However, it is the goal of the design, evaluating concepts for strength is apt. The criterion allows for scaling and modularity of the concept. In other words, the strength criterion is evaluated as a comparison with the current Spindel-tech modules and system. The actuation force had a similar evaluation. However, the comparative approach does not reject concepts. The rejection is based on failure to meet criterion by the concept without comparison. For example, the helical horizontal concept has a complex actuation requirement which poses chances of low attachment quality or functional failure while attaching. This is the rejection reason for the concept.

The partial solutions are evaluated for any change in performance when implementing the concept with the current Spindel-tech system. For these, + indicates positive impact, but - indicates adverse effect, making the solution not pass the criterion. For fully synthesised concepts, + indicates the potential to pass criterion, while - is for failing to meet criterion.

The criterion of design realisation is to analyse whether a concept would scale to the dimensions of the system or not. An example is *Sewing wire* concept (12th in Table 9). The concept requires a thread to be attached to the wire in the module. A separate thread as part of the device, not referring to thread in the fabric. The thread will hook onto a hook in the cave, providing higher strength. For this to work thread has to attach to the wire without hindering its penetrating ability. A parallel can be found in sewing needles. Though thinnest needles have 0.4mm tips, the part where the thread passes through a hole is typically not smaller than 0.6mm thick. To realise the system, the wire needs to be considerably thicker. The thread also needs to be thick to add strength, but that would hinder the motion of the fabric. Hence, the system is not realisable at the scale of the modules.

Another aspect of the criterion is to check manufacturing feasibility. Similar to the design realisation aspect, this aspect checks for whether the concept is manufacturable or not.

Table 9: First elimination matrix (+:Meets the criterion, ?: Not enough information, -:Does not meet criterion)

Concept	Criterion	Strength in Y+	Strength in Z	Attachment Quality & Repeatability	Actuation Complexity (#of steps)	Actuating Force	Safe to use	Functional Failure possibility	Design Realization & Manufacturing Feasibility	Knowledge Gap	Decision	?	+
Full Synthesised concepts													
1	Direct dish	+	+	?	+	?	+	+	+	+	+	2	7
2	Flat stack	+	+	+	+	?	+	?	+	+	+	2	7
3	Magnetic Pins - non penetrating	?	?	?	+	+		?	-		-		
4	Camera shutter	+	+	?	+	?	?	+	+	+	+	3	6
5	Umbrella Penetration	+	-				?	-	-	?	-		
6	Helical vertical	+	+	+	+	?	?	?	+	+	-		
7	Helical Horizontal	?	?	-	-	?		-	-		-		
8	Devils jaw - Linear	+	+	-	+	+	-	?	?	+	-		
9	Spaceship	+	+	+	+	+	+	?	+	+	+	1	8
10	Twisted Earing	+	?	+	?	?	?	?	?	+	+	6	3
11	Crab Hook	+	+	+	+	?	+	?	+	+	+	2	7
12	Sewing wire	+	+	?	+	+	+	?	-	?	-		
13	Static dance	?	?	?					?	?	-		
14	Active cave Safety pin	?	?	-	-						-		
15	Flower	?	-					-	-		-		
Partial concepts for Improvement													
16	Fatboy cluster	+	+	+	+	+	+	+	+	+	+	0	9
17	Reinforced fat module	-	-				+	+	?	+	-		
18	Helping cave	+		+			+	+	+	+	+		
19	Cluster		+	+			+	+	+	+	+		
20	Adhesive material			+			?	?	+	?	+		
21	Tilted gear	?	?	+	+	?	+	+	+	+	+		
22	Thick wire	+	+	+		+	+	+	+	+	+		
23	Wire Snap lock								-		-		
24	Moving cave cover	+	+	-				-			-		
25	Passive Magnetic Locking								-		-		
26	Long wire	+	+	?	?	+	+	?	?	+	+		
27	Pothole			+			+	?	+	+	+		
28	Hinged cave - rail	?	?					?	-		-		
29	Metalic Module	+	+	?					?		-		
30	Remote cover-up	+	+	?	+	+	+	+	+	+	+		
31	Small diameter wire	+	+	?			+	+	?	+	+		
32	Mini cave	?	?	?	+	?	+	+	+	+	+		
33	Alternate actuation			+	+	+	+	+	+	+	+		
34	Cam-push			+	+	+	+	+	+	?	+		
35	Push rotation			+	+	+	+	?	?	+	+		

An example of this is *Wire snap lock* (23). The concept requires a snap groove to be manufactured in the corner of the cave. In order to accommodate wire thickness about 0.4mm the snap features would be smaller than that size. In injection moulding, this feature would require a moving insert of 0.3mm thickness, which can easily break during the mould removal. It is possible to 3d print such a feature, but the material strength is a trade-off in that case. Another example of rejection under this criterion is the *Flower* (15) concept. The concept's design is too complex, and hence even if tiny components are manufactured, the assembly would be highly complex. Therefore, the Flower concept was rejected based on low strength, functional failure possibility and design realisation criterion.

The *devil's jaw-linear* (8) is rejected for safety concerns along with attachment issues. Though it is possible to create safety contraptions while not in use, the device has high chances of skin piercing when attaching or using it. The *umbrella penetration* concept (5) has a knowledge gap regarding its safety, actuation mechanism, design and manufacturing feasibility. Moreover, based on its attachment mechanism and observations from the strength testing of the existing design, it is hypothesised that the concept's strength in Z would not be optimal, with a high possibility of functional failure. Hence, it is not chosen for a prototype-based evaluation.

6.3.2 Prototype based evaluation

Through the learning process aided by prototyping and experimentation, the remaining concepts were detailed and evaluated. The Table 10 represents the result of the process. As the primary focus was on strength improvement and attachment quality, most of the prototyping revolved around that. The concepts which do not improve anything are rejected along with the concepts with some issue. Consideration for other requirements like safety created a holistic but organic process of evaluation and elimination.

The concepts rejected for safety issues are *twisted earring* (10) and *cave protrusions*. The cave protrusions was an idea that came during this phase. These are small protrusions on the top edge of cave entrance as features. Both these concepts have pointy protruding elements, even when not being used, make them prone to get stuck to clothes or fabric, which might damage both the cloth and the device. For the twisted earring, the protruding hooks could harm the user. A feasible design, for pulling the hooks back in the device when not in use would have taken this concept further in the evaluation process.

Camera shutter (4) and *Direct dish* (1) were tested partially. The most significant aspect to test for the camera shutter was if the fabric would get captured deep enough for the pins to pierce and hold it. A 3D-printed prototype (Figure 64) of its upper and bottom module was tested on both tightly-woven and loosely-woven fabrics. It was seen that unless the fabric is very thin, light and flexible, it would not get captured effectively. For the direct dish concept, just the concave top surface was printed and tested, and had the same issue with fabric capture, so the design was not developed further for testing.

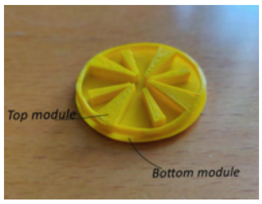


Figure 64: 3D-printed partial prototype of *the camera shutter*

Both the *crab hook* (11) and the *uni-axis crab hook* (11b) were tested using hand-made prototypes with a pair of *5t* wires (Figure 65). The aim was to analyse the performance of these two concepts under Z directional force. It was observed that the crab hook took a directional force of 27.7 N and the uni-axis crab hook took 39.9 N force before failing. The uni-axis crab hook showed considerably higher force carrying capacity, which would increase with the number of modules in the device. As more number of modules can be accommodated in lesser space in both the concepts, than the equally spaced circular orientation of modules in the existing design, they were kept for the final evaluation.

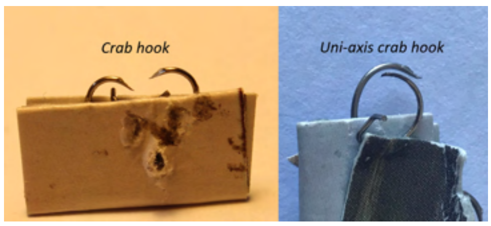


Figure 65: Hand-made prototypes of two types of *crab hooks*

For the *flat stack* concept(2), just the performance of the vertical orientation (wire's axis of rotation parallel top surface of device) of the module was tested. This was done with a similar hand-made prototype, but using four 5t wires in a circular spaced orientation as in the existing design. The force this prototype took before failing under Z directional force was 44.6 N. This is similar to the existing 4m-5t configuration of the spindel-tech. However, since the flat stack concept can have more number of modules arranged linearly, unlike the existing design, it was kept. At this stage, the *spaceship* (9) concept was rejected, as it might increase the fabric capture and penetration, but the force bearing capacity would be similar or lower than the existing design. Also, it was theoretically concluded that farther the wires are placed towards the periphery, lesser will be there combined effect against external forces, explained in Holding force technical model.

A functional 3D-printed prototype of the *cluster concept* (19) (Figure 66) was made to test both attachment quality and strength. There are three clusters with a pair of modules in mirrored orientation, so it has six modules of existing design. For the 4t module, the strength was tested with all three clusters in the device, and for 5t module, it was tested with just one cluster. Under Z directional force, it was observed that it performed similar to the existing design. This concluded that it is not stronger unless the modules are placed much closer in the cluster, so the wires have a combined opposing effect against force application. However, the attachment quality was observed to be considerably better than the existing design of the device, because the wires opposite rotation in clusters creates a pinching condition on the fabric, and makes the attachment less dependable on the amount of pressure applied during actuation.

Figure 66: 3D-printed prototype of *cluster concept*

The *remote cover-up* (30) concept was tested by printing a changed design of the module gear, but usable on the existing module. The gear hub was made higher to accommodate the 'covering element' of the remote cover-up concept. For testing, a piece of 0.6mm straight wire was used as the covering element (Figure 67). The aim was to analyse the effect of the covering element on the wire during its rotation, and it was observed that the wire gets a downward push just before reaching the cave entrance. This has two benefits - first, it does not allow the wire to go over the cave into a loose condition. Second, the attachment would have a higher force bearing capacity as the covering element would resist the wire from bending. The design was developed further using CAD, which gave two outputs - first, the covering element as a part of the gear hub would be difficult to manufacture by injection moulding. Second, it would be a protruding element resulting in safety issues and prone to breaking even when the device is not in use. Hence, another design for covering the wire was developed, and a hand-made prototype was made to test. This is a *sheet metal component* mounted along the periphery of the device and covers the wire during attachment (Figure 68). A strength test was performed on a single module with this cover, under Z-axis directional force, which resulted in it taking 55.3 N force before failure. This is significantly higher

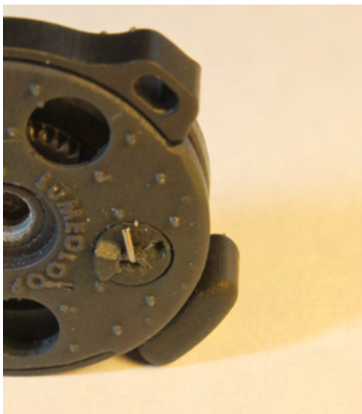
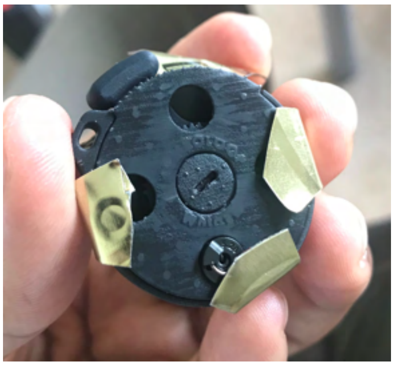


Figure 67: Prototype of first variant of *remote cover up*

than any other strength test on a single module. The main reason is that the bending force on the wire from the fabric is transferred to the sheet metal component, reducing deformation in the wire. So this altered design of the remote cover-up concept was kept for final evaluation.



(a) Prototype of sheet metal variant of *remote cover-up*

(b) Effect on sheet metal cover after test

Figure 68: Sheet metal variant *remote cover-up* concept

Concepts which were parametric changes to the cave of the existing design, like the*helping cave* (18), *mini cave* (32) and *no-roof cave* (32b) were 3D printed to be tested (Figure 69). The helping cave concept resulted in a rather opposite effect on fabric attachment than expected. The extended side walls push the fabric away from the attaching surface, increasing chances of a trajectory deflection resulting in loose condition. Also, the wire tends to rub along the inner extended wall, leading to more resistance and higher chance of slipping off the gear. so the concept was rejected. Two types of *no-roof caves* were tested, one with back wall, and another without. The attachment quality in the no-roof cave was not better than in the existing design as also tested during the performance investigation. Hence, it was concluded that the roof of the cave is important for avoiding slipping of fabric from the wire after attachment, and also under Y- directional forces (See Table 7). The *mini cave* concept was however kept, because it could be combined with the *remote cover-up* where the wire gets pushed into the cave by the covering element.

Figure 69: L-R : No-roof cave 1; No-roof cave 2; Helping cave + Mini cave

The *tilted gear* (21) concept was kept as it allows usage of *thick wire* (22) without increasing the actuation force for attachment. As described in the technical model of the existing design, increasing the thickness of the wire would result in its higher functional strength, even if the material of the wire is kept same. Initially it was assumed that if the actuation force from bending of the wire at the slope can be decreased, the *smaller diameter wire* (31) can be used, but using it would result in a lower depth of penetration, which is not ideal for good attachment quality. The *long wire* (26) concept was visually analysed using CAD to check the possibility of rotating the wire more than in the current design, so it is deep enough creating a self-locking loop. However, once the wire goes into the cave and back towards its lower trajectory, it hits the gear track, which would cause resistance on the wire from bending.

The *pothole* (27) concept was tested by making a ditch on the existing module, and it did not result in better fabric capture and penetration. Also it would be a problematic feature for injection moulding at that small dimension, as the wall thickness would vary from the other features of he module. The *gecko tape* (20) was not available so a similar solution was tested on the module surface, which was a temporary adhesive tape. It is good for capturing fabric on the surface, but a problem is observed that it attracts a lot of dust over time and would need frequent replacement, so it is rejected.

Actuation concepts of *alternate actuation* (33), *cam push* (34) and *push rotation* (35) were kept to be used in the chosen concepts. To test the alternate actuation concept, a manual alteration was made to the driving gear of the device (Figure 70). Set of gear teeth were grind to allow only alternate driven gears to be actuated during rotation of lever. A significant decrease in actuation force was observed, but also an increase in the lever travel. But considering that for more number of modules and higher strength of the device, decreasing actuation force is of higher priority among the two ergonomic use parameters, the concept is kept.

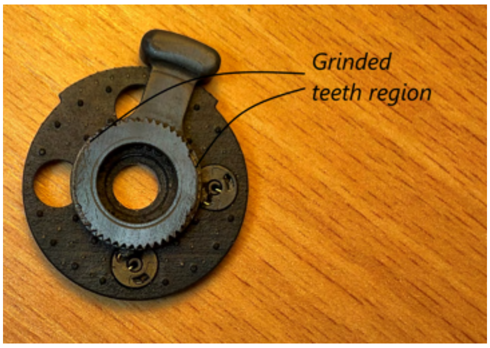


Figure 70: Prototype for testing *alternate actuation*

Table 10: Prototyping based learning and concept evaluation (+: Improved compared to reference, :similar to reference, -: Not acceptable performance; reference is B module and 5mBstd system)

Concept	Criterion	Strength	Attachment quality and Repetability	Other	Prototype type	Decision
1	Direct dish	-	-		3D-print	-
2	Flat stack	+	+		Wire prototype	+
4	Camera shutter	+	-		3D-print	-
9	Spaceship	-	+		Theoretical	-
10	Twisted Earing	+	+	- (Safety)	Design	-
11	Crab Hook	+	+		Wire prototype	+
11b	Uni-axis Crab Hook	+	+		Wire prototype	+
19	Cluster	~	+		3D-print	+
18	Helping Cave	~	-		3D-print	-
32	Mini cave	~	(+)		3D-print	(+)
32b	No roof cave	-	~		3D-print	-
	Cave protusions (fabric capture)			- (Safety, failure)	Crafting	-
21	Tilted gear	+	~	- (Size)	Design	+
26	Long wire			- (Design)	Design	-
27	Pothole	=	=		Crafting	-
31	Small diameter wire	+	-		Wire prototype	-
22	Thick wire	+	~		Wire prototype	+
	Rubber like material			+ (pressure)	Rubber tape	+
20	Adhesive material (Gecko tape)				Temporary adhesive tape	(-)
30	Remote cover-up	+	~		3D-print	+
33	Alternate actuation	~	+	+ (Actuation force)	Crafting	+
34	Cam-push	~	+	+ (Ergonomics)	Design	+
35	Push rotation	~	+	+ (Ergonomics)	Design	+

6.3.3 Material exploration

At this stage it was important to analyse the material alternatives for the wire, as some of the selected concepts from previous stage like the *tilted gear, uni-axis crab hook, crab hook and flat stack* could potentially increase the strength of the system considerably, without changing other parameters of the wire (see Figure 27).

The functional requirement of the wire has highest priority for yield strength (σ_y) to increase functional limit. Also, Young's modulus E is important to consider as it is directly proportional to stiffness. Low stiffness would result in higher deformation, and higher deformation would lead to higher fabric slipping. There is no optimising aspect like minimise weight, as the strength is top priority. Hence, the Yield strength (σ_y) and Young's modulus (E) are directly considered rather than indicators like E/ρ.
In the Appendix B.5a and B.5b, the red coloured materials are alloys like Inconel, and turquoise coloured records are stainless steels. These charts are plotted for bulk material property and not wire. In drawing process of wire, the tensile strength and yield strength (σ_y) increases due to surface hardening. The smaller the diameter of the wire, higher would be the increment. In the process ductility is reduced slightly. The tensile strength of 0.4mm diameter wire after drawing would become approximately 2000-2500 MPa (SIS, 2011), considerable higher than the bulk strength. The Yield strength (σ_y) also increases. However the chart gives indication of possible materials.

It is evident from the chart, that the Young's modulus (E) is fairly constant in SS. Currently used AISI 304 SS alloy would already have tensile strengths over 2000 MPa in wire form. Hardened AISI 304 is marked in Appendix B.5a. It already has high strength with little room for improvement. Some super-alloys have higher yield strength (σ_y), however the price for those is considerably high as can be seen in Appendix B.5b. Hence, the material in use currently is already optimal for performance and cost perspective.

This finding dictates that the material properties can not be changed as intended, so design parameters are the only factors to increase functional limit and stiffness. Moreover, need to increase design parameter like r_w, the actuation force would also increase. Hence concept should consider actuation force reducing ideas more proactively to counter the effect.

6.4 Concept selection

6.4.1 Synthesis of partial concepts

Concepts selected from prototype-based evaluation were further synthesised based on the design requirement parameters. The primary intent for combining these concepts was to fulfil the essential parameters of the system - maximising directional ultimate strength (f_u^{sys})and functional limit(f_f^{sys}), increasing attachment quality and minimising actuation force(F_w^{sys}). Other parameters like the damage to fabric, number of unique components and system size (D_{sys} andt_{sys}), were also weighed.

Nine synthesised concepts were kept for the final selection (Figure 11). The technical names for these are based on the system configuration naming defined in Table 2. The concepts are described below :

- **Twisted 20** : This is a 20 module system, where the modules are placed in a *twisted orientation*. These are the type B modules with 4t wires, and the combination is chosen because it requires lesser actuation force. The performance of twisted module orientation for strength was tested to be better under X and Y directional forces, than the module orientation in the existing design of the system. The actuation system is a lever-gear, same as the existing design.
- **Twisted 16** : This concept is same as the previous one, but is a 16 module system. The intent was to decrease the diameter of the device, which would allow better pressure distribution while actuating the attachment. This was kept as an alternative if the strength of the system could be compromised by a small margin.
- **Twist-Alt 10** : This is a 10 module system, with the type B modules in *twisted orientation*. Because the 5t wires are used, the number of modules required in the system is lesser to achieve a high strength. *Alternate actuation* concept is used with the lever, to keep the actuation force low.
- **Twist 9** : It is a 9 module system of type B twisted modules. Since the 6t wires are used to increase the force carrying capacity, a *triple alternate actuation* is used to further reduce the actuation force. The triple alternate actuation was a new concept added at this stage as the use of thicker than 0.5mm wire was considered. The driving gear has teeth placement such that it actuates every third gear at a time.
- **The snail** : This concept is a 6 module system of type B modules with 5t wires. It is a combination of the *cluster* and the sheet metal variation of the *remote cover-up*. This gives the system a synthesis of increased strength and attachment quality, without using more number of modules and not exceeding the wire thickness of 0.5mm.
- **Relaxed twist** : This concept is a 4 module system that uses a module with an alteration to the existing design. The module is termed as *relaxed* as the motive is to ease the resistance on the wire from bending when it changes trajectory at the slope. This is done by increasing the separation between two abutments (α) and increasing the height of wire pathway (H_w). Because there is decreased actuation force by less bending of wire, 8t wires are used for increased force carrying capacity of the system. The modules are placed in a *twisted orientation* for the same reason.
- **Tilted 8** : The concept is a 8 module system. It uses *tilted orientation* of modules, because of which the module would have a minimal or no slope for bending the wire. The idea is also an alternative way of ‘relaxing’ the wire to decrease the actuation force, and allow using thicker wire for higher system strength. The actuation is done with a *bevel gear* lever.
- **Uni-axis crab hook** : Among the two variations of the crab hook, the uni-axis variant was kept at this stage due to the better performance in Z directional force carrying capacity. The system consists of 10 modules with 5 modules in each linear stack. The actuation force for this concept is considerably lower as uses the vertical module (axis of wire rotation is parallel to top surface of device). It does not use a lever-gear transmission, but a *cam-push* actuation.
- **Geared vertical** : This is an alteration to the flat stack concept with 10 modules.The modules used are the vertical type, like in the flat stack, but the arrangement is in a equally spaced circular orientation, instead of in linear stacks. The concept uses 6t wires for increased system strength and the actuation is done using the *push-rotation* mechanism.

Table 11: Synthesised concepts for final selection

ID	Unique name	Technical name	# modules	Type of modules	Wire Thickness (mm)	Actuation type	System Dia (mm)
1	Twisted 20	20mB4tLTwisted	20	Twisted B	0.4	Lever	80
2	Twisted 16	16mB4tLTwisted	16	Twisted B	0.4	Lever	50
3	Twist-Alt 10	10mB5tAltTwisted	10	Twisted B	0.5	Alternate Actuation	40
4	Twist 9	9mB6t3AltTwisted	9	Twisted B	0.6	Triple Alternate Actutaion	40
5	The Snail	6MB5tRCAltCluster	6	Cluster- mirrored B	0.5	Alternate Actuation	30
6	Relaxed twist	4mR8tLTwisted	4	Relaxed	0.8	Lever	30
7	Tilted 8	8mB6tLTilted	8	Flat vertical	0.6	Lever	40
8	Uni-axis Crab hook	10mF6tCP	10	Flat vertical	0.6	Cam-push	40
9	Geared vertical	10mF6tPR	10	Flat vertical	0.6	Push rotation	40

6.4.2 Final Selection

Thirteen criteria were considered to evaluate the nine synthesised concepts and the best performing one are chosen. These criteria were based on the target requirements. The evaluation is done based on these criteria, using a Kesselring matrix. The criteria and the reason for using them are described below:

- **Directional Ultimate strength per module** : The minimum directional ultimate strength for a concept is calculated using the values from the results of the strength testing and the relations in the technical models (Figure 27). The criterion is considered for a single module to keep the evaluation unbiased, as each of the nine concepts use different number of modules. The target value of force carrying capacity per module for evaluation is kept as 50N, as the aim is to maximise the combined directional ultimate strength of the system to 200N, and for stability at least four equally spaced modules are essential.
- **Number of modules in system** : The number of modules each concept uses effects its directional ultimate strength(f_u^{sys}), functional limit(f_f^{sys}), size (D_{sys}), actuation force(F_w^{sys}), quality of attachment and the number of steps in its assembly. Besides this, another intent to include this criterion is its directly proportional effect on the cost of a particular concept. As a requirement of minimising the number of modules, the target value for evaluation is kept as 4 modules.
- **Functional limit** : Functional limit here is the holding strength of the system, i.e, how much load (m_{obj}) it can take (of a hand-held object) without functionally failing, in other words, without the wires bending to a point where they get vulnerable to detach from the fabric. The criterion is used per module for each concept to keep an unbiased evaluation.
- **Actuation force** : Actuation force (F_w^{sys}) determines the user-friendliness or ease-of-use of the concept. This was calculated based on the results from the actuation force testing and technical models (Figure 27), and it is directly proportional to the number of modules in the system. However, as the synthesised concepts use different actuation mechanisms, the actuation force for them cannot be directly judged by the number of modules they use, so it is an essential criterion to evaluate. The target value for evaluation is kept as 1N, as the intent is to minimise the actuation force.
- **System diameter** : The diameter of the system (D_{sys})is an important criteria, as it effects the distribution of pressure applied on a system while actuating for attachment. Smaller the diameter, better is the pressure distribution. The concepts

have different system diameters, and hence, have to be compared based on this criterion.
- **System thickness** : The thickness of a system (t_{sys}) effects the force distribution to all its modules in an attached condition. Thicker the system, longer will be the distance between the object it is holding and its attached surface to the fabric. This leads to a more concentrated bending moment on just one or two modules even in a resting condition, as the (m_{obj}) is shifted farther from the attached surface.
- **Number of unique components** : This criterion is important to analyse the concepts as it effects the assembly complexity, and also the manufacturing cost of a system. The aim is to keep the unique components same or lower than the existing design.
- **Number of assembly steps** : The number of assembly steps increases with the number of modules and the number of unique components in a system. It is essential to analyse the concepts based on this criterion as it directly effects the assembly complexity and the cost of a system, hence, it is intended to be minimised.
- **Quality of attachment** : Attachment being the primary function of the system, the quality of attachment is the most essential criterion for analysing the concepts. It is quantified on a grade of 1 to 5 for this evaluation, based on the results from the prototype based evaluation of the concepts, and the attachment testing.
- **Ergonomic use** : Ergonomic use of the system is quantified here on a grade of 1 to 5, based on two factors, the actuation force (F_w^{sys}) and the type of actuating mechanism.
- **Fabric damage** : The damage a particular system causes to the fabric is an essential criteria for a user. Here it is quantified for evaluating the concepts based on the thickness of wire ($2r_w$) the system uses. Higher the thickness, higher is the fabric damage.

Although all these criteria are important for the evaluation, they are weighted against each other to analyse the importance of each in choosing the final concept using a Kesselring matrix. A pair-wise comparison of the criteria is done using a matrix as shown in Appendix B.2. The Kesselring matrix evaluating the concepts is shown in Table 12.

It shows that *the snail* has the highest score among the other concepts. Two other concepts closest to the snail are, *Relaxed Twist* and *Tilted 8*. For the Relaxed Twist, the score on functional limit per module and the directional ultimate strength per module (f_u) is the same as the snail. This shows that if a system uses 8t ($2r_w$=0.8mm) wires, it can achieve the same strength with lesser modules, as one using a combination of 5t ($2r_w$=0.5mm) wires and *remote cover*. But as the $2r_w$ increases, it leads to greater fabric damage, and a user would prefer lower fabric damage over higher strength of the system, which makes *the snail* still a better concept than the two.

The score on actuation force (F_w^{sys}) is best for the *Tilted 8* out of the top three concepts. This is because it uses the *flat vertical* type of modules, which do not cause resistance from bending on the wire, as the wires are tilted at the desired angle (ϕ) with the gears. However, it scores lesser on the other criteria, which are of higher weightage, and the F_w^{sys} for *the snail* would be considerably lower than the existing design due to the alternate actuation mechanism. The score for quality of attachment is similar in *Relaxed Twist* and the *Tilted 8*. Still, it would possibly be better in the *Tilted 8*, as in the *Relaxed Twist*, modules have a slightly lower depth of penetration (D_p) due to the lower angle of the first

Table 12: Kesselring Matrix evaluating the 9 synthesised concepts

Criterion	Weightage	Target score	Not fulfilling	Target value	Twisted 20 (20mB4tLTwisted)			Twisted 16 (16mB4tLTwisted)			Twist-Alt 10 (10mB5tAltTwisted)			Twist 9 (9mB6t3AltTwisted)			The snail			Relaxed Twist (4mR8tLTwisted)			Tilted 8 (8mB6tTilted)			Uniaxis Crab hook			Geared Vertical		
	w	S	min	max	V	S	T	V	S	T	V	S	T	V	S	T	V	S	T	V	S	T	V	S	T	V	S	T	V	S	T
Directional Ultimate Strength (f_u) [N]	11	5	20	50	9	0	0	9	0	0	16	0	0	26	1	11	55	5	55	61	5	55	26	1	11	26	1	11	26	1	11
No. of modules in system (n) [1]	6	5	20	4	20	0	0	16	1	6	10	3	18	9	3	18	6	4	24	4	5	30	8	4	24	10	3	18	10	3	18
Functional limit - Holding strength (f_f) [N]	15	5	2	20	3	0	0	3	0	0	6	1	15	10	2	30	25	5	75	23	5	75	10	2	30	10	2	30	10	2	30
Actuating Force (F_w^{sys}) [N]	9	5	30	1	52	0	0	33	0	0	26	1	9	32	0	0	13	3	27	35	0	0	8	4	36	10	3	27	10	3	27
System Size (diameter) (D_{sys}) [mm]	4	5	80	30	80	0	0	50	3	12	40	4	16	40	4	16	30	5	20	30	5	20	40	4	16	40	4	16	40	4	16
System Size (thickness) (t_{sys}) [mm]	4	5	18	6	10	3	12	10	3	12	10	3	12	10	3	12	10	3	12	12	3	12	13	2	8	13	2	8	13	2	8
Number of Unique components [#]	7	5	10	7	7	5	35	7	5	35	7	5	35	7	5	35	9	2	14	7	5	35	7	5	35	9	2	14	8	3	21
Number of Assembly steps [#]	4	5	80	20	103	0	0	83	0	0	53	2	8	48	3	12	34	4	16	23	5	20	43	3	12	63	1	4	63	1	4
Number of steps to Actuate [#]	6	5	8	2	5	3	18	5	3	18	5	3	18	5	3	18	6	2	12	5	3	18	5	3	18	5	3	18	5	3	18
Quality of Attachment [1-5 Good]	16	5	1	5	1	0	0	2	1	16	3	3	48	3	3	48	4	4	64	3	3	48	3	3	48	4	4	64	4	4	64
Ergonomic use [1-5 Good]	6	5	1	5	1	0	0	3	3	18	3	3	18	1	0	0	4	4	24	4	4	24	4	4	24	5	5	30	5	5	30
Fabric damage ($2r_w$) [mm]	12	5	1	0	0.4	5	60	0.4	5	60	0.5	4	48	0.6	3	36	0.5	4	48	0.8	0	0	0.6	3	36	0.6	3	36	0.6	3	36
Concept score	500		0	5			125			177			245			236			391			337			298			276			283
Performance ranking						9			8			6			7			**1**			**2**			**3**			5			4	

$$S = \frac{V - min}{max - min} \qquad T = S * w \qquad score = \sum T$$

penetration (ϕ) and using higher thickness (0.8mm) wires. *The snail*'s attachment quality is higher due to the cluster arrangement of the modules, which allows better capture and control of the fabric.

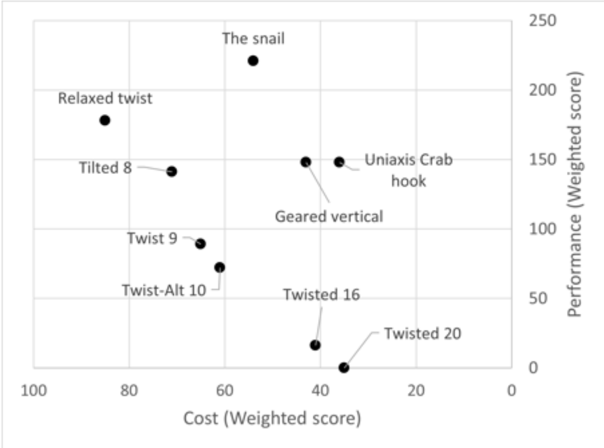


Figure 71: Performance v/s Cost comparison for the concepts (Weighted score from Kesselring matrix)

A comparison of the concepts on performance and cost is made based on the weighted scores from the Kesselring matrix. The criteria included for performance of a concept are directional ultimate strength (f_u), functional limit (f_f), quality of attachment and force for actuation (F_w^{sys}). The criteria included for cost are number of modules (n), number of unique components and number of assembly steps. The graph (Figure 71) presents the results of his comparison, showing *the snail* is better in performance, but due to the more number of unique components, it may increase the cost higher than the *Relaxed Twist* and *Tilted 8* (lower weighted value). However, as the performance of the system is of higher importance than the cost of the system, *The snail* is the chosen concept.

7

Detailed Design

This chapter describes the details of the proposed design, the chosen concept. It explains the design decisions and considerations made and the reasoning behind them. Additionally, the chapter presents a system configuration for the concept, providing the pros-cons, compatibility and use-cases respective to each configuration.

7.1 The concept

'The Snail', the chosen concept, is a modular and scalable concept that improves almost every performance indicator. The Ability to attach removably and the visual and functional resemblance of the Remote cover to the shell has inspired the name 'The Snail'. The remote cover increases the strength of attachment by about 2.5 times. It also utilises clustered arrangement and alternate actuation. Figure 72 presents *The Snail* concept.The design features of *The Snail* are mentioned in the list with a short description.

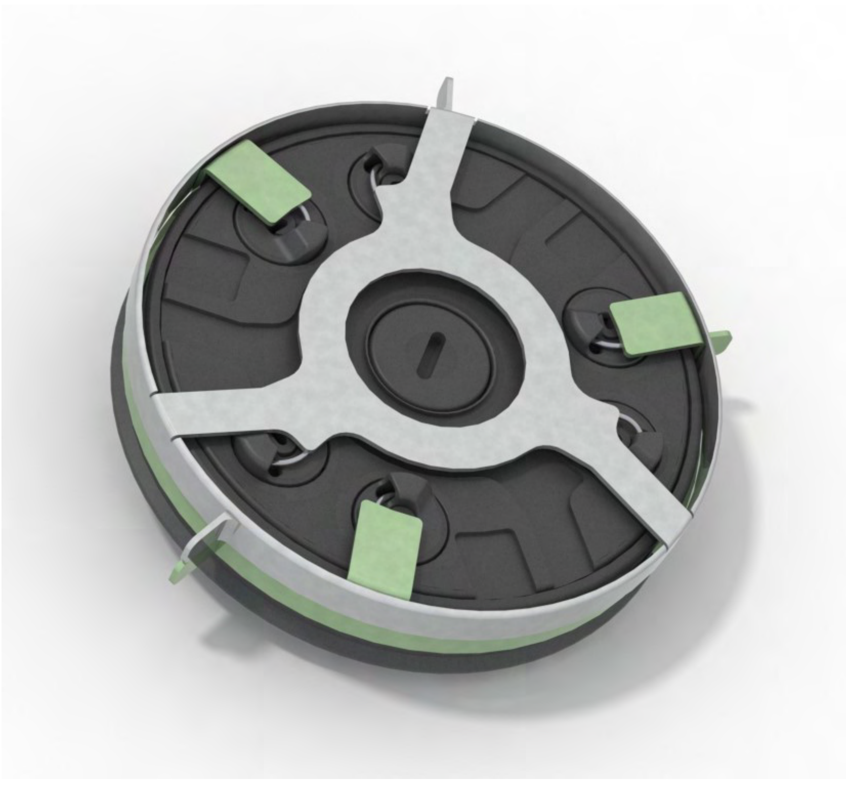


Figure 72: *The snail* in an attached state

- **Cluster arrangement**: A novel module arrangement to improve attachment and the reduce stress concentrations on one module
- **Remote cover**: A new component to support the wires when in attached condition to reduce stress and deformation in wires. It increases strength of the modules. The remote cover is actuated separately from the modules.
- **Alternate actuation**: Improved gear based actuation system which reduces actuation force requirement by half. Actuation is carried out in two stages, in each alternatively placed modules are actuated.
- **Relaxed modules**: With a parametric change in the module design, the spring-like bending is utilised more and high force demanding three-point bending is minimised. The change reduces actuation force as well as opens up possibility of achieving higher penetration angle.
- **Improved gears**: Gears are fitted with snapping slots where the wire will be snapped. This feature specifically prevents wire from slipping out of its position resulting in poor attachment and lower strength.
- **Distribution flanges**: The flanges are added around the device, especially in gravitational direction, when used with big and heavy objects. Functionality of the flange is to reduce stress concentration on modules because of application of moment. It would also reduce magnitude of oscillatory forces.

The device now has two separate actuation system that control the device. One for the module actuation as described in Chapter 3, and an additional system for the remote cover. The module actuation changes between two steps, Resting and Attached (see Figure 14 in Chapter 3). The remote cover has two states, Flushed and Covered, as shown in Figure 73b and 73f. The process of attachment and detachment is presented in the list below. The combination of the states attained in different process steps are tabulated in Table 13.

For a user, the process of attachment and detachment of *The Snail* is as follows

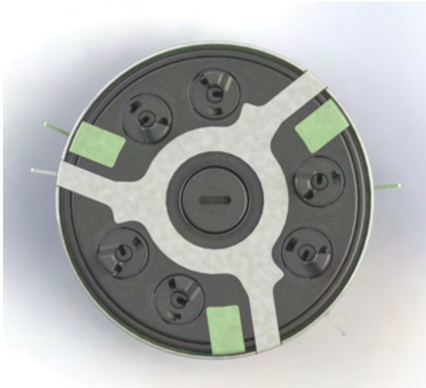
1. Flush the device with fabric
2. Rotate the device to attach (or actuate the lever) (Figure 73d)
3. Lock the wires by rotating *remote covers* - pinching action (Figure 73f)
4. Ensure attachment
5. Rotate the device to detach (or actuate the lever)
6. Rotate *remote cover* to Flushing state - pinching action

Table 13: Actuation states of Module and Cover in usage process

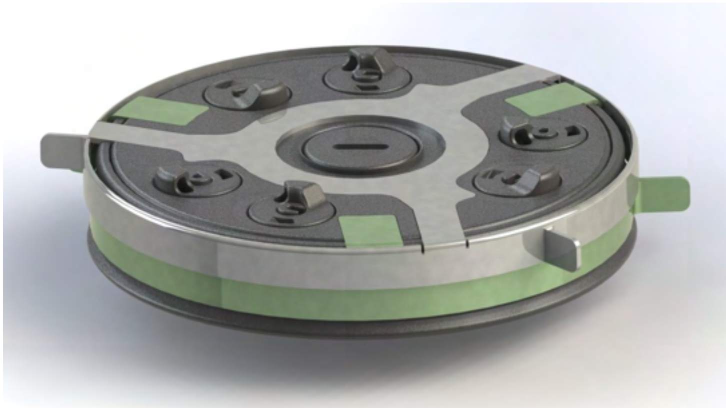
System State	Module state	Cover state	Process step
Not in use (Figure 73b)	Resting	Flushed	Before 2, after 5
After Penetration (Figure 73d)	Attached	Flushed	Between 2 and 3
Attached to fabric (Figure 73f)	Attached	Covered	After 3 till 5
Detached	Resting	Covered	Between 5 and 6

When not in use, the system is kept in a flushed state. Once the device is on the fabric (Step 1) the modules are actuated to attach (Step 2), followed by a actuating the Remote cover to covered state to secure the wires (Step 3). In case of cluster, both covers (see figure 72) are actuated simultaneously with a pinching action.

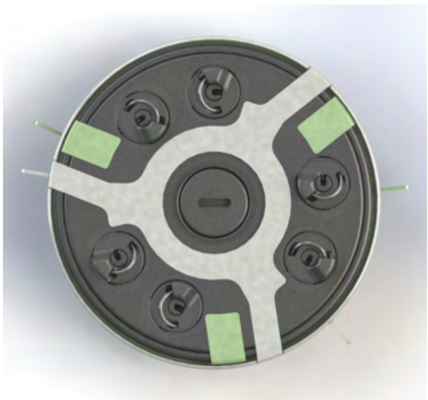
The device features a quick one-step detachment process. The designed process removes the step for ensuring detachment. This is enabled by actuating modules prier to the cover, which would push out all the fabric to slip-off the wire in every conditions. The wire would not be holding on to some threads after the step 5. The last step, 6, is not required to be carried out immediately. It can be done anytime before doing step 2 when attaching next time.



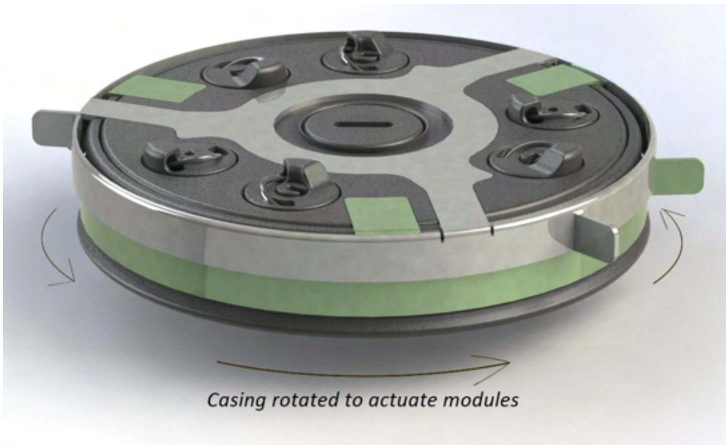
(a) The Snail - Clusters



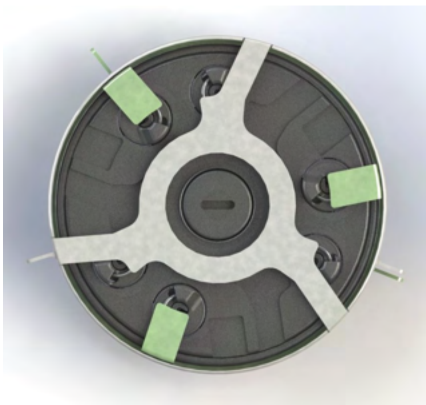
(b) Not in use - Resting + Flushed state



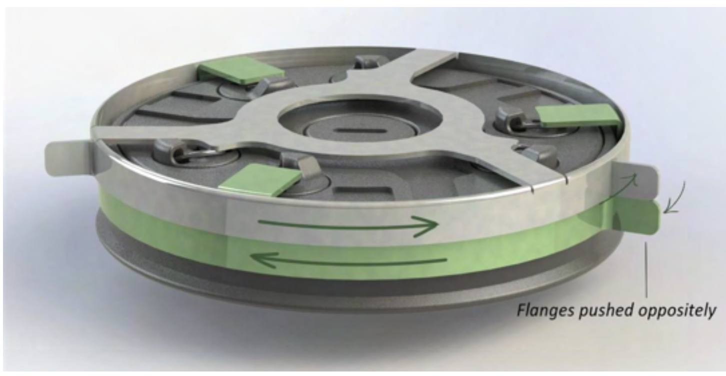
(c) Attached + Flushed state



(d) Step 2: Attached + Flushing state



(e) Attached + Covered state



(f) Step 3: Attached + Covered state

Figure 73: Step-wise functioning of *the snail*

7.2 Design details

The snail is based on the 'Spindel-tech' technology. The features are either additions or improvements of the technology. The following subsections describe all design feature changes and additions to the 'Spindel-tech'.

7.2.1 Attachment sub-system

Cluster arrangement

The modules are placed in a cluster formation where each cluster has two modules facing each other. The rotation direction is the same for both types of modules in a cluster but the wires of these modules travel in the opposite direction due to the mirrored orientation. The opposite travel captures the fabric oppositely, aiding in easier penetration and better fabric control. Overall, the cluster design attains a better attachment condition. By having two attachment points nearby, the design distributes inevitable force concentration. This distribution is beneficial in an unsymmetric loading conditions like unsymmetric pull in Z. The nearer two modules in a cluster, the higher the benefits. The cluster arrangement has better strength under parallel forces (parallel to attached surface, $F_{ext}(x, y)$), as when the fabric tends to slip out of one wire, there will be resistance from the second wire which is facing the opposite direction. Moreover, compared to 6 modules oriented in Twisted composition (X- direction positioned radially), the Cluster design eliminates low strength orientations in application of parallel force $F_{ext}(x, y)$.

Remote cover

The remote cover covers the wire from the slope-side to support it by reducing stress and deformation. Figure 73f shows how the remote cover is placed in an attached state of the system. The cover rotates to change between covered condition and flushing condition. During this rotation the cover also changes its vertical height (See Figure 73f and 73b). The flushing condition is to enable good flushing of fabric with the module surface. When in flushing condition, the cover does not affect attachment. Actuation of the modules is carried out in the flushing condition of the remote cover, and once attached, the remote cover is actuated to cover the wires on each module.

The remote cover is a set of two components, one for each type of module in a cluster. They are actuated in opposite rotational directions to reach the actuated condition from the flushing condition and vice versa. Both the components are mounted on the outer wall of the casing, in an angled slot. The slot is at an angle, which facilitates the upward motion of the cover during rotation, to reach the covered condition, and downward motion to reach in flushed condition (Figure 74).

Relaxed modules and Wire

The height of the wire pathway (H_w) is increased in the modules. This would reduce three point bending of wire and allow wire to bend in a spring-like fashion more. As the actuation force counters the bending stiffness of wire (three-point bending), increasing H_w would reduce the actuation force f_w. Increasing abutment separation (α) would also reduce three-point bending, however it reduces the angle of change of rotation plane (ϕ)

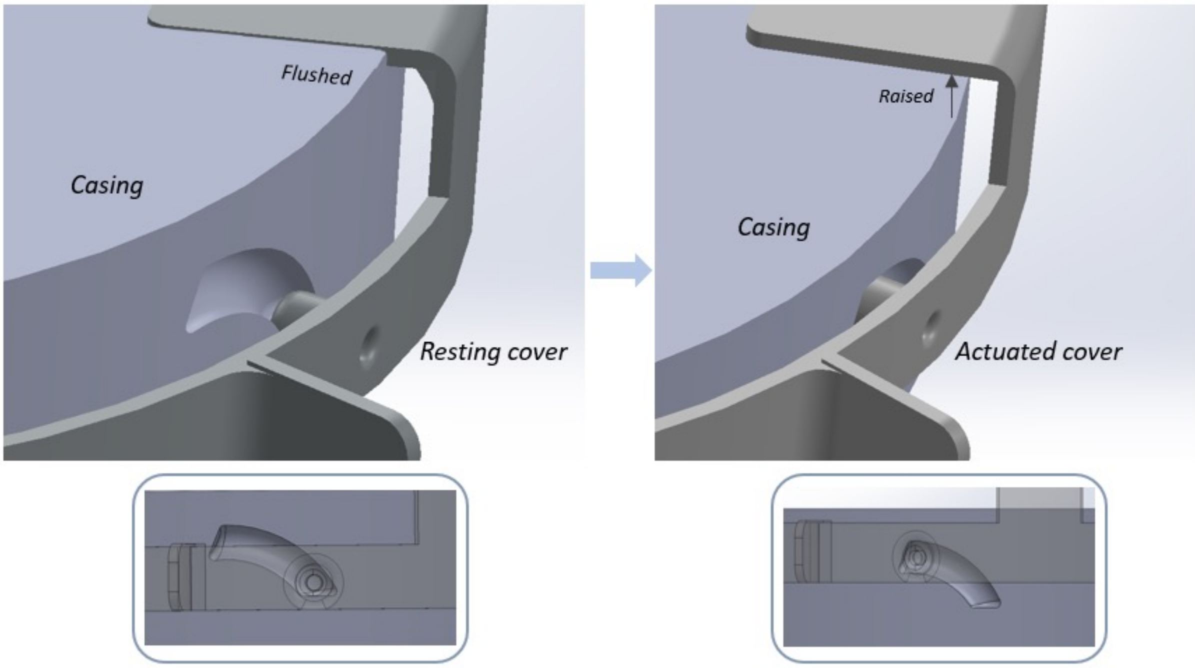


Figure 74: Illustrated motion of remote cover on the angled slot (Flushed condition to Actuated condition)

and angle of first penetration (β_1). In contrast, Increasing H_w allows a higher ϕ and β_1 with lower actuation force. The relaxation would marginally increase the thickness of the modules.

Stainless steel spring tempered (hardened) 0.5mm thickness r_w wire is used in the system. 0.4mm thickness wire has high deformation and $f_{u,z+}$ strength achieved is 20N, compared 50N with 0.5mm wire. Having reduced actuation force, 0.5mm wire only pose a marginally higher fabric damage risk compared to 0.4mm wire. With optimised value for Relaxed module, 0.6mm wire can also be considered to increase ultimate strength $f_{u,z+}$ to over 80N. However, going above 0.6mm wire thickness r_w would cause more fabric damage.

7.2.2 Actuation sub-system

Alternate actuation

The alternate actuation is an alteration to the existing design of the central driving gear of the system. The teeth on the driving gear are placed such that they mesh every alternate driven gear at a time, reducing the actuation force by splitting it. In the *snail*, there are six modules, arranged in three clusters. So the driving gear drives one module from each cluster at a time, and then the second module of each cluster. Although, due to this, both modules in a cluster do not rotate at the same time, but, the module that attaches first improves the fabric capture for the second one, keeping the main intent of *cluster orientation.* The actuation for this concept is done by rotating the full casing (See figure 16), and not using a lever, as the driving gear is on the lower casing. This is specifically to allow space on the periphery for actuation of the *remote cover.* Figure 75 shows the arrangement of this concept in a three cluster system.

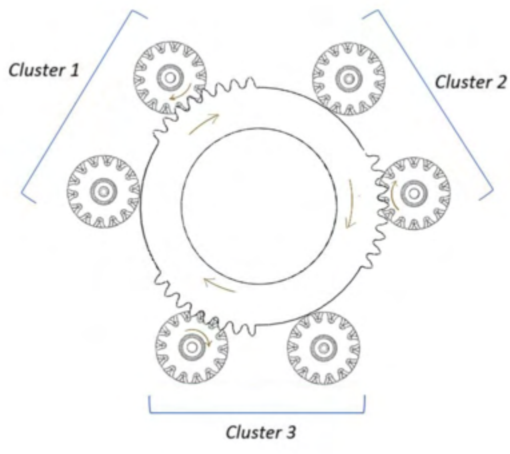


Figure 75: Alternate actuation concept for *the snail*

Improved gears

This is an improvement to the gears in the modules, that hold and drive the wire. As a solution to the problem of wire slipping off the groove in gears during actuation, there are small projections along the upper edge of the groove to snap fit the wire during assembly (Figure 76). This prevents the gear from loosing control of the wire rotation, in turn, preventing the problem of *wire not reaching the cave* during attachment (see Section5.6).

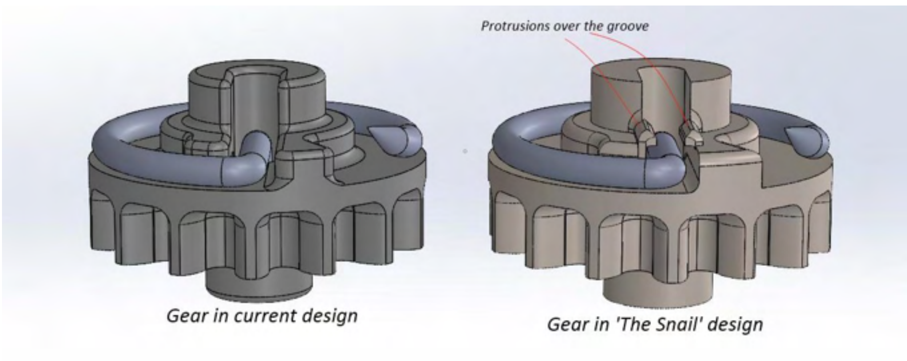


Figure 76: Improved gear design against the original design

7.2.3 Structural sub-system

Distribution flanges

The distribution flanges (Figure 77) are essentially extended structural support behind the casing to distribute the weight of a hand-held object to all modules of the system in an attached condition. In most cases the size of *the snail* will be smaller than the object it is holding with it. This would result in increased load from bending moment on one or two modules, so these flanges on the casing (that holds the object) would restrict tipping and oppose the bending load on the attached system.

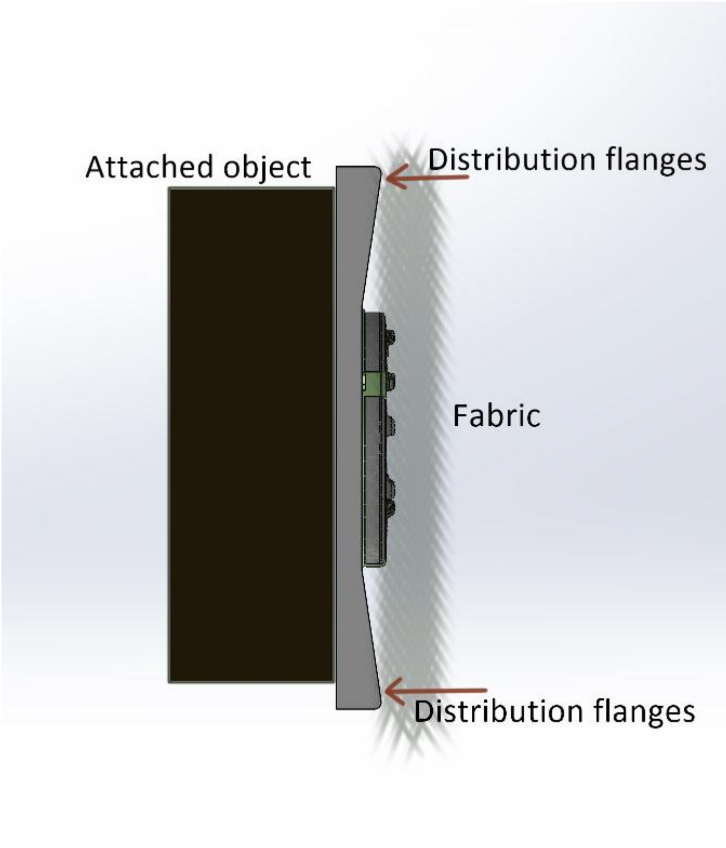


Figure 77: Illustration of distribution flanges on the casing

Remote cover

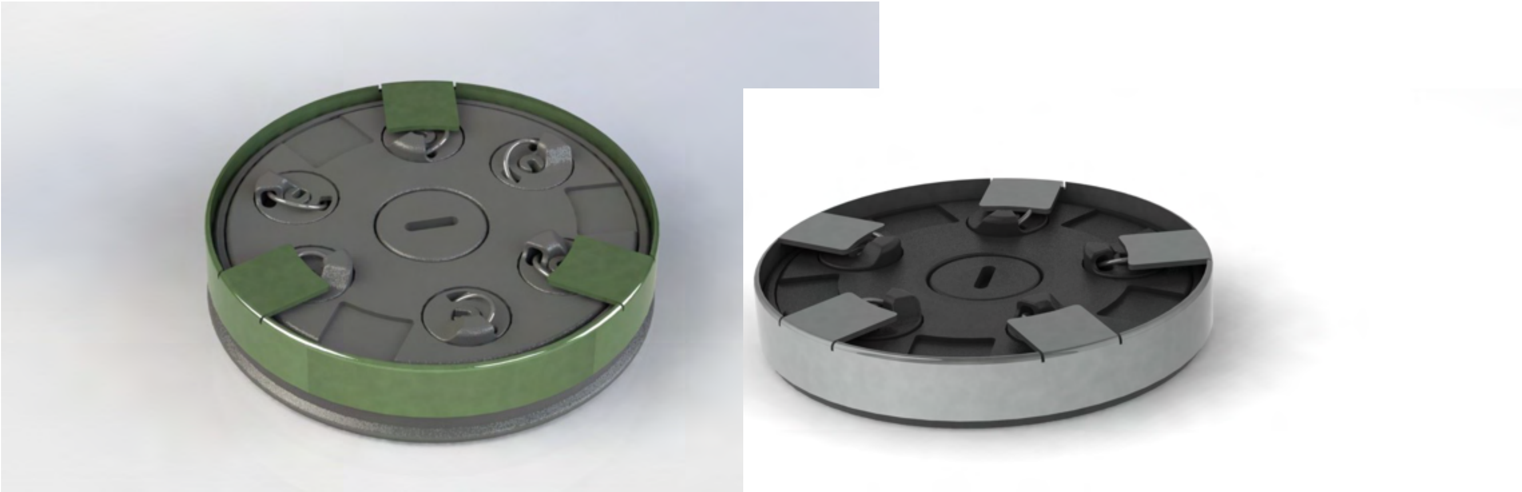
The *remote cover* plays a significant role in the structural support of the system as well. As it is a sheet metal component mounted externally onto the main casing of the system, in the attached state, any external force on the attachment will be transferred directly to the casing through the cover supporting wires. This would prevent damage to the system's individual modules and internal components by diverting forces away from weak points.

7.3 System configuration

The snail is a modular concept. The modularity is to accommodate for various objects and user requirements. The modularity is not limited to the attachment modules (number and placement), but rather other components of the system as well. Table 14 tabulates these five components and variants of each component.

7.3.1 Component variants

The *Cluster* and *Twisted* are variants of attachment module type, which mainly dictates placement and orientations of modules. Figure 78a showcases the *cluster* orientation, while Figure 78b shows the *Twisted* placement. The *remote cover* can be two covers moving in opposite directions, a *single cover* (uni-directional), or *no-cover* (like standard system). Figures 78a and 78b shows Single cover variants.



(a) Clusters with Single Remote cover and rotation based actuation (6 modules, 3 clusters)

(b) Twisted placement with Single Remote cover and rotation based actuation (5 modules)

Figure 78: System Variant configuration

Actuation system has two component, actuation method and actuation input. The actuation method is based on variation of the driving gear. A fully threaded standard driving gear is referred to as *Single*, referring to the simultaneous actuation. Alternate actuation of modules is refereed to *alternate*, half modules at a time (Figure 75), and *triple alternate*, where one third modules are actuated at a time working on similar concept as the Figure 75. The actuation input, is the way in which user would give a input to the system. Lever and rotation are two simple options, as discussed in Figure 16 in Chapter 3. There are other possibilities of actuation like pressure based actuation, or spring loaded actuation.

The fifth configurable component is flanges. Flanges can be *Uniform* flange, i.e., having the same thickness around the system, or *Long* flange, i.e., increased thickness in the gravitational direction. It is not necessary to have a flange for light and small objects. Other configurable components are module variant and wire thickness, which is considered as optimisation parameters rather than variants for *the snail*. However, once optimised, module variant and wire thickness options should be added to the configuration to make it exhaustive. Another component not included in the configuration is the object mount because it is unique for each object.

7.3.2 Configuration rules

A system configuration has one variant of each component. However, system configuration follows certain rules. The configuration rules reflects aspects like incompatibility of components, size dependency, and components' connection to use case. Table 14 lists down component variants, their merits and their compatibility in system. 'Primary use case' gives a generic guideline of when should the component be included. Double variant

of the remote cover would cover each module in cluster system, while single variant does the same thing for Twisted variant. The *Cluster* can work with *Single cover* and *No-cover* variants with reduced strength. Such compatibility are mentioned in Table 14.

Table 14: Variant configuration - Options and compatibility

Component	Variant	Benefit	Drawback	Compatible with?	Primary use case
Attachment Module	***Cluster***	Better attachment Reduced stress Concentration	Needs Double remote cover	Double cover Single cover (Only 60% strength) No cover (<40% strength) Alternate, Single actuation	Default choice when size is >30mm
	Twisted		Lower attachment quality Force concentration on module	Single cover No cover (<40% strength) Alternate, Single, Triple Alternate	Size smaller than 30mm
Remote cover	***Single***	Simple assembly and usability		Both Cluster and Twisted	Twisted
	Double	Covers all modules of cluster	Slightly increased diameter	Only with Cluster	Cluster
	Non	Less actuation steps	Considerably Low strength and safety	Both Cluster and Twisted	
Actuation method	***Alternate***	One Half actuation force	Double rotation angle	Systems where n is even Lever for >40mm system Lever 30-40mm with No cover Rotation, Other	Default choice
	Single	Minimum rotation	High actuation force	Lever, Rotation, Other	< ~ 6 modules
	Triple alternate	One Third actuation force	Three times rotation required	Twisted (n = multiple of 3) Lever for >50mm system Rotation, Other	Twisted (multiple of 3) Typically big system
Actuation input	***Lever***	Defined orientation Actuation with Object attached	Cover design becomes complex		
	Rotation	Unifrom pressure	Unclear final orientation		Single or Double Remote cover
	Other	Ergonomics, Quickness			
Flanges	***Non***	Small size		Lever, Rotation, Other	Small and Light objects
	Uniform	Reduced force concentration Reduced oscilatory forces Longer lifetime		Rotation (symmetric system)	Big and heavy objects For use in High oscilation condition
	Long	Reduction of force concentration induced by gravitation Longer lifetime		Lever (Fixed orientation system)	Big and heavy objects

Firmness of attachment restricts the size of a cluster system. It is not possible to have system of less than about 25mm diameter using *cluster*. On the other hand, with increase in size the number of clusters needs to increase. For example, for 40mm diameter system, due to firmness concerns, 8 modules are required, while 6 twisted modules can be placed in 40mm system.

To alternately actuate the modules, number of modules (n) should be a multiple of number of actuation batches. For *alternate actuation* n should be multiple of 2, and for *triple alternate actuation* n should be multiple of 3. The *alternate actuation* doubles the driving gear rotation angle compared to single actuation. The rotation angle is also increased with smaller system diameter. The high rotation angle restricts the compatibility of a actuation input method with actuation method.

The flanges, or the force distribution elements, are dependent on the type of system which is built. If the system has a fixed orientation of attachment, a long structure can be incorporated after looking for design compatibility with object integration. Flanges are only required for heavy or big objects, or repeated asymmetric loading usage condition.

7.3.3 Sizing

Sizing refers to answering questions of how many modules should a system have, and what should be the size of the system? The size of the system is decided by the requirement of user based on object and fabric to be used, and user conditions.

The first restriction on system size is physical restriction posed by object or attachment placement on the fabric. The physical restriction limits the possible system sizes. Secondly, the number of modules (n) should be looked at based on the extreme usage condition possible. The conditions would deffer for each object and user group. The strength of these systems can be calculated using equations 14 and 15. These should be in addition to the holding capacity m_{obj}^{sys} calculation based on number of modules (n), and mass distribution of object to be carried (m_{obj} and d_{obj}) (equation 11).

The object weight plays little role in sizing of the system, because each module is capable of holding most hand-held objects. However, the distribution of mass and size of object would affect the resting force distribution (and concentration) and firmness of the attachment. Ergonomics of handling is also affected by mass distribution and size of the object.

Alongside the ultimate strength comparison, actuation force needs to be considered. Different module, cover and actuation combination would require different actuation force. Rearrangement of equation 1 helps to get value of the F_w^{sys} based on pre-tested values of F_w (Table 3).

Using variant configuration and rules of configuration, potential configuration can be put together to achieve strength and actuation force in a given size. When size is not limiting, actuation force would be a limiting factor. Lastly, cost comparison and usability analysis can be utilised to choose the final configuration and size.

7.4 Design considerations

7.4.1 Material selection

The material considered for *the snail*'s casing, modules, and gears is POM (Polyoxymethylene) polymer, and for the covers, is stainless steel sheet metal of 0.396 mm thickness. The wire material is stainless steel spring tempered (hardened). Essentially, the module and the wire material considered is same as used in the existing design of the system. As the dimensions of the modules and gears are relatively small, with significant design features which need close tolerances, POM is considered for its suitability in applications demanding dimensional stability and sliding ("Detailed information of POM and its features", 2021).

7.4.2 Manufacturing and assembly

The design details that *the snail* features, has some essential alterations from the existing design. These alterations were designed considering the feasibility of manufacturing them using conventional processes. Standard tolerances are used relative to the component functionality. Although there are more number of unique components in the concept, as compared to the existing design, the additional number of assembly steps are kept simple and non-time consuming. The particular assembly step of meshing the driving gear with the driven gears, before closing the casing, is made easier by the *alternate actuation* mechanism, as there are less number of gears to be meshed during assembly. Wire snap on gear adds an additional step of pressing the wire into its position. Also, manufacturing such a small feature is difficult and hence expensive. However, its benefit has been conclusively observed during prototyping, which seem to out perform the cost. It would increase the lifetime and reliability of the system drastically, which is a considerable improvement against the increased difficulty of manufacturing.

7.4.3 User-friendliness and Ergonomics

A significant change in *the snail* from the existing design, in the aspect of user-friendliness, is the alternate actuation which reduces the actuation force (f_w) by half. Although it has another associated effect, of increased lever (or actuating rotation) travel, but it is taken as a trade-off for a higher priority actuation force reduction. There are two flanges each on both the sheet metal covers of the *remote cover* (Figure 73f). For the covers to be actuated, one flange from each cover is pushed towards each other, which makes it a pinching action for the user, and hence, easier to operate. When the system has to be detached, the modules are actuated back to resting state first, and then the covers are actuated to flushed state. This ensures the fabric has completely detached from the wires and the system can be safely pulled away without damaging the fabric. One ergonomic issue which can be improved further, is the usage with thick gloves. This has not been verified with a fully working prototype, but is assumed that the lever like flanges on covers, and the pinching motion for both actuating into covered and flushing state would be relatively easier. It is also better to include a lever based actuation for the modules, as compared to the full rotation of the system.

7.5 Prototyping and testing

The main components of *the snail*that were to be analysed for its performance, were tested during the prototype-based evaluation in the concept development phase. The *alternate actuation*, *cluster orientation* and sheet metal version of the *remote cover-up* , which constitute the essential changes of *the snail* from the existing design, were tested and verified individually before combining them into this single synthesised concept.

However, to verify the feasibility of *the snail* it was necessary to detail the design virtually using CAD. Firstly, the sheet metal cover was designed , to analyse it's better assembly on the system casing. Some options were tried out -

- The cover has three covering components covering three clusters each, and a single plastic component (lever) drives them together (Figure 79). This design could be also used with a lever type module actuation, but the diameter of the system has to be increased in order to reduce the lever travel.

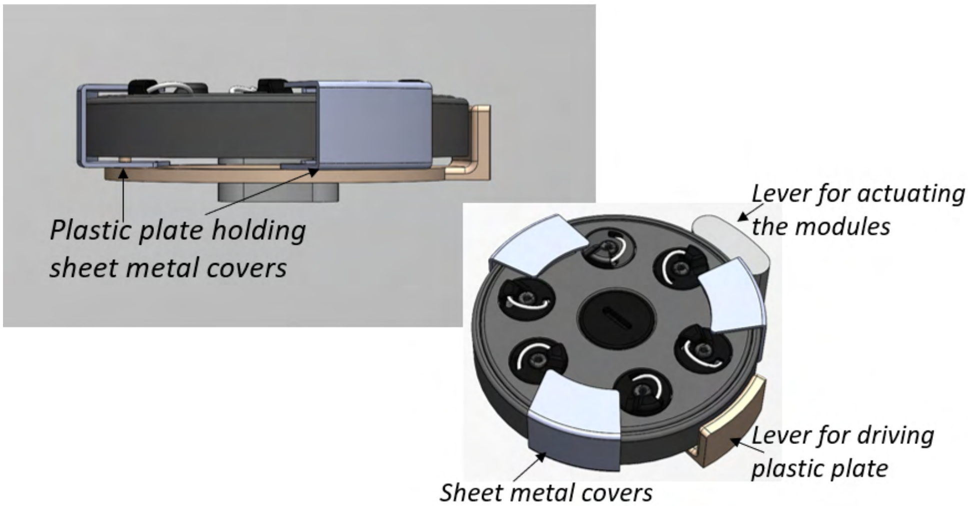


Figure 79: Visual prototype of a plastic-lever type remote cover

- The remote cover covers only a single module in each cluster (Figure 78a). Since the remote cover here is just a single component rotated in one direction, the main intent to cover only one module here was to avoid the negative effect of cover on the farther module, on which it would start covering from the cave-entry side. This solution also added the idea of keeping the cover in flushed state.

The final design for having two sheet metal covers as a *remote cover* came from covering both modules from the slope side, as it would be safer for the wire and it would not allow the wire to bend and slip out under external forces on the attachment. To allow both the covers to be accommodated on the device in a flushed state for better attachment, the diameter was also increased from 30 mm to 35 mm. This design was then detailed for manufacturing and assembly feasibility.

8

Evaluation

In this chapter, the final design is evaluated. The evaluation process answers two questions - Where does the design stand against external products used for similar functionality? Does the design fulfil the requirements list set out for an improved design?

8.1 Performance and fulfilment of requirements

The proposed concept has been tested partially as discussed earlier. Separate components of the concept were tested as partial concepts and during the prototype based evaluation in the concept development phase. However to validate the concept as an improved design of the whole system, it has to be evaluated with all the criteria of the target requirements list. The Table 15 shows the values of each criteria for the existing design (5mStd) and *the snail*. The existing design here is the five module system that uses Type B module and 4t ($2r_w$=0.4mm) wires.

The snail performs better than the existing design on all the strength criteria. Its cost would naturally be more than the existing design as the number of unique components are increased. This is a trade-off with the device strength, but considering that the approximate cost of manufacturing for one module is 10 SEK, the cost for the device would still be limited to 150 SEK. This would include the two additional sheet metal components.

The lifetime of the device is not accurately computed in the study, as the current design has functional issues such as the slipping of wire on the gear (Figure 50), fatigue on the module body due to wire bending at the two abutments (Figure 24) at the slope and wearing of gear teeth over time, which makes the lifetime of device highly dependant on the type of usage. But it is hypothesised that *the snail* would have an increased lifetime based on these aspects, due to the modified gear, relaxed modules and alternate actuation mechanism. Although the sheet metal remote cover in the snail may have a wearing effect on the plastic casing of the device over time. From the failure aspect of the device, i.e, when it would be subjected to high external forces during attachment, *the snail* would have a better lifetime as it has a higher directional ultimate strength ($f^{sys}_{u,dir}$) and functional limit (f^{sys}_{f}).

The attachment quality would be better in *the snail* than the existing design due to the cluster orientation of he modules. But for other attachment criteria, it is similar as they both depend on the type of fabric and the type of back-support during attachment.

For the safety criterion during usage, *the snail* would be similar to the existing design as the depth of penetration (D_p) is same in both the designs. So for work wear, as the

Table 15: Requirement evaluation

ID	Requirement	d/w	Value	5mStd	The Snail
	Strength				
1	Support minimum resting weight(m_{obj}^{sys})[g]	D	200	600	5000
2	Maximise resting weight capacity(m_{obj}^{sys})[g]	W	1000		
3	Minimum directional ultimate strength($f_{u,dir}^{sys}$)[N]	D	100	47.5	222
4	Maximise minimum directional ultimate strength ($f_{u,dir}^{sys}$)[N]	W	200		
5	Minimum functional failure strength(f_{f}^{sys})[N]	D	10	15	150
6	Maximise minimum functional failure strength(f_{f}^{sys})[N]	W	50		
	Cost and Lifetime				
7	Maximum Manufacturing cost per device[SEK]	D	150	$\sim$ 50	<150
8	Lifetime - Number of cyclic operations (Min. of all components)[#cycles]	W	1500	-	-
	Attachment				
9	Allow Flexible placement on the body	D	Yes	Dependant	Dependant
10	Allow secure attachment - independent of Bodily or Cushioned back-support, and orientation	D	Yes	Dependant	Dependant
11	Firmness of attachment - Minimise wobble	W	Yes	Dependant	Dependant
12	Wide Fabric compatibility	W	Yes	Yes	Yes
	Safety				
13	Should not harm the user when in use[#cycles]	D	2	Dependant	Dependant
14	Should not harm the user when actuating without fabric or holding[#cycles]	W	10	Yes	Yes
	User-friendliness				
15	Allow usage with gloves	D	Yes	Dependant	Dependant
16	Ergonomic design for holding and actuation	W	Yes	Dependant	Dependant
17	Maximum Force of actuation(F_{w}^{sys})[N]	D	20	9	13
18	Minimise Force of actuation(F_{w}^{sys})[N]	W	2		
19	Maximum number of steps involved[#of steps]	D	6	5	7
20	Minimise number of steps involved[#of steps]	W	2		
	Design and Assembly complexity				
21	Minimise number of unique components in the system[#]	W	7	7	9
22	Maximum Number of components in the module[#]	W	3	3	3
23	Minimise Number of assembly interaction steps[#]	W	30	28	35
	Working environment				
24	Maximise 'Maximum operating temperature' [°C]	D	Yes	Yes	Yes
25	Minimise 'Minimum operating temperature' [°C]	D	Yes	Yes	Yes
26	Should be operational in mild rain	D	Yes	Yes	Yes
	Size				
27	Maximum Width[mm]	W	40	30	35
28	Maximum Length (Height)[mm]	W	40	30	35
29	Maximum thickness outward from the fabric[mm]	W	10	10	8
	Other				
30	Must be able to disassemble to a degree that the materials can be recycled or re-manufactured[%mass]	D	80	100	100
31	Allow for easy and quick replacement of Vulnerable components	W	Yes	Yes	Yes
32	Allow usage by diferently abled users	W	Yes	Dependant	Dependant

fabric thickness would be higher, safety is not an issue as the wire would not penetrate deep enough to harm the user. For the safety criterion when not in use, both the designs do not have any protruding components which would tend to harm the user.

Usage with gloves, ergonomics of the device is dependant on the design of the external attachment, which can be customised based on the type of hand-held object to be attached. The number of actuation steps in *the snail* are higher due to the remote cover, but as the strength of the device is of higher importance here, there is a trade-off. *The snail* also has lesser actuation force, despite having more number of modules, which makes it more user-friendly.

Overall, for *the snail*, having a higher directional ultimate strength ($f^{sys}_{u,dir}$), functional limit (f^{sys}_{f}), and better attachment quality, is a trade-off for some other less essential requirements.

8.2 External benchmark

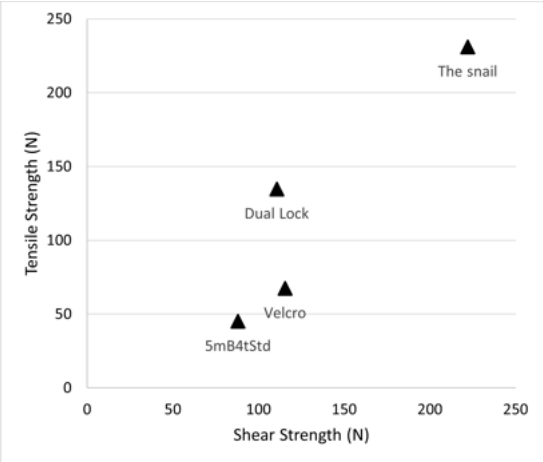
The safety pins have a similar concept of wire piercing and locking as the technology. However, it is not feasible to attach hand-held devices to fabrics using them due to low strength, wobbliness, cumbersome use, and safety issues.

The Hook and loop fasteners, known as Velcro®, are a widely used product for a similar purpose. If one side of the material (strip) is placed on a large area, it can also deliver flexibility in the position. This functionality is not possible to achieve by other fastening products like button and clips. Dual lock fastener is similar to Hook-&-Loop fasteners (see Appendix B.1b).

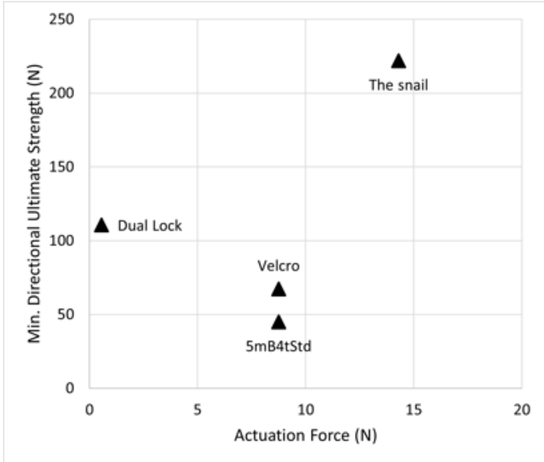
Hook-&-Loop fasteners degrade with each detachment because detachment breaks the loops with which the hook were attached (Zhang et al., 2019). Ultimate failure (detachment) also follows the same mechanism of detachment. Hence even at failure, the fastener would be reusable. However, the degradation limits the life of the fastener. In interviews, security personnel complained about Velcro® going bad quickly. Dual lock fastener is supposed to have an improved lifetime and strength compared to Velcro®.

A 35mm diameter patch of *Velcro®* and *Dual lock* are considered to compare performance with *the Snail* and *5mStd*. The diameters of the snail and 5mStd are 35mm and 30mm, respectively. Zhang et al. (2019) did an experimental analysis of tensile, shear and peel strength of Velcro® and Dual lock fasteners, which is taken as reference. Peel force (to detach two sides) is considered as actuation force for these fastening products. Figure 80 plots tensile vs shear strength and minimum directional strength vs actuation force. The 5mStd is just short of Velcro in strength. The dual lock has very little actuation force and moderate strength. The snail has the highest strength, almost equal in both tensile and shear directions. It also has the highest actuation force among these. The actuation force of snail does not account for the relaxation of modules, which would reduce it.

It can be concluded that with minor improvements, the current system can out compete Velcro®. Moreover, the Snail is a superior concept. The downside of snail would be low flexibility, higher actuation force and not being usable after failure. On the other hand, Velcro and Dual lock struggle with low lifetime and strength and have the pre-assembly procedure to fix or stitch both the mating parts before usage.



(a) Shear stress vs Tensile strength of systems.



(b) Minimum directional ultimate strength vs. Actuation force

Figure 80: Performance comparison

9 Discussion

A discussion on the development process is presented in this chapter. The work process and utilised methods are reflected upon for possible shortcomings, improvements, and potential sources of error to be acknowledged. The chapter also includes an outlook for ethical, societal and environmental considerations regarding the development work.

9.1 Scope for improvement

Although the proposed design has been detailed for the feasibility of manufacturing and assembly, it has not been tested as a full working prototype. Hence, here is a list of recommendations that promotes further improvements in design :

- The sheet metal remote cover of *the snail* is currently mounted on the outer walls of the device casing. Currently, it is made of two individual components. In order to make it a single component and still cover both the modules in a cluster efficiently, exploration of design solutions should be done. The angular distance by which the remote cover is rotated should be optimised by reducing the space and orientation angle between modules of the cluster. An alternative mechanism for covering the modules should be explored, such that the wires are actuated and covered in a single actuation step.
- For actuating the modules, a spring loaded push (button-type) mechanism for rotating the driving gear should be explored. This would considerably improve the ergonomics of the system as the user would just have to press the system to he fabric for attachment.
- Different design alternatives for the adapting to all type of hand-held objectives must be explored. A more detailed understanding of the users, and the hand-held equipment they want to attach will facilitate this. If not universal, the design must be adapted to a focused hand-held object, and the actuating touch points can be placed on the casing according to the shape and dimensions of the object.
- A prototype of the proposed design must be tested as a full system in actual usage condition in order to analyse the drawbacks and further optimise it.

9.2 Reflection on Process

The methodology for the project was structured into each phase from a product improvement perspective. The technical investigation explored the design and functional parameters of the device, but the material was not investigated in detail. Material exploration was kept as a potential solution to improve the design after analysing the device's performance. As a parametric solution to increase the strength, alternative materials for wire were explored during the prototype-based concept evaluation. The most vulnerable component in the system is the wire. Hence, to better understand the effects on the various design parameters, and therefore the functional parameters, the material exploration must be done in the technical investigation phase. This would give an early clarity for the concept generation phase of the project, where the ideas will be based on more precise material understanding.

The concept generation phase of the project resulted in a number of solutions for different problem areas. The solutions which were generated using the bottom-up approach were evaluated using partial prototypes, to understand their feasibility. Due to paucity of development time, the scope for completely testing all solutions was altered to make evaluation decisions based on theoretical models. On the other hand, it was easier to prototype and test partial concepts which were adaptations to the existing design, as smaller components could be prototyped and used in the same system for testing. Also, if the concept development phase could have been initiated during the performance investigation phase, more number of ideas would be generated.

The technical models are used for making significant evaluation decisions during the concept development, and also for validating causes for problems observed in the performance investigation phase. It is recommended to make a more detailed version of the technical models, which accounts the effect of various external parameters on the functional parameters of the device. Currently, there is usually small dimensional or assembly variations between each prototype tested. But as the dimensions of the device components are very small, even minimal variations effect the functional parameters considerably. Technical models can be efficiently used in the future optimisation of design by including the range of errors in the relationship of these different parameters.

9.3 Sources of error

In technical models, stress assessment is based on a simplified model. The model does not consider pre-stressed conditions at the top abutment or high deformation resulting in a change in forces due to fabric slipping. Due to this, it can not yield an exact limit of the force or stress. Though the numerical value may not be exact, the relationships between parameters are unlikely to change because of simplification. The understanding of the relationship is valuable for the design.

All of the modules and systems used in experimentation were processed and assembled by the authors. Though it was based on the teaching by the company, the tacit knowledge developed by experience would be missing from the authors' process of assembly. This difference may have caused some variation in the assembled system compared to one assembled by the company, potentially inducing deviation in the performance. However, all modules being similarly assembled, the error does not affect the comparability and analysis of the results.

Observing and classifying attachment condition requires a good view of the attachment point. Sometimes, the fabric needs to be moved to get a clear view. This action can create some changes in the attachment condition, like 1p-stuck can become 2p. Due to this, erroneous observation is possible in attachment testing, observing changed condition rather than the original one. However, the error is minimised by being gentle with motions and continuous observation.

Subjective assessments are not repeatable and hence have the potential to add error in observation. Attachment goodness (of a system), or fabric damage, is an example of such subjective parameters. Having the same observer would reduce the error in the study, even though not repeatable. In order to counter error by the subjective assessment, parallels to a quantified property were derived from observations of experiments. Assessment of the attachment quality is primarily based on the angle of penetration and depth of penetration. For fabric damage, the thickness of the penetrating element (wire) is used as an approximation.

Rapid prototypes for concepts may not be in a state for a fair comparison to benchmark, or in some cases, not in a state to be properly evaluated at all. Moreover, the number of prototypes made would also be limited, restricting the possibility of destructive testing. Though the assessments are made in the best way possible for a prototype, the explained issues create a potential error in observation because of its quality or less sample size. However, given the delimitation of time, the decisions are taken based on the observations made while acknowledging uncertainty where deemed necessary.

9.4 Ethical, societal, and Environmental aspects

The product does not pose ethical conflict when in use. Because of its general-purpose functionality, it may enable some third party to indulge in non-ethical aspect. However, the functionality offered by the product does not go beyond what is already fulfilled by other widely used products like Velcro®, except for doing it more effortless. Hence, there is a little ethical dilemma in whether the product should be developed or not.

During the development process, no personally identifiable information was collected from anyone who interacted with authors. All interviews and interactions were conducted after the explicit consent of the other party. Moreover, no illegally or unethically sourced information was used, and no unlicensed software was utilised.

Inclusive design (design for all) is considered a vital part of developing such a product. Although a detailed study of these was out of scope, the requirement list includes the requirement to enable this. As the requirement list guides the development, the Inclusive design and ergonomics principles were loosely considered in the design and evaluation.

Similar to Inclusive design, environmental consideration crucial. It is ingrained in the product with conscious design decisions. The product is a modular system with replaceable components and easy repair potential. It offers 100% material separation via disassembly, and used materials are 100% recyclable. The environmental impact is limited to production, distribution and afterlife phases. Having no impact while in use, there is a potential for a material swap in future to reduce its impact. In the process of development, destructive testing is used for performance investigation. The amount of waste can be seen as high, though only modules are destructed, amounting to a small weight in total. However, the performance testing, leading to a more robust system, would eventually reduce the number of failures in use, cumulatively reducing plastic waste.

10
Conclusions and Recommendations

The project's primary goal was to improve the design of the device, make it more robust, and increase the quality of its main function of attaching hand-held objects to fabric. To meet this goal, a set of objectives were fulfilled by first analysing the design and functional parameters of the device, and then its performance of various functions was analysed in detail. Based on the observations and results from the performance investigation, target requirements for an improved design were specified. The concepts were generated considering the problems in the existing design. These concepts were further developed and evaluated based on the target requirements, resulting in a synthesised concept which fulfils the primary goal of increasing the robustness and attachment quality.

The snail, improves upon the current system by about 2.5 times, while compared to external benchmark it is 2 times stronger. Moreover, the delivery of a modular and configurable system along with configuration rules and sizing guideline creates wider opportunity of adaptation.

One of the key take-away from the study is to minimise or avoid 3-point bending and depend more on spring-like bending. Relaxed modules are an example of this. This would reduce actuation force and allow for thicker wire resulting in high strength. Another limiting factor is fabric damage, which limits thickness of wire. However, marginal increment in thickness would increase functional limit with power of three. Another important takeaway is a extra safety factor should be considered when sizing system because of the chain-reaction like instantaneous failure of system once a module fails. This factor would be on top of the factor q, attachment quality.

When designed with focus on ergonomics and usability, the dependency on user would reduce, which would increase repeatability. The study specifically used high strength fabrics to avoid fabric breakage, however, the strength of fabric is a weak link in the force-flow. If the system strength is higher than fabric strength, the fabric would break upon failure, causing permanent damage, which is not desirable. Hence, a user centred approach is required to identify the specific needs, usage requirement and the fabrics, and strength should be sized accordingly.

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A

Experimental results

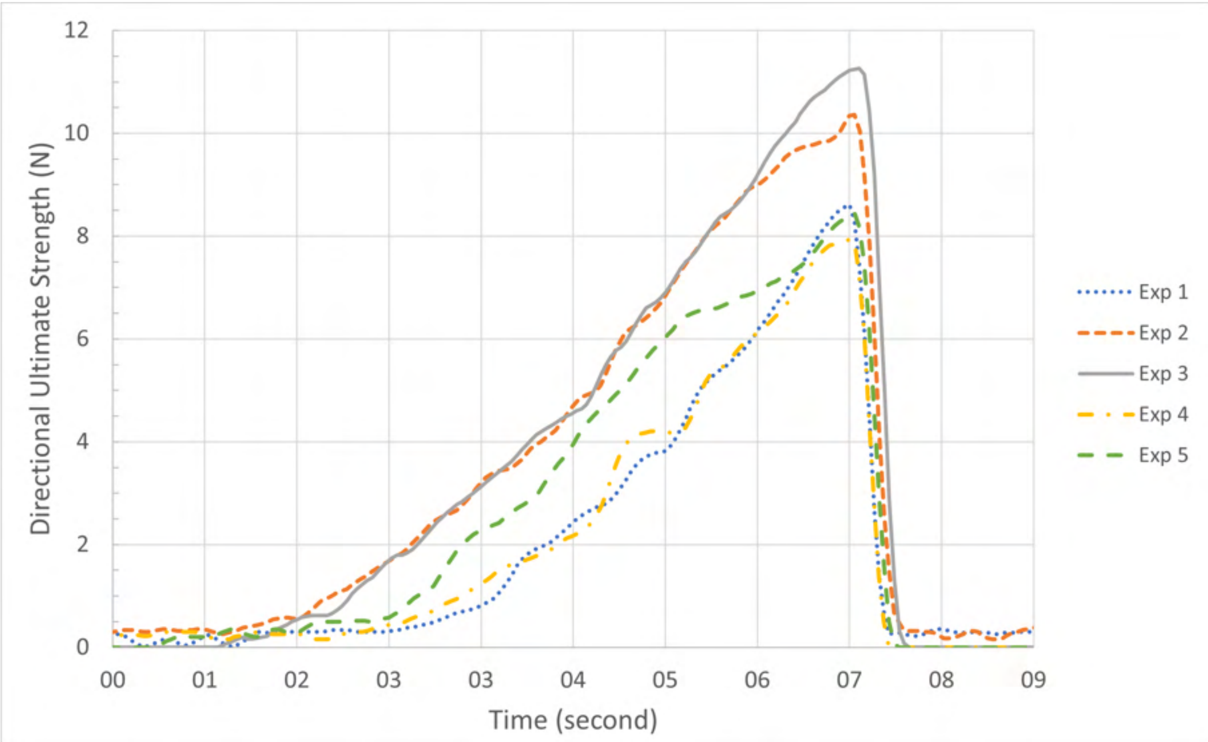


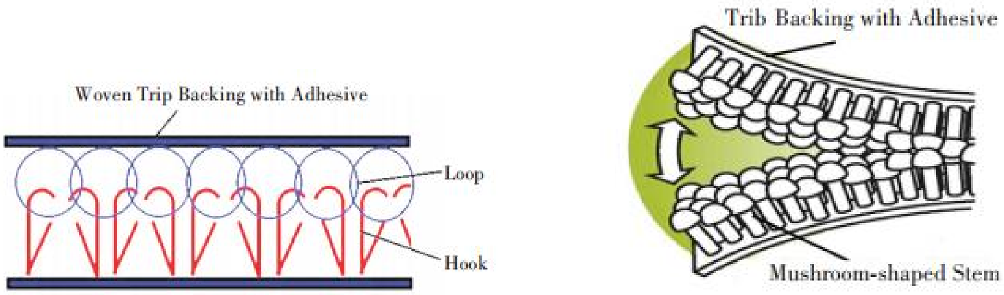
Figure A.1: Plot of logged data for test in Z direction 1mB4t

ID	Force direction	Module Variant	Wire thickness [mm]	# of tests	# of modules	Average Peak Force [N]	Standard deviation [N]
UTM1	Y+	B	0	3	1	**9.0**	0.2
UTM2	Y-	B	0	5	1	**24.3**	6.0
UTM3	X+	B	0	3	1	**15.2**	2.9
UTM4	X-	B	0	3	1	**24.2**	0.3
UTM5	Z	B	0	5	1	**9.5**	1.3
UTM6	Y+	A	0	3	1	**11.2**	0.6
UTM7	X-	A	0	3	1	**21.3**	2.3
UTM8	Z	A	0	3	1	**10.3**	1.2
UTM9	Y+	C	0	3	1	**10.1**	0.4
UTM10	X-	C	0	3	1	**26.8**	0.2
UTM11	Z	C	0	3	1	**8.8**	0.3
UTM12	Y+	C	1	3	1	**16.4**	0.9
UTM13	X-	C	1	3	1	**35.1**	0.7
UTM14	Z	C	1	3	1	**17.5**	0.6
UTM15	Y+	4mB	0	3	4	**56.6**	14.2
UTM16	Z	4mB	0	4	4	**23.2**	5.3
UTM17	45Y+	4mB	0	2	4	**63.2**	1.6
UTM18	Y-	C	1	1	1	**33.3**	
UTM19	X-	B-mold	0	3	1	**21.9**	1.0
UTM2m	Y-	B-mold	0	3	1	**21.2**	2.6
UTM20	Y-	B-mold	0	2	1	**33.5**	2.4
UTM21	X-	BT-mold	1	1	1	**32.9**	
UTM22	Y-	BT-mold	1	1	1	**48.7**	
UTM23	Y+	C-NoCave	0	1	1	**10.0**	
UTM24	Y-	C-NoCave	0	1	1	**20.6**	
UTM25@1p	Z	C-NoCave	0	3	1	**4.8**	0.1
UTM25@2p	Z	C-NoCave	0	3	1	**7.9**	0.7
UTM26	Z	BT-mold	1	1	1	**14.8**	
UTM27	Z	BT-mold	1	1	4	**58.7**	

Figure A.2: Strength test results

B

Concept Development and Evaluation



(a) Velcro fastening Mechanism **(b)** Dual lock fastener

Figure B.1: Hook-and-loop type fasteners

Criterion / Values (m_i)	Directional Ultimate Strength (f_u) [N]	No. of modules in system (n) [1]	Functional limit - Holding strength (f_f) [N]	Actuating Force (F_w^{sys}) [N]	System Size (diameter) (D_{sys}) [mm]	System Size (thickness) (t_{sys}) [mm]	Number of Unique components [#]	Number of Assembly steps [#]	Number of steps to Actuate [#]	Quality of Attachment [1-5 scale]	Ergonomic use [1-5 scale]	Fabric damage ($2r_w$) [mm]	$\sum m_i$	$w = \frac{\sum m_i}{\sum\sum m_i} \times 100$
Directional Ultimate Strength (f_u) [N]	1	3	1/2	1	3	2	1	3	2	1/2	2	1	20.00	11
No. of modules in system (n) [1]	1/3	1	1/3	1	1	1	1	3	3/4	1/3	1	1/2	11.25	6
Functional limit - Holding strength (f_f) [N]	2	3	1	2	5	3	2	3	3	1	3	1/2	28.50	15
Actuating Force (F_w^{sys}) [N]	1	1	1/2	1	2	2	2	3	2	1/2	1	1	17.00	9
System Size (diameter) (D_{sys}) [mm]	1/3	1	1/5	1/2	1	1	1/2	1	1	1/3	1/2	1/3	7.70	4
System Size (thickness) (t_{sys}) [mm]	1/2	1	1/3	1/2	1	1	1/2	1	1	1/3	1/2	1/3	7.99	4
Number of Unique components [#]	1	1	1/2	1/2	2	2	1	2	1/2	1/3	1	1/2	12.33	7
Number of Assembly steps [#]	1/3	1/3	1/3	1/3	1	1	1/2	1	1/2	1/3	1	1/2	7.16	4
Number of steps to Actuate [#]	1/2	1/3	1/2	1/2	1	1	2	2	1	1/2	1	1/2	10.83	6
Quality of Attachment [1-5 scale]	2	3	2	2	3	3	3	3	2	1	3	2	29.12	16
Ergonomic use [1-5 scale]	1/2	1	1/3	1	2	2	1	1	1	1/3	1	1/2	11.67	6
Fabric damage ($2r_w$) [mm]	1	2	2	1	3	3	2	2	2	1/2	2	1	21.53	12

Figure B.2: Pair-wise comparison matrix for weightage of criteria

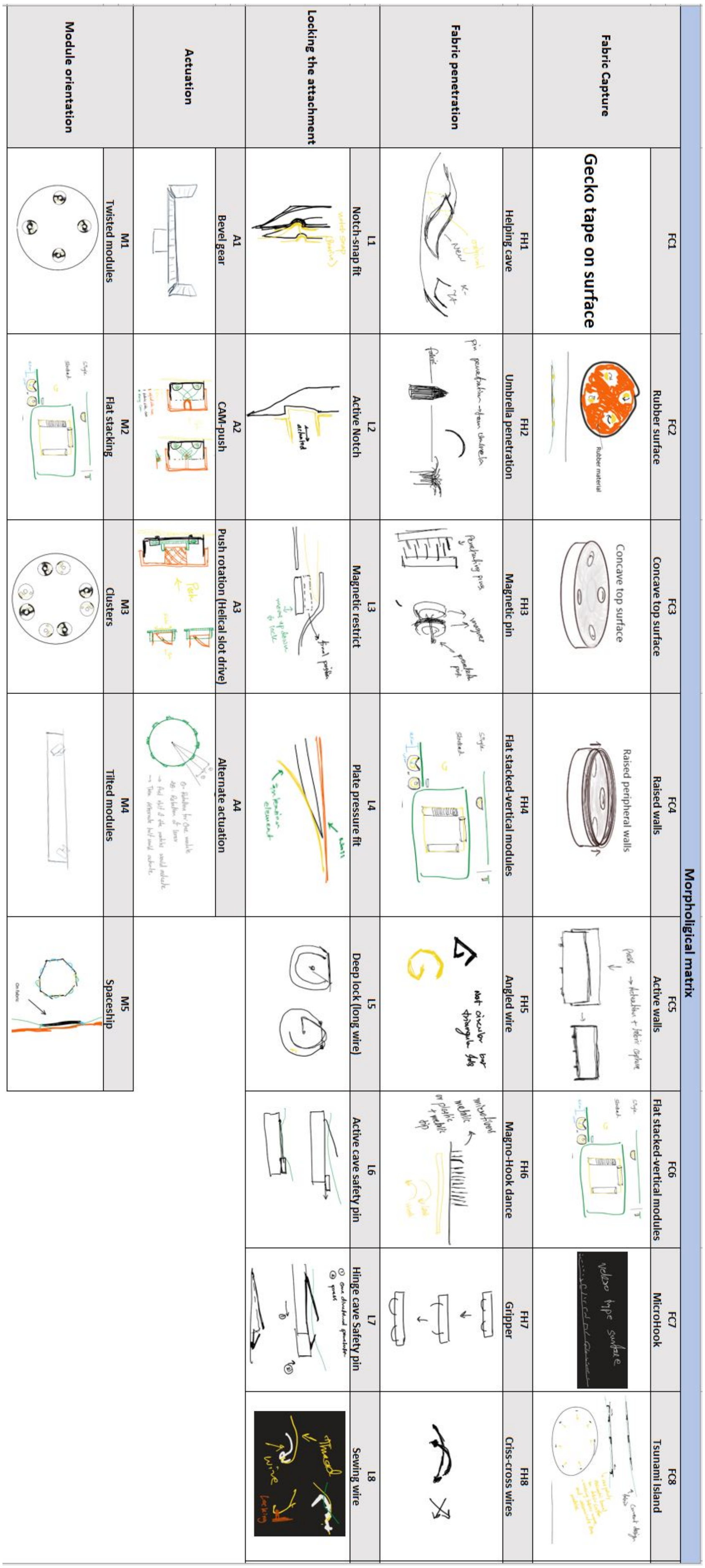


Figure B.3: First section of Morphological matrix showing concepts for each problem area

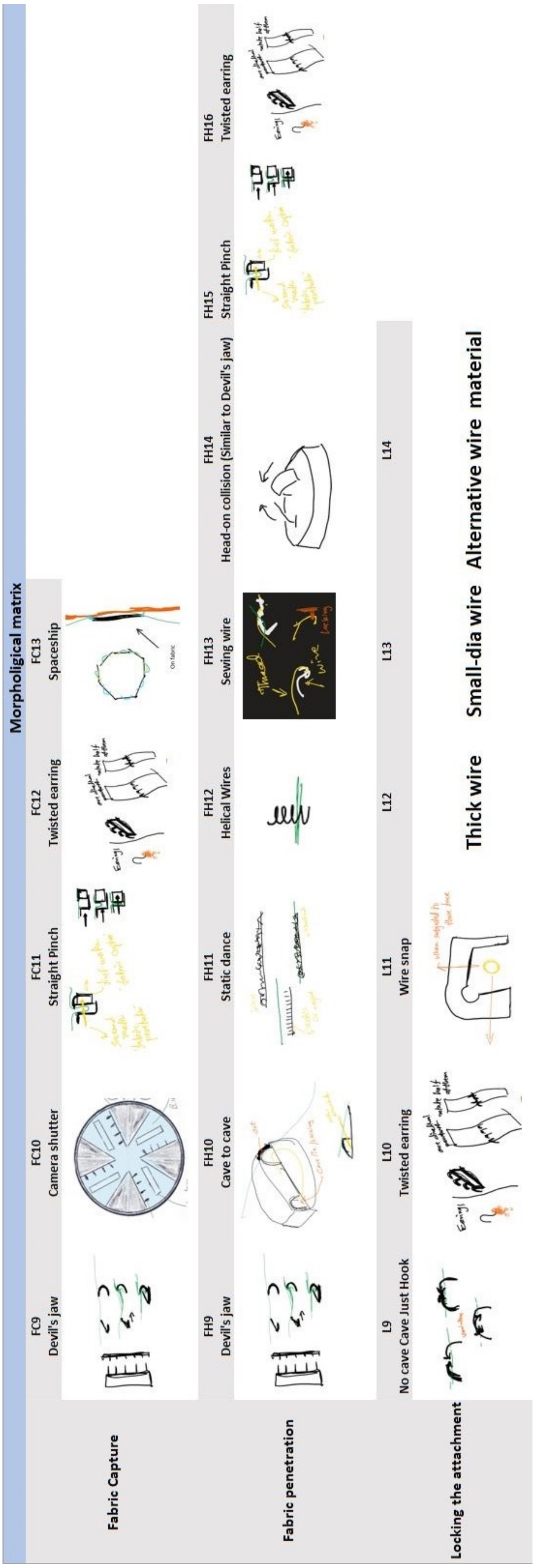
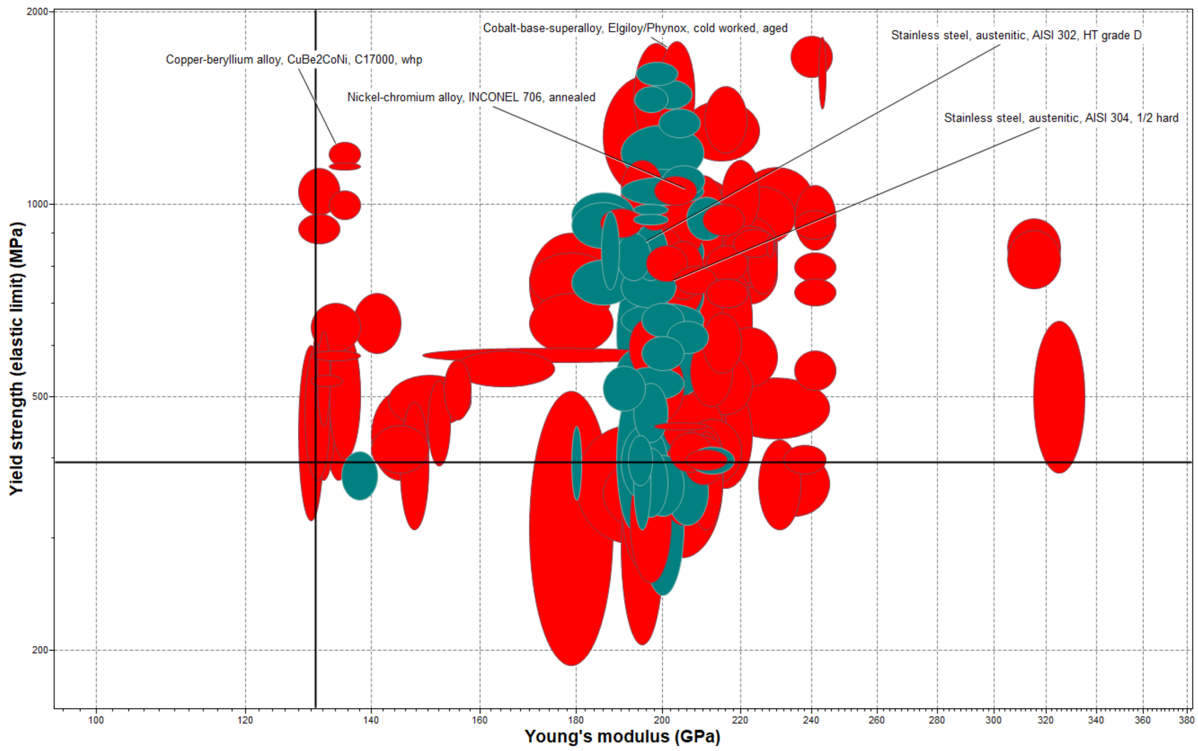
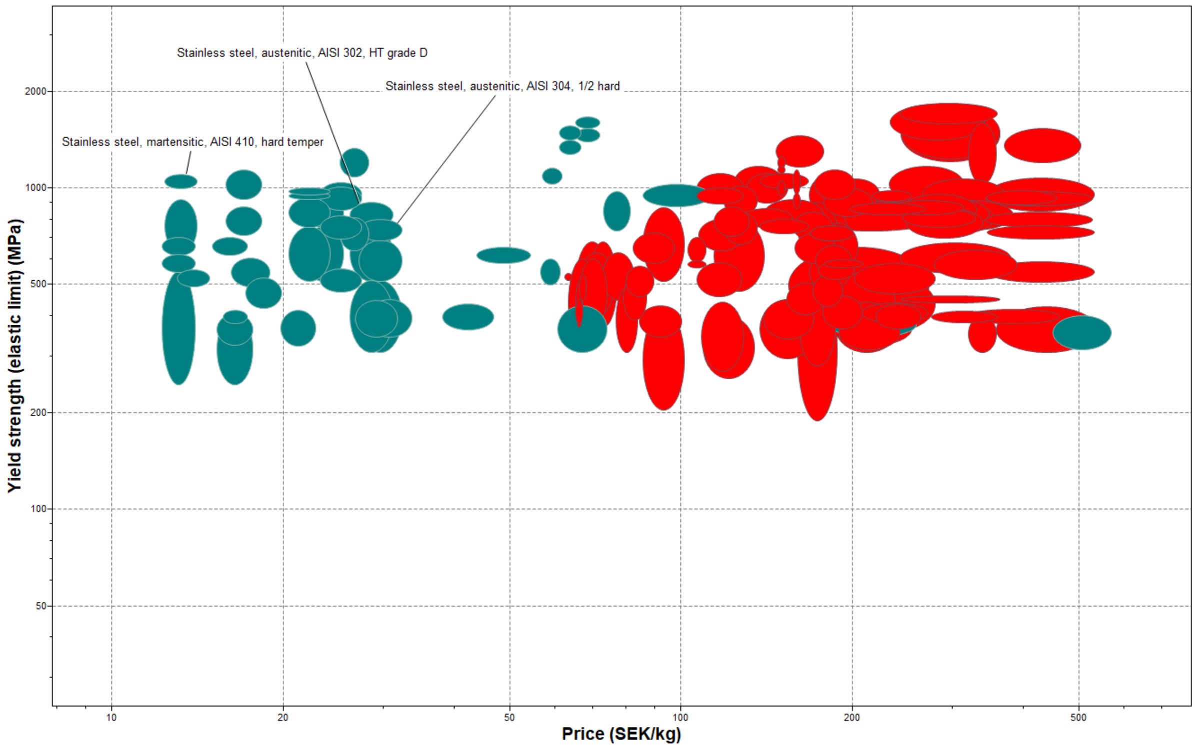


Figure B.4: Second section of Morphological matrix showing concepts for three problem areas



(a) Yield strength (MPa) vs Young's modulus (GPa)



(b) Yield strength (MPa) vs Price (SEK/kg)

Figure B.5: Material charts

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