

InnovateUK

Automatic-Sorting for Circular Textiles Challenges and Emerging Technologies

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Executive Summary

- The Automatic-Sorting for Circular Textiles project aims to catalyse the development of an Automated Textile Sorting and Pre-processing facility (ATSP) for Non-Reusable Textiles (NRT).
- A previous report titled “Automatic Sorting for Circular Textiles: Technology Market Review” investigated the commercially available technologies for Conveyance, Fibre Identification & Sorting, Disruptor Removal and Size Reduction against the requirements of the ATSP and during this process several challenges were highlighted across the technology areas.
- This report explores those challenges in further detail and researched Low Technology Readiness Level (TRL) & Emerging technologies that could act as potential solutions to further enhance future iterations of technologies for textile recycling.
- The review has emphasised the need for a deeper understanding of the “condition of supply” to establish a consensus and guidelines for the downstream physical (size, fabric structure, colour, etc.) and chemical (dye tolerances, disruptor/elastane tolerances, etc.) requirements of feedstock for the range of recycling processes.
- In addition, a list of In-Development technologies & providers has been included to highlight a number of novel techniques and processes that could impact the textile recycling landscape in the future.

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Abbreviation	Meaning
ACT	Auto-Sort for Circularity of Textiles
AI	Artificial Intelligence
ANN	Artificial Neural Networks
ATSP	Automated Textile Sorting and Pre-processing facility
BSP	B-Spline Patch
CNC	Computer Numerical Control
CNN	Convolutional Neural Networks
F2F	Fibre-to-fibre
ID	Identification
KME	Ken Mills Engineering
MIR	Mid-Infrared
ML	Machine Learning
MTC	Manufacturing Technology Centre
NIR	Near-Infrared
NRT	Non-reusable Textile
RGB	Red, Green, and Blue
RT	Reusable Textile
TBC	To be confirmed
TRL	Technology Readiness Level
TSD	Topology Spatial Distances
UV-Vis	Ultraviolet-Visible
VIS	Visible

ACT Project Goals

- Create a world class, state-of-the-art blueprint for an ATSP.
- Build understanding of the next-generation sorting and recycling landscape.
- Incentivise regional material recycling versus export/dumping of NRT.
- Drive the transition from linear to circular textiles in the UK.
- Create new markets, jobs and foreign, direct investment opportunities whilst cementing the UK's position as a global leader in innovation and textiles circularity.

Report Aim

To explore the technological challenges related to Conveyance, Fibre Identification, Size Reduction and Disruptor Removal, and identify emerging technologies & trends that could be potential solutions to those challenges.

This InnovateUK consortium is formed of 18 companies.



Background Information

Overview of the Automated Sorting & Pre-Processing Facility

The primary (mechanical) and emerging (chemical) recycling routes for NRTs require their feedstock to match certain specifications, such as fibre contents and physical size. Chemical recyclers, in particular, face difficulty in acquiring consistent and reliable feedstock for their recycling processes at production volumes large enough to allow for financial sustainability.

The objective of the ATSP is to sort NRTs into categories based on their fibre contents & colour (if required), and then process them to remove any disruptors (for example, buttons and zips), before cutting the textiles to the specific size requirements of the recycler(s) and supplying the feedstock to close the loop on fibre-to-fibre recycling.

In a previous report titled “Automatic Sorting for Circular Textiles: Technology Market Review” the technologies available for Conveyance, Fibre Identification & Sorting, Disruptor Removal and Size Reduction were evaluated against the requirements of the ATSP and during this process several challenges were highlighted across the technology areas.

This is a follow-on report that aims to investigate those challenges further, and researches complimentary & emerging technologies that may improve the efficiency of existing equipment or inspire alternative developments.

Brief Summary of Market Review

The market review of the commercially available technologies for Conveyance, Fibre Identification & Sorting, Size Reduction and Disruptor Detection & Removal highlighted that there is generally not a one-size-fits-all solution for any technology area, and each has challenges that are limiting the capacity or capability of the equipment. In addition, it highlighted the importance of Material Feeding, which was not previously reviewed, and the impact this has on downstream processes. The below table highlights the key challenges for some of the equipment in their respective technology areas.

Overview of Technological Challenges			
Technology Area	Commercially Available Technology	Technology Limitations	Challenges
Material Feeding & Conveyance	<ul style="list-style-type: none"> Floor Conveyors Overhead Conveyors Pneumatic Conveyors 	<ul style="list-style-type: none"> Control of Material Presentation / Feeding 	<ul style="list-style-type: none"> Bulk textile to single textile Overlapping of Textiles Material "Hangup" Robotic "Double Picks"
Fibre Identification & Sorting	<ul style="list-style-type: none"> Near-Infrared Spectroscopy Ultraviolet-Visible Spectroscopy RGB Camera Machine Learning 	<ul style="list-style-type: none"> Throughput is limited by the textile feeding mechanism Accuracy of the sorting system is dependent on the validity and size of the reference data library 	<ul style="list-style-type: none"> Overlapping of Textiles Multi-layer Fibre Identification Carbon Black Dye Identification Pigment & Dye Classification Elastane Identification Fabric Structure Identification
Size Reduction	<ul style="list-style-type: none"> Shredders Guillotine Cutters Rotative Cutting Machines Tearing Machines 	<ul style="list-style-type: none"> Configuration of equipment: Lack of clarity around physical Feedstock specification for chemical recyclers 	
Disruptor Detection & Removal	<ul style="list-style-type: none"> Ballistic Separators Garnetting/Tearing Machines 	<ul style="list-style-type: none"> Multiple passes required to ensure disruptors are removed Low Material Yield Percentage 	<ul style="list-style-type: none"> Disruptors hidden from sensor equipment Limited control removing disruptors Disruptor Removal techniques requires Pre-Processing (Size Reduction)

Material Feeding & Conveyance: Challenges

Material Feeding & Conveyance Overview:

The feeding and movement of textiles & garments affects all processes across the ATSP facility. There are several considerations surrounding material feeding to ensure reliability and efficiency for following processes. Conveyance and the movement of materials dictates the throughput of the facility and provides the conditions for the technologies (Fibre Identification & Sorting, Disruptor Removal and Size reduction) to operate.

Conveyance methods in the recycling industry are typically reliant on tried and tested conveyor belts to handle large volumes of material in a consistent and reliable manner. Textiles are no different. Belt conveyors offer a predictable means of transporting textiles from A to B. However, there are some intricacies which pose challenges for how the materials are fed and presented for the follow-on processes.

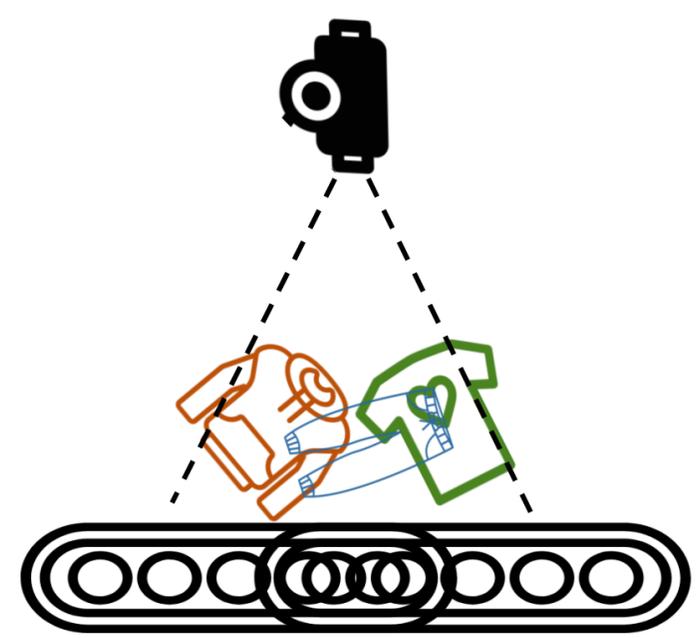


Source: Eastman.com [2024]

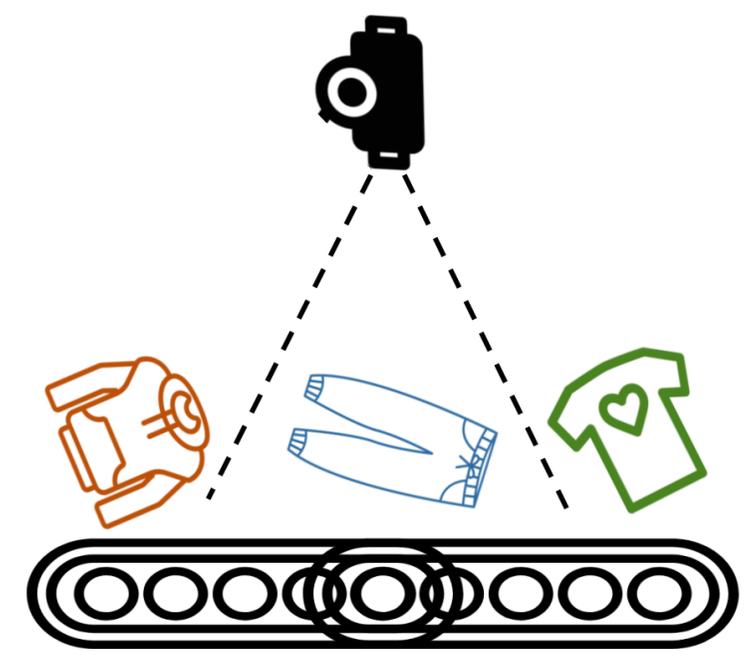
Material Feeding & Conveyance Challenges

Common challenges that are faced across all materials movement & conveyance technologies for garments in automated sorting and pre-processing applications are:

- Overlapping/garment presentation
- Garment singulation
- Robotic feeding: "Double Picks" & "Missed Picks"

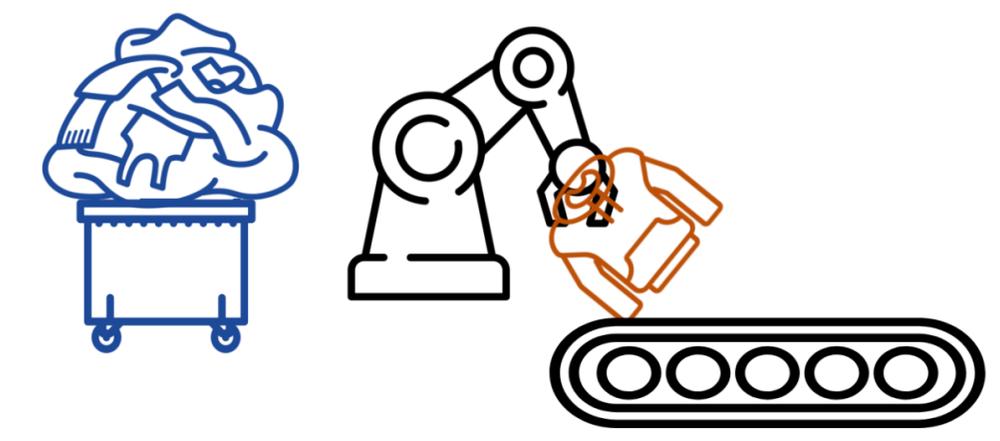


When garments are input into conveyance systems from tightly-packed bales, they are naturally overlapped and folded onto themselves. This makes it difficult for automatic fibre sorting and detection of trims to be carried out accurately. To overcome this, **garment singulation** needs to take place.



For singulation of garments to occur as quickly as possible to enable the throughput needs for a future sorting & pre-preprocessing facility, an automated solution is needed in lieu of manually inputting single garments on to a conveyor.

This can be achieved with a series of bale-breaker systems with spikes or via robotic arm 'pick and place' feeding.



Robotic feeding integrated with machine vision to direct the robot arm where to go to pick up an individual garment can be an effective way to singulate garments with limited human intervention.

Errors occur with the robot gripping end effectors inadvertently picking up more than one garment in a single pick, or missing a garment if the material is not gripped effectively in the picking action.

Challenge: Garment Singulation

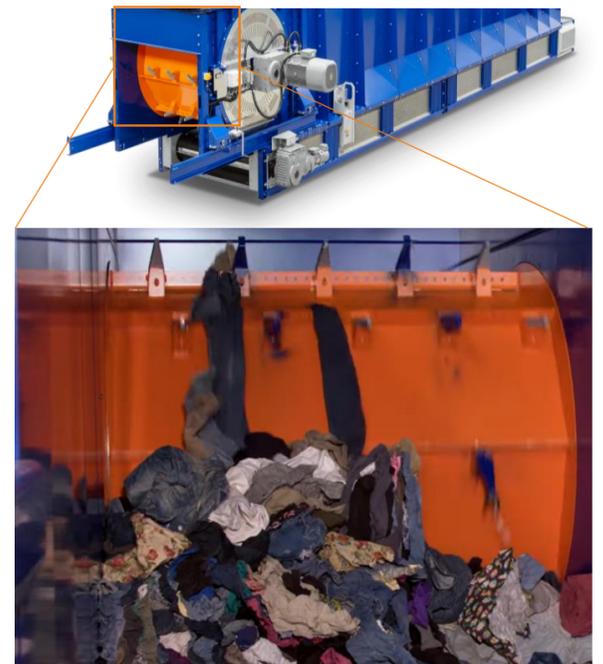
For the ATSP, it is expected that textiles will mostly be delivered in large bales of mixed fibre garments. Opening and pulling the tightly packed bales apart into smaller, more manageable pieces is a crucial step for enabling subsequent processes.

Mechanical Bale Breaker/Auto-feeding:

- Break large, tightly compact textile bales into smaller batches for further processing.
- Bale breakers can operate in several ways including spiked rollers, rotating beaters or fluted drums that penetrate the bale and begin to separate the garments. [\[see further details of Ken Mills Engineering technologies in 'In-Development Technologies' section\]](#)
- Further singulation of garments is possible through additional mechanical processes, but there is a limit to the control of individual garment positioning through these systems, so overlapping cannot be fully eliminated.

Robotic Pick and Place:

- Robotic feeding offers an additional solution with enhanced accuracy, efficiency and flexibility for garment handling.
- However, has limited throughput potential and can experience operational errors through "missed picks", where no textile is engaged with the robotic gripper, and occasionally "double picks" where multiple garments are engaged in the gripper.
- Opportunities exist to integrate robotic picking and placing with fibre-ID sensors to enable singulation and sorting to occur as a single step [\[see further details of Matoha's technologies in 'In-Development Technologies' section\]](#)



Mechanical Spiked Roller

Source: Stadler-Engineering.com [2024]



THOR | Robot Separator

Source: Inwatec.dk [2024]

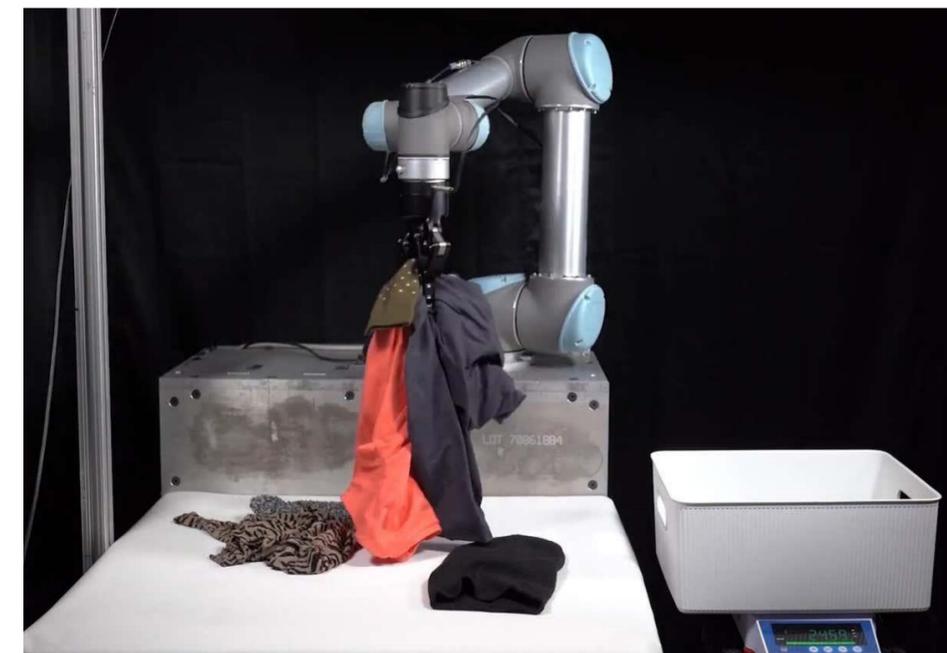
Challenge: Robotic Feeding “Missed Picks” & “Double Picks”

While mechanical bale breakers perform the initial de-bulking of textile items, robotic technology executes the precise singulation.

Establishing a robotic pick and place system for textile handling necessitates careful end effector selection, considering material type, size, and texture. Equally crucial is pick programming, which demands algorithms to adjust for surface variations, ensuring accurate picking, particularly with piled or unevenly stacked textiles, where techniques like “picking from a peak” can enhance consistency and reliability.

“Missed Picks” & “Double Picks” can occur for a variety of reasons such as:

- Garment Positioning; The robotic system is taking input from cameras and sensors, making adjustments on-the-fly and at speed.
- Programming Errors; Inaccurate or incomplete programming of the robots path or grip parameters may cause the system to overlook items or misjudge their location.
- Environmental & Mechanical Factors; The design of the robots gripper may not be optimized to pick up textiles reliably, or poor lighting and excessive dust could interfere with sensors.



Source: NewScientist.com [2023]

Material Feeding & Isolation: “Missed Picks” & “Double Picks”

Selecting the right end effector for textile recycling, can reduce the likelihood of “Missed Picks” & “Double Picks”, streamlining the feeding process by effectively grasping and manipulating textiles while reducing the need for complex programming. A range of grippers could be applicable for this application. Among all possible gripper types, 3 have been identified by the MTC for comparison testing with different textiles.

Trial plans have been devised to determine the most suitable gripper type from these options. Representative grippers from these gripper categories were selected for testing, assessing the operational efficiency of the different gripper types relative to different garments, whilst considering other parameters such as grip strength, percentage of missed picks and percentage of double picks occurring.

These trials are currently underway on MTC sites in Liverpool and Ansty.

Getting a Grasp of Grippers ^[1]			
	Vacuum Grippers	Mechanical Grippers	Needle Grippers
			
	Vacuum Gripper	2-Finger Gripper	Electric Needle Gripper
Manipulation Method	Suction force from vacuum creates a secure grip.	Mechanical clamping provides a strong, stable hold.	Needles penetrate and secure textiles.
Surface Compatibility	Excellent on flat surfaces; may struggle with folded or textured fabrics.	Versatile on a wide range of textured surfaces.	Suitable for most fabrics.
Precision	High precision on flat surfaces, less on irregular shapes.	Good precision for defined shapes; may struggle with irregularities.	Moderate precision, influenced by needle design and placement.
Maintenance	Minimal maintenance with periodic checks on vacuum systems.	Regular maintenance required for mechanical components.	Regular maintenance required, especially for needles.

[1] The Manufacturing Technology Centre (2023) *Getting a Grasp of Grippers*. UK.

Preliminary Trial Validation: Needle Gripper

Needle grippers have been designed for use with porous materials but still need to be validated for the handling of NRTs.

Preliminary validation testing with a needle gripper were conducted in collaboration with Schmalz and the MTC. A wide variety of fabric types were tested, and the gripper worked with all available fabric types (denim, cotton, wool) and the results provided confidence for further trials. Double picks remain a concern, but as the gripper has adjustable stroke, this could potentially be fine-tuned to only pierce a single textile layer and reduces the chance of a “double pick”.

Given these findings, further optimization tests will focus on refining needle length. Comprehensive trials will then be conducted alongside other grippers that have been selected for testing.



Initial Gripper Trial with Schmalz at MTC Liverpool

Challenge: Material “Hangup”

“Material hangup” refers to issues encountered when cloth items, such as clothing or textiles, become caught or entangled in machinery or conveyance systems during processing or handling. This can lead to disruptions, decreased efficiency and damage to both the textiles and the equipment.

Material hangup can occur due to a variety of factors:

1. Structure and Texture of Textiles

Irregularities in textiles such as pockets, tears and loose fibres make them prone to catching on equipment surfaces leading to entanglement.

2. Static Electricity

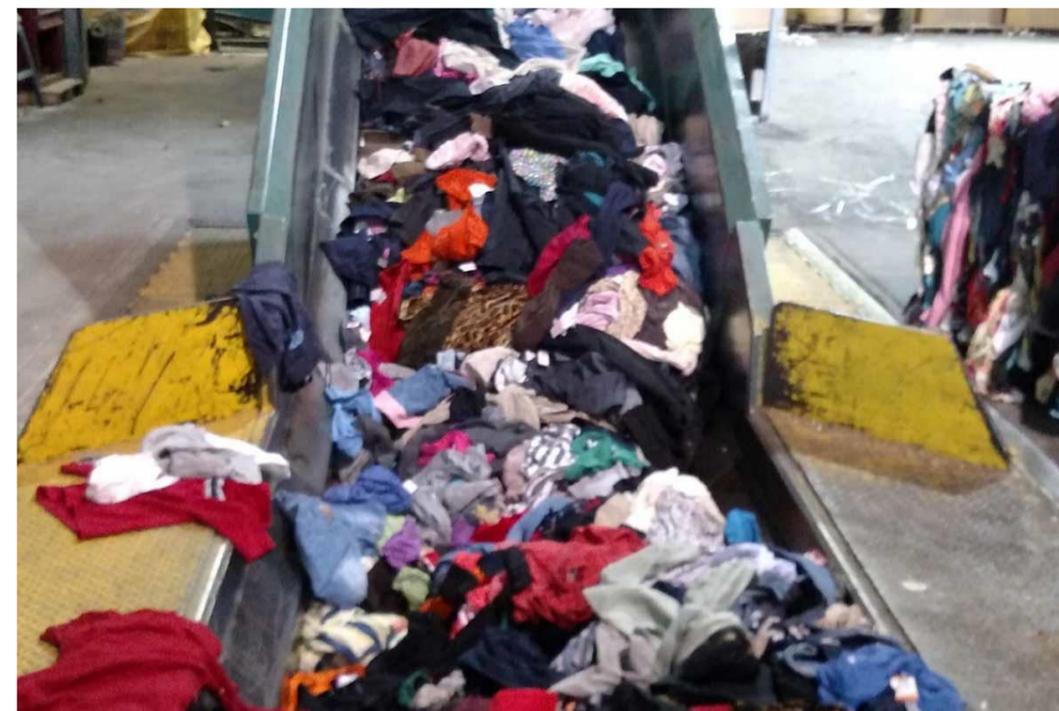
Static electricity can build up on textiles which increases the likelihood of them clinging to the equipment surfaces, or each other, particularly in dry environments or when the materials are moving quickly.

3. Mechanical Interference

Some components of the conveyance system or equipment may have sharp edges, tight spaces or protrusions where material can become caught. This issues is compounded when there are irregularities in the textiles as mentioned above.

4. Material Properties

Different properties of textiles such as their elasticity can contribute to material hangup when they are not handled appropriately.



Bulk Clothing on conveyor
Source: marenengineering.com [2023]

Design Considerations: Material “Hangup”

From an engineering perspective, there are a few strategies that can be implemented in an effort to reduce the likelihood of material hangup or reduce the impact when it occurs:

1. **Smooth Surfaces:** Remove sharp edges and rough textures from the design of processing and conveyance equipment to limit the opportunities for textiles to catch or snag.
2. **Anti-Static:** Incorporate earthing bonds and anti-static treatments or materials into equipment and their processes to minimise the buildup of static electricity, reducing the tendency of textiles to cling to surfaces or to each other.
3. **Guidance and Clearance:** Providing guiding mechanisms, maintaining appropriate conveyor angles and clearance tolerances to enable the system to deal with the inherent random nature of textiles during conveyance.
4. **Sensing & Monitoring:** Implementing sensors along conveyor lines or potential hangup points to detect blockages or irregularities when they occur can limit the disruption material hangup may cause to the process.
5. **Regular maintenance:** Address potential sources of material hangup, such as worn components.

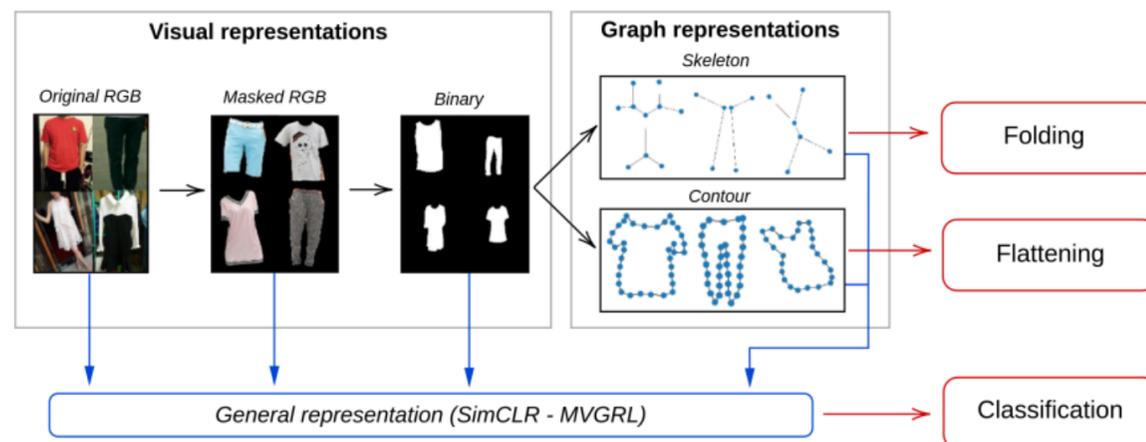
When selecting equipment for processing textiles it is important to be aware of material hangup and the problems it can cause. Some equipment providers, mostly for size reduction, have introduced “Anti-Wrap” technology that focuses on cutting / reducing entanglement to prevent equipment damage.

Material Feeding & Conveyance: Complementary & Enabling Technologies

Garment Presentation: Flattening

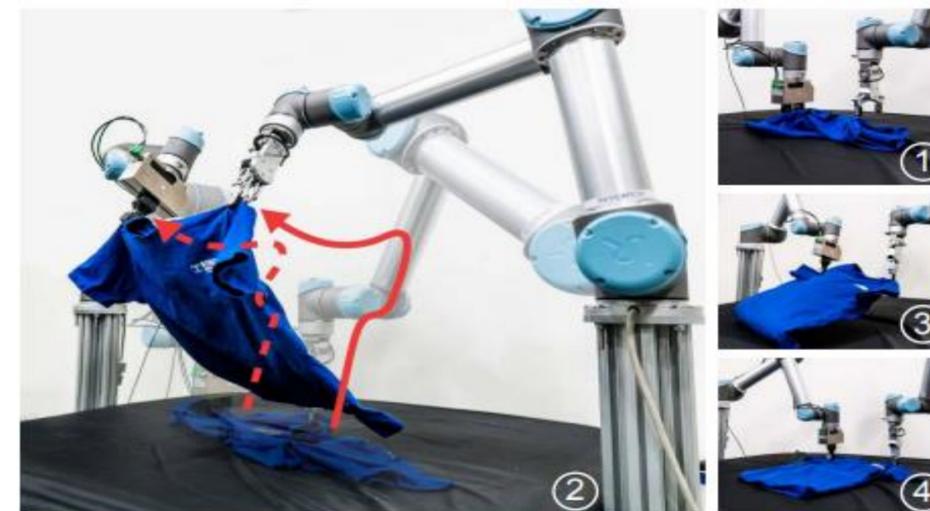
A key challenge in automating textile processing is the tendency of textiles to cluster on top of themselves, making it difficult for machines and sensors to accurately analyse garments. Garment flattening is a crucial *preliminary step* in the automation of precise textile processes. By making the whole garment accessible for sensors and automation systems, several challenging areas of textile recycling (both pre-ATSP and within ATSP processes, such as RT vs NRT classification and precise disruptor removal), become more accessible. Flattening presents itself as one of the most difficult tasks in automation and robotic manipulation.

Many research efforts [[see summary in Appendix 01](#)] have attempted to grapple with this complex task culminating in several publications discussing single and dual arm manipulation, novel control techniques, and advanced vision systems leveraging traditional image processing to more contemporary machine learning approaches. This method however is still in development, yet current efforts are showing progressive results which is why we consider it as a valuable step in the process. Through the foundations of already present research, we can get a better sense of how to frame this problem for an industrial setting such as the ATSP.



(a) AI Based Cloth Layout Detection

Source: Representing clothing items for robotics tasks [2022]



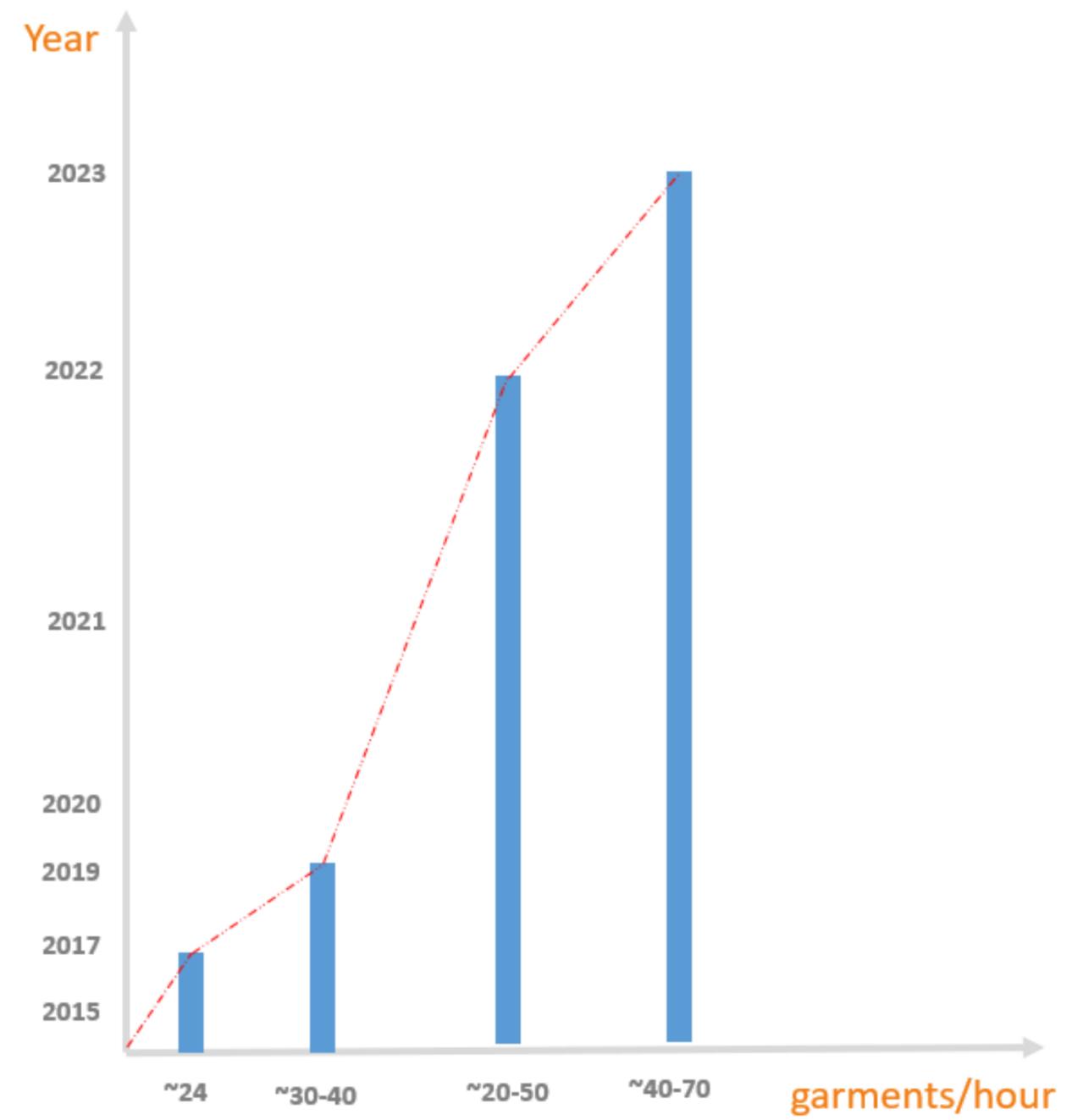
(b) Flattening Process

Source: FlingBot: The Unreasonable Effectiveness of Dynamic Manipulation for Cloth Unfolding [2021]

Garment Presentation: Flattening

After considering the pros and cons of each method, it's evident that further refinement and testing are needed to validate their effectiveness for flattening in an industrial environment like the ATSP. While the flattening process may not be as speedy as anticipated, these lab-tested low TRL technologies show promising incremental throughput gains. With advanced robotic and computing systems, throughput could potentially increase by up to tenfold in industrial settings. This suggests that the groundwork has been laid, supported by research publications in this field, indicating that this is a feasible objective worthy of further development. The next step is to delve deeper into one of the proposed methods and devise a flattening procedure tailored specifically for industrial applications.

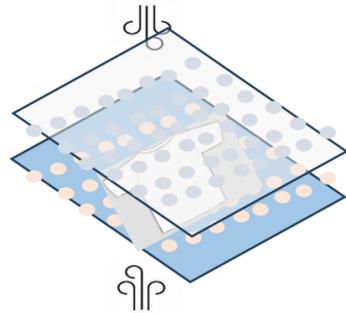
- Low TRL Tech.**
- **Cloth Funnels: Canonicalized-Alignment for Multi-Purpose Garment Manipulation**
 - **SpeedFolding: Learning Efficient Bimanual Folding of Garments**
 - **Representing clothing items for robotics tasks**
 - **A Data-Centric Approach For Dual-Arm Robotic Garment Flattening**
 - **Semantic State Estimation in Cloth Manipulation Tasks**
 - **FlingBot: The Unreasonable Effectiveness of Dynamic Manipulation for Cloth Unfolding**
 - **Dual edge classifier for robust cloth unfolding**
 - **Cloth Region Segmentation for Robust Grasp Selection**
 - **Quasi-Direct Drive for Low-Cost Compliant Robotic Manipulation**
 - **Improving and Evaluating Robotic Garment Unfolding: A Garment-Agnostic Approach**
 - **Regrasping and Unfolding of Garments Using Predictive Thin Shell Modeling**



Flattening low TRL technology throughput progression over time

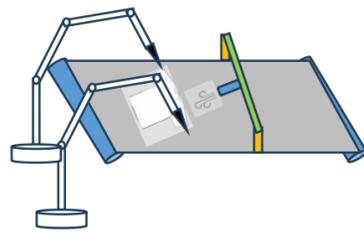
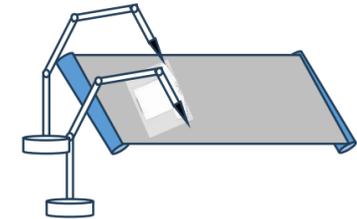
Garment Presentation: Flattening – Future Research Areas

Below are some potential avenues that could be explored further, based on current research efforts and other avenues of mechanical exploration.



Pneumatic and Mechanical Devices: Can we develop a system that uses pneumatics and mechanical devices to flatten the garments for processing? For example, a press or an array of pneumatic air pressure chambers can be used to manipulate the garment to a flat enough state for pre-processing before disruptor detection and removal.

Robotic Manipulation: Dual arm manipulation is the best way forward for a flattening step if dealing with a robotic system. A combination of manipulation techniques and the use of gravity monitored by a vision system can flatten garments successfully.



Robotic Manipulation and Pneumatics: The final potential design presents itself as a hybrid approach that uses dual arm manipulation and pneumatics to optimize the flattening step. This goes one step farther to make the most of flattening step with increased speed without strictly relying on gravity and manipulation techniques.

Flattening Garments for textile recycling			
Strength	Weakness	Opportunities	Threats
<ul style="list-style-type: none"> Makes the entire ATSP highly customizable Lots of research threads to help pull through the technology 	<ul style="list-style-type: none"> Low TRL technology Demands rigorous development and testing 	<ul style="list-style-type: none"> Uplifting to high TRL Commercial viability Could be useful for other parts of ATSP process flow besides Disruptor Removal such as NRT vs RT 	<ul style="list-style-type: none"> Potentially slow speed of operation Development work needed

Summary & Conclusions

*The input mechanism of feeding textile items onto conveyors has been noted as **the largest bottleneck for fibre identification as garments need to be singulated**, and selecting a conveyance method that affords more control over the input method of the garments could see large increases in throughput efficiency of the facility.*

Challenges Identified from Market Survey	Emerging Technology that could address these challenges?	Estimated TRL status	So WHAT? What to monitor for future? Where relevant?
<ul style="list-style-type: none"> Controlled feeding and singulation of textile items onto conveyors 	<ul style="list-style-type: none"> Automated bale breaking & controlled conveyance systems (e.g. KME system) 		<ul style="list-style-type: none"> Combination of bale breaking and auto-feeding should be trialled in conjunction with emerging robotic feeding technologies to find the optimum solution to meet an ATSP's throughput requirements
<ul style="list-style-type: none"> Garment presentation: overlapping of multiple garments when put through automated scanning systems 	<ul style="list-style-type: none"> Integrating fibre-ID with robotic picking and placing 		<ul style="list-style-type: none"> Developing and trialling emerging technology to establish the capabilities and limitations (speed, accuracy) of such systems
<ul style="list-style-type: none"> Accuracy and reliability in robotic pick and place systems for highly variable post-consumer textiles 	<ul style="list-style-type: none"> Robotic handling of high-variation textiles; bespoke grippers for textile feeding systems 		<ul style="list-style-type: none"> Gripper-textile compatibility trials to establish the most suitable end effector design
<ul style="list-style-type: none"> Garment presentation/visibility of whole garments impeding downstream (and upstream) ATSP processes 	<ul style="list-style-type: none"> Automated garment flattening 		<ul style="list-style-type: none"> Development of robotic and pneumatic automated manipulation of garments



Fibre Identification & Sorting: Challenges

Challenges of Fibre Identification & Sorting

To allow the ATSP to produce consistent and high-quality feedstock, the mixed textiles need to be categorised into aggregate bins based on their fibre composition and if required, their colour. The market review has shown that fibre identification solutions utilise a few key technologies to accurately categorise and sort the textiles based on their material composition: Near-Infrared Spectroscopy, RGB Cameras, Ultraviolet-Visual Spectroscopy and Machine Learning.

The technologies on the market for fibre identification and sorting are well-established, with more manufacturers particularly from a waste recycling background, transitioning into textile sorting. One consideration when assessing the accuracy of these technologies, is the validity of the training data sets they have been developed from. There is not an industry-standard 'single-source-of-truth' database that has been compared against the different automated fibre-ID technologies. One recommendation for the industry would be to create an open-source lab-verified database to create a baseline to compare all technologies against.

Common challenges that are faced across all the Fibre Identification technologies are:

- Overlapping of Garments during scanning (set by conveyance)
- Further Identification & Classification
 - Multi-layer fibre identification
 - Carbon Black Dye identification
 - Elastane identification
 - Colour Classification
 - Fabric Structure Identification (Knitted vs Woven)



Pneumatic Garment Sorting

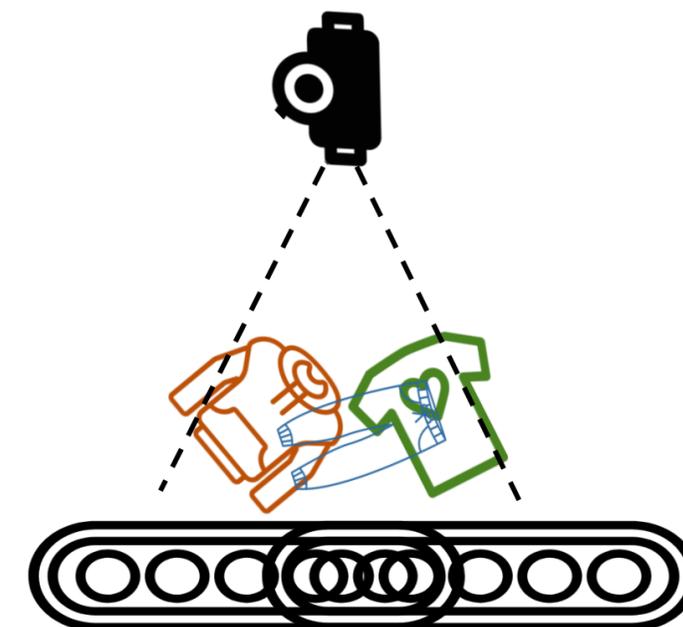
Source: Sorting for Circularity Europe, Fashion for good [2023]

Overlapping Garments During Scanning

Overlapping of Garments During Scanning

The problem of overlapping of garments was partially addressed in the section concerning Material Feeding & Conveyance, as a challenge of feeding and isolating. When this issue occurs prior to fibre identification and sorting, it can cause several problems:

- The detected fibre type might be obtained based solely on one of the garments, for example the top garment if the scanner is located above the conveyor. This is because the technologies currently used for the fibre identification (such as NIR) do not have the ability to penetrate the textiles, limiting identification to what they can see on the surface.
- Overlapping may cause errors in the sorting process as 2 garments may be mis-sorted into the same classification bin due to their proximity. If the garments are of different fibre compositions, the purity of the batch reduces.
- Additionally, scanning systems which take measurements from multiple points in a garment (vs a single data point) may infer multiple garments as a single garment. The spectrum used for the garment classification is obtained as an average from all the collected data points, so this could cause mis-identification of fibre composition (resulting in sorting errors) if garments are not singulated when scanned.



Manual singulation of garments on a conveyor line

Source: a-tex.uk [2024]

When overlapping occurs, the accuracy of the sorting system decreases, decreasing the level of purity of the final sorting batch.

Overlapping of Garments During Scanning

Both mechanical and chemical recyclers require accurate fibre-sorted feedstock for their recycling processes. Overlapping garments in the fibre identification step pose a potential risk to the quality of the feedstock.

Potential solutions:

- Singulation of garments at the feeding stage:
As discussed earlier in the Challenges of Material Feeding & Conveyance section, controlling the singulation of garments during the material feeding stage, is currently the most robust method for eliminating garment overlap in the downstream processes, in particular fibre identification and sorting.
- Detection and intervention of overlapping garments:
Some existing sorting systems utilise an RGB camera to identify the location of garments on the conveyor line. Utilising the same camera systems and combining them with more sophisticated algorithms (such as Machine Learning) enables the exact shape of the garment to be detected and used to:
 - Identify *when* overlapping occurs – machine detection software that can account for overlapping samples and allow for further handling (e.g. redirected back into the feeding system)
 - Classify different garments fibre composition *during* overlapping occurrences- however, it would still require an additional precise automated sorting solution to mitigate for sorting errors (e.g. robotic pick and place sorting)

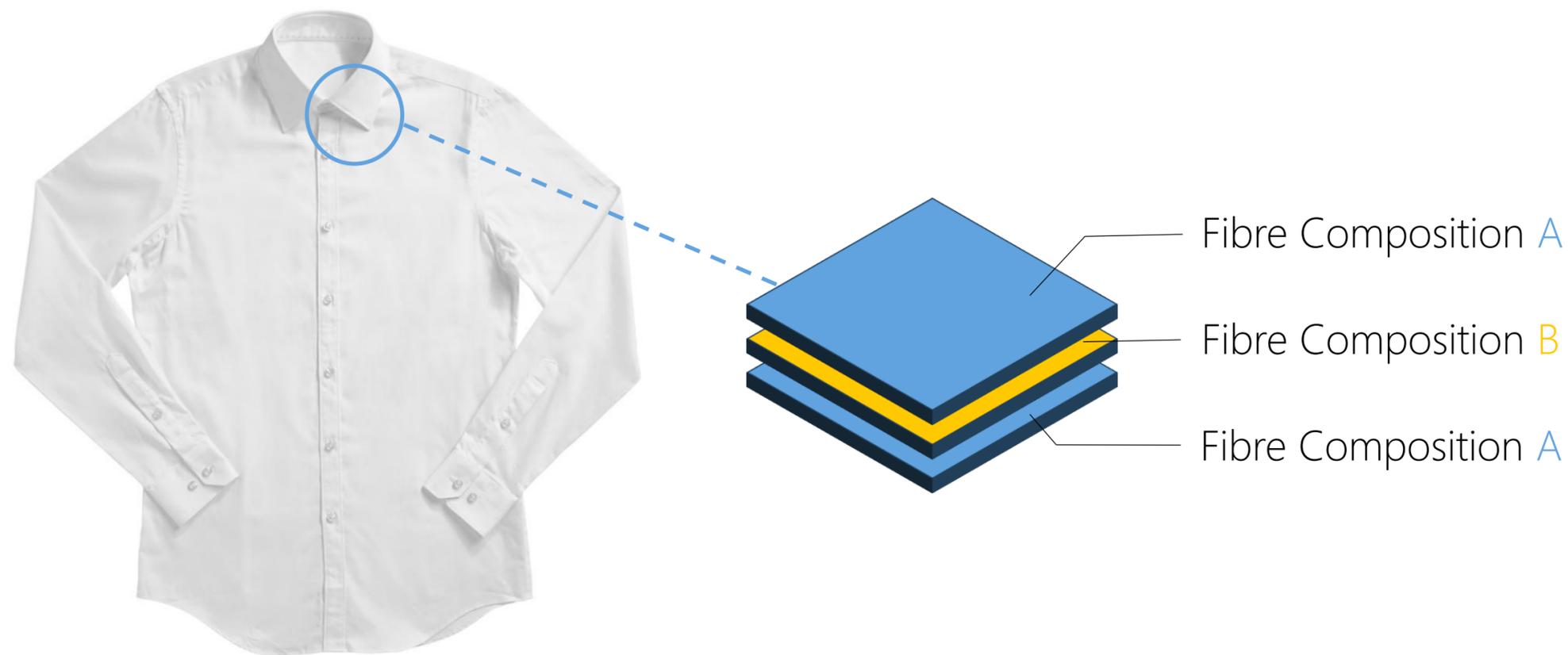
Considering the previous Market Review Summary, it is pertinent that garments are singulated as effectively as possible at the initial material feeding stage to ensure that all downstream processes can be operate efficiently, particularly fibre identification and sorting. This development effort at the feeding stage would be the most impactful for operations of an ATSP when compared to any development effort to intervene and correct sorting errors resulting from overlapping garments.

Further Identification and Classification

Multi-layer Fibre Identification

Multi-layer garments are textiles that are made of two or more layers of fibre material. As with overlapping garments, current classification methods do not have the ability to penetrate through garments and analyse multiple fibre compositions. This makes the identification of multi-layer garments extremely difficult, and at the time of writing this report there is no method available to satisfy this need.

Approximately
9%
of all clothing
in recycling
streams are
multi-
layered^[2]



[image source: [Cambridge Dictionary](#)]

For an ATSP, identifying multi-layer garments is critical to maintaining batch purity. This responsibility currently lies with pre-sorting facilities such as Salvation Army Trading Company Ltd and relies on a skilled workforce to identify and pre-sort garments on several criteria including Re-Usable or Non-Reusable Textiles and Multi-Layer Textiles.

[2] Characterisation study of the incoming and outgoing streams from sorting facilities, Refashion- April 2023.

Multi-layer Fibre Identification

Explored solutions:

- Penetrating methods to identify multi-layer garments:

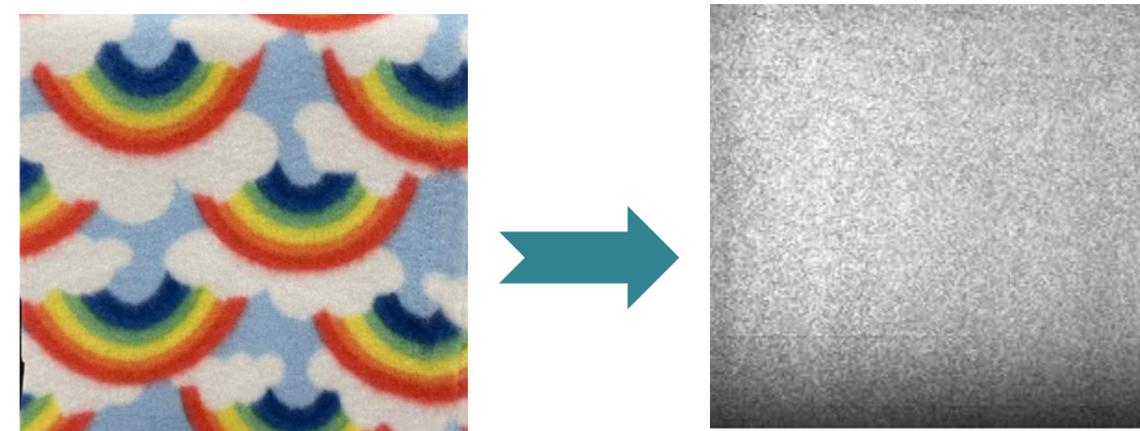
There are some technologies that are capable of penetrating through the layers, and these have been investigated on the capability for identifying distinct layers:

- Backscatter X-ray** – This technique detects the radiation that is *reflected* from the target object and is more suited to shallow image capture when compared to traditional X-ray that relies on the transmission of X-rays *through* the object.^{[3], [4]}

Initial tests conducted at the MTC did not show any clear distinction between the layers, thought to be due to low density of the fabric layers- demonstrating that it is not suitable for multi-layer fibre identification.

- Terahertz 3D Imaging** – Terahertz waves sit between Infrared and Microwaves on the Electromagnetic Spectrum. This non-contact technology was explored for its high penetrative qualities (when compared to infrared) whilst being safer than X-Rays. This method is capable of identifying and measuring multi-layer thicknesses for applications such as coats of paint.^[5]

Initial discussions with technology developer and provider Optikan [\[see further details of Optikan's technologies in 'In-Development Technologies section\]](#) indicated that their scanner cannot detect multi-layers in textiles, again, due to the low density and similarity of the materials.



Backscatter X-ray tests of Multi-Layer Garment
RGB image (left), corresponding X-ray (right)

[3] <https://electronics.howstuffworks.com/gadgets/high-tech-gadgets/backscatter-x-ray.htm> [accessed: 23/04/2024]

[4] <https://www.analyticon.eu/en/x-ray-scanning.html> [accessed: 23/04/2024]

[5] <https://optikan.com/> [accessed:18/04/2024]

Multi-layer Fibre Identification

Possible mitigation:

- Cutting garments into smaller swatches to separate layers:
 - If there are no joins or bonding connecting the layers, when cut into small pieces the layers will naturally separate reducing them to single-layer materials for processing. However, along joins or other bonded layers, they will not be able to separate.
 - Some sorting systems are compatible with a high volume of small swatches, and this same size reduction approach is also used for classifying and removing disruptors. Cutting the garments before fibre identification can reduce the risk to batch purity from multi-layer garments by allowing individual layers to be classified and sorted. However, turning 1 garment into multiple swatches will increase the throughput demand of the aggregate sorting system.
- This mitigation introduces an additional challenge where the multi-layer swatches, still connected by joins or bonding, will not be able to be accurately identified and sorted, posing a risk to batch purity. While this may reduce the batch purity, the overall weight percentage of the sorting error will likely be less than when compared to an entire multi-layer garment.
- One further consideration is that the size of the swatches would affect the length of the recycled fibres, likely limiting the feedstock to chemical recyclers as mechanical recyclers require long fibre lengths.

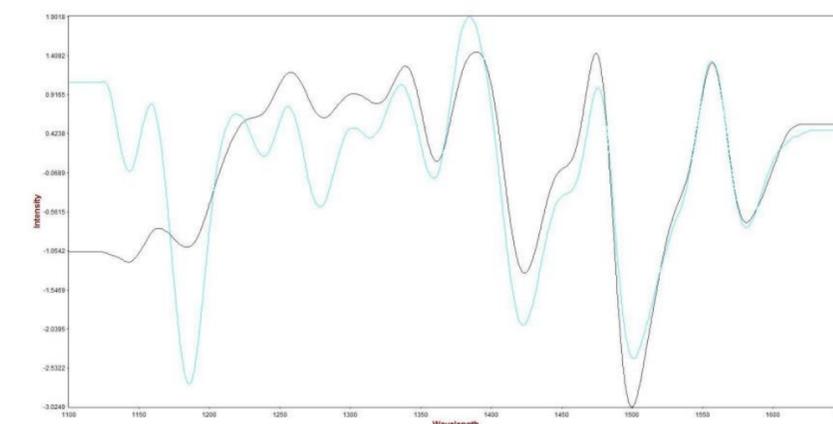
Carbon Black Dye Identification

A known problem found amongst sorting system providers is the affect Carbon Black Dye has on identification results. These dyes are used in some black and dark grey garments.

NIR technology is used as the primary method of identifying fibre composition in all the current industrial-scale Fibre Identification and Sorting solutions. Near-Infrared spectroscopy covers wavelengths from approximately 1100nm to 2500nm.^[6]

Carbon Black Dye increases energy absorption to the material affecting NIR measurements.^[7] Longer wavelengths are more successful in the direct detection of carbon^[8], and plastic recycling industries are moving toward the utilisation of Mid-Infrared spectroscopy to detect carbon black colourant (which is commonly used in plastics).^[9] More advanced analysis algorithms (e.g. evolution algorithm) can overcome the effect of Carbon Black Dye on NIR spectroscopy, however, this might reduce the overall accuracy of detection, and requires further studies.^[7]

Technology providers confirmed Carbon Black Dye can be problematic for the fibre identification process. The scale of the problem is generally based on the frequency of carbon black dye used in textile manufacturing. Technology providers have reported that they are seeing carbon black dyes less frequently, and as a result are spending less effort attempting to deal with this challenge.



Example of black dye effect on NIR spectroscopy of wool (paper does not verify carbon black dye usage) [9]
blue colour – pure wool, black – dyed sample

[6] Scotter, C.N.G. - 'NIR Theory - Molecular Spectroscopy', in.

[7] Cura, K., Rintala, N., Kamppuri, T., Saarimäki, E., & Heikkilä, P. (2021). Textile recognition and sorting for recycling at an automated line using near infrared spectroscopy. *Recycling*, 6(1), 11.

[8] Bellon-Maurel, V., & McBratney, A. (2011). Near-infrared (NIR) and mid-infrared (MIR) spectroscopic techniques for assessing the amount of carbon stock in soils—Critical review and research perspectives. *Soil Biology and Biochemistry*, 43(7), 1398-1410.

[9] Rintala, N. (2019). NIRS identification of black textiles: Improvements for waste textiles sorting.

Carbon Black Dye Identification

Possible solutions:

- Mid-Infrared spectroscopy:
MIR spectroscopy covers wavelengths from around 2500nm to 25,000nm.^[10]
This wavelength enables the detection of Carbon Black Dye. Technology Provider PellencST have developed a prototype solution incorporating Mid-Infrared, for such detection.
- Contact Sensing - Tribo-Electric Sensor (TES) by SONY:
A potential alternative fibre identification technique was identified through the Market Review report. Sony are developing a contact sensor that measures the electric charge-transfer characteristics of a material. In a similar way that each fibre type has measurable spectroscopic characteristics, each fibre type has triboelectric charge-transfer characteristics that can be measured and classified. This technique has not yet been tested for carbon black dye detection – a collaboration between the MTC and Sony will look to explore this specific classification further. [\[see further details in 'In-Development Technologies section'\]](#).
- Further development of the textiles database:
Carbon Black Dye is not detectable directly with NIR, however its' effect on specific fibres, if consistent, may be quantifiable. For example, it is hypothesised that cotton with the carbon black dye produces a recognisable unique pattern, different from other fibres with and without the dye. If so, incorporating more textiles with Carbon Black Dye in the dataset used for training & tuning the detection model could allow for the classification of material containing Carbon Black Dyes. Study of Cura et al. indicates that advanced algorithms can overcome, to some extent, the effect of this dye on NIR.^[11] Further research into this solution could eliminate the Carbon Black Dye challenge while utilising the same equipment already available in sorting solutions.

[10] Scotter, C.N.G. - 'NIR Theory - Molecular Spectroscopy', in.

[11] Cura, K., Rintala, N., Kamppuri, T., Saarimäki, E., & Heikkilä, P. (2021). Textile recognition and sorting for recycling at an automated line using near infrared spectroscopy. *Recycling*, 6(1), 11.

Elastane Identification

Some chemical recyclers reported that they can not accept any traces of elastane in their feedstock, while others have reported they fine tolerances and can only accept small amounts per batch.

Some of the sorting system providers reported difficulty when detecting elastane in blends with cotton. While other sorting providers report their technology is capable of detecting even a small amount of elastane. These conflicting reports could be down to a couple of reasons.

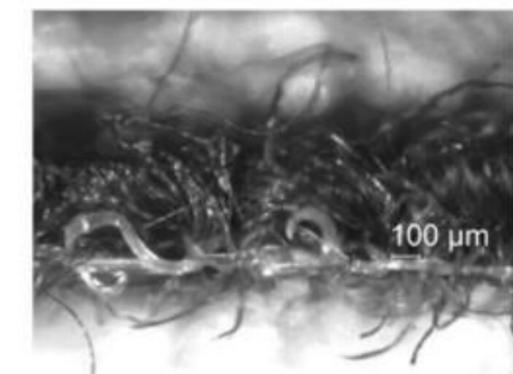
Elastane, also known as Spandex or Lycra, is a synthetic fibre that is known for its exceptional elastic properties.^[12] Elastane can be incorporated in garments in two ways;

- Firstly, elastane can be wound around the yarn in a blend or fed in as a separate material. In this scenario, parts of the elastane should be visible when using such techniques as NIR.
- Secondly, the elastane could be in the core of the constituent yarn, which would mostly remain hidden from the view. In this case, its effect on the spectrum might not be significant enough for detection,^[13] making its identification more challenging or impossible.

It is unclear why there is a disparity concerning the difficulty of elastane detection as the same technology is used by different sorting companies (NIR spectroscopy). This disparity might be related to the utilisation of different algorithms and datasets (e.g. insufficient elastane samples in the training database). Additionally, different companies may have based their observations and tests on a different type of elastane incorporation method (as described above).



(a)



(b)

Microscopic images of elastane-containing cotton blends [13]. (a) Elastane in the core yarn; (b) Knitted cotton, elastane is fed backside

[12] *What is elastane fabric: Properties, how its made and where*, Sewport. [2024]

[13] Cura, K., Rintala, N., Kamppuri, T., Saarimäki, E., & Heikkilä, P. (2021). Textile recognition and sorting for recycling at an automated line using near infrared spectroscopy. *Recycling*, 6(1), 11.

Elastane Identification

Possible solutions:

- Incorporating more textiles with cotton/elastane blends in the training dataset
Current sorting machines are based on the same NIR technology with some producers claiming the ability to detect elastane. As with carbon black dyes, it might be possible that incorporating more samples with elastane into the detection model will allow for consistent identification of blends containing elastane. This solution would have to be tested for different elastane incorporation formats to check if elastane can be detected both as a separate material and as part of the core yarn.
- Contact Sensing - Tribo-Electric Sensor (TES) by SONY:
As previously mentioned re: carbon black identification, this technology is based on different sensing principles than current identification technologies. As the TES is still in development, it has not been tested for the detection of elastane. Due to its direct contact detection, it could potentially detect changes of the material's electric charge-transfer characteristics due to the presence of elastane, even in the core of the yarn.

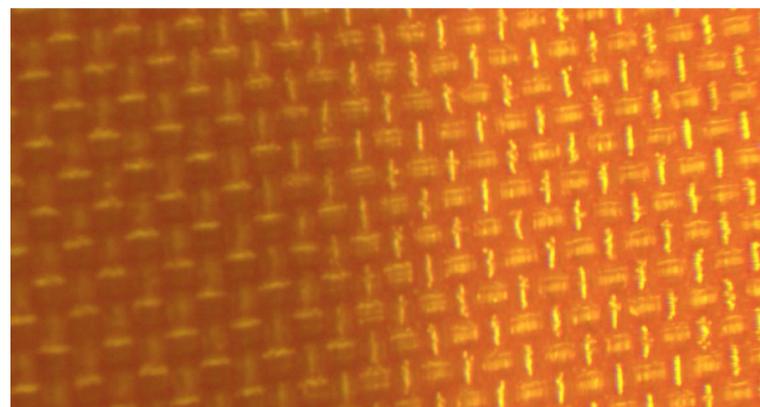
Colour Classification

Some textile recyclers require their feedstock to be sorted by colour to minimise complexity of their recycling process. Due to the structure of the fibres, the accuracy of the colour identification can vary.

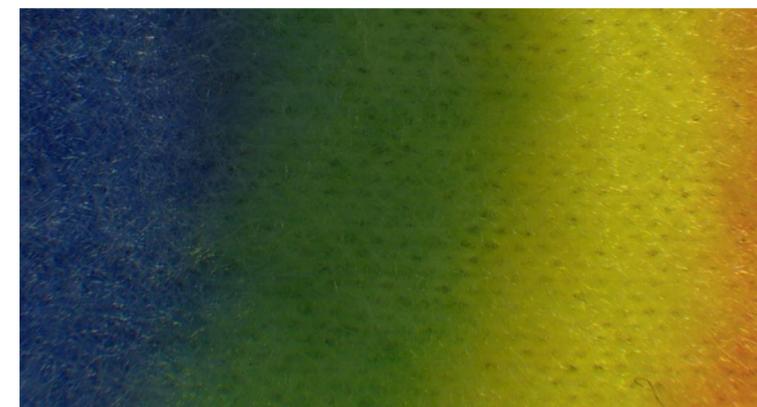
The visible colour and its tone vary depending on the ambient light and its angle (towards the yarn). Additional calibration might be needed to accommodate these variations. Some of the traditional image processing techniques can partially remove the effect of the shades on the colour.

Additionally, it is common that garments are not made of a single-colour material, instead they are often ornamented with different patterns in different colours. This would have to be distinguished from wrinkles and folds of a lying sample. Apart from aforementioned Carbon Black Dye, no other dyes were found to disturb the fibre identification.

Additional investigation of the recycler's requirements might be needed to justify further research and tests towards more precise colour classification.



Examples of light angle affecting the colour (through the textile and through the thread)



Examples of multicolour textile sample

Colour Classification

Possible solutions:

- RGB cameras
This is a common solution used for colour identification. The information provided resemble the one produced by the human eye. The information is limited and some calibration and compensation for light condition and its angle change (throughout the sample) might be needed.
- Visual Spectroscopy
Provides more comprehensive information compared to the RGB camera (continuous values throughout the whole visible spectrum is provided instead of three values for red, green and blue colours). Some of the sorting machine producers utilise this technology to identify the colour.
- Machine Learning Methods
These type of algorithms could be used together with Visual Spectroscopy and RGB camera. They can be trained to detect colour based on historic/provided data of how humans classified the sample. These algorithms can learn to recognise complex patterns and can be especially useful to distinguish wrinkles or folds from a colour changes in the sample, allowing effective multi-colour detection.

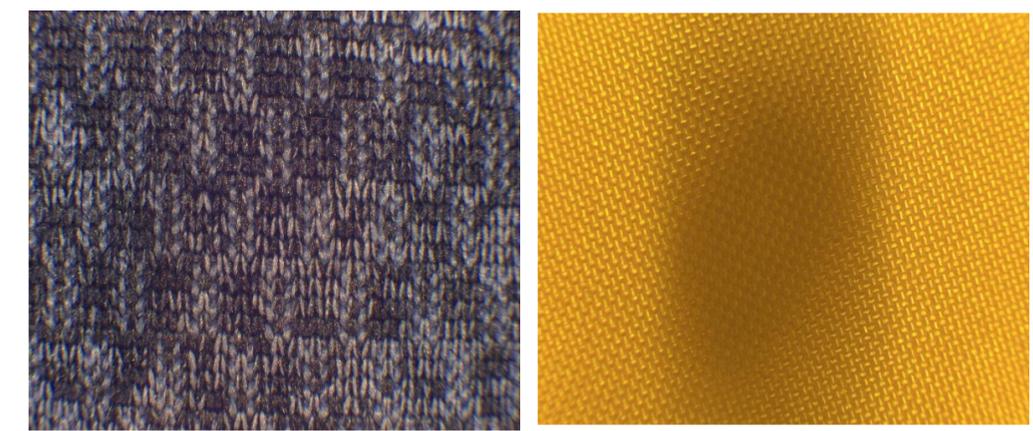
Fabric Structure Identification

The Identification and classification of textiles based upon their fabric structure, woven or knitted (or non-woven), has been highlighted as a future development area by technology provider Valvan. This type of identification has not been explored in much detail and has not been implemented in an automatic sorting process yet.

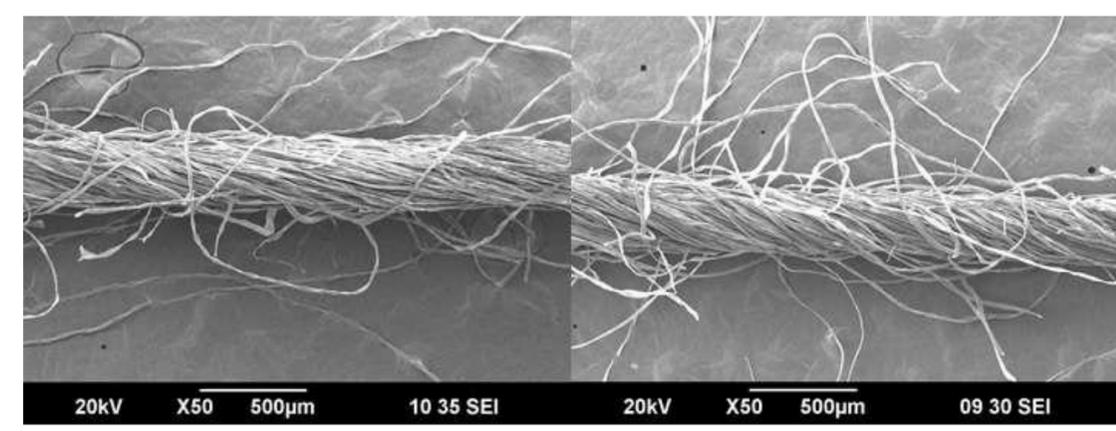
There are other differences between different fabric structures such as yarn count and yarn twist type. As there is generally more twist in woven yarns and less twist in knitted yarns – it is much easier to untwist and recover fibres from knitted yarns- so there could be a benefit to having this sorted for mechanical recycling feedstock.

The quantification of yarn count and yarn twist type by the sorting system is less important; however, when designing a fibre identification model, it would be beneficial to determine if these would in any way influence the results. Incorporating a variety of structures in the dataset could also improve the general properties of the identification model.

Additional investigation of textile recycler’s requirements is needed to justify further research towards textile structure identification.



Examples of high-resolution images of knitted & woven textiles

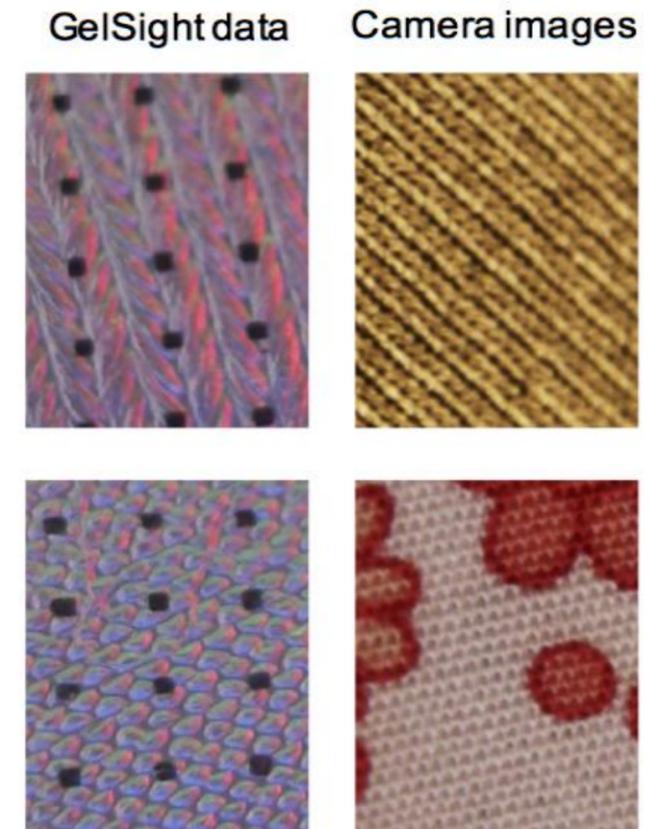


Microscopic view of different yarn twists
Source: [The Hong Kong Polytechnic University](#) [2015]

Fabric Structure Identification

Possible solution:

- 1D/2D imaging systems or 3D imaging systems
Line scanners or area scanners could be used to capture images of the visible fabric structure at the surface of the material. Laser or Volume scanners could be used to acquire the volumetric images of the visible fabric structure. Both solutions combined with machine learning techniques can then be used to classify the fabric structure as Knitted or Woven, given a sufficient training dataset. However, as there are large variations of yarn counts (yarn thicknesses) used in textiles, either high resolution cameras need to be utilised - to acquire clear images of the denser (smaller) fabric structures - or alternatively smaller fields of views. In most cases the fabric structure remains the same across the entire fabric, therefore sampling a smaller area with a camera of less resolution might be a cheaper alternative.
- Gelsight Tactile Sensor
The Gelsight sensor, when pressed against a surface, produces a height map which can be treated and analysed as an image. The technology provider has built a database with 40 classes of tactile textures, including fabrics. The system claims that it can correctly categorize materials from this database with high accuracy.^[14] If not already present, knitted vs woven characteristics could be added to the database.
- Texture recognition from tactile images and vision
Some academic research has been conducted in the field of combined camera-tactile sensors. "A new fusion method named "Deep Maximum Covariance Analysis" aims to learn a joint latent space for sharing features through vision and tactile sensing". Initial results of the algorithm show recognition performance of greater than 90%.^[15]



Tactile sensor vs camera images for different textile samples

Source: [14]

[14] Li, R., & Adelson, E. H. (2013). Sensing and recognizing surface textures using a gelsight sensor.

[15] Luo, S., Yuan, W., Adelson, E., Cohn, A. G., & Fuentes, R. (2018). Cloth texture recognition using vision and tactile sensing.

Summary & Conclusions

*Based on the feedback from textile recycler's spoken to, the most important aspect to them was to have **very accurate fibre-sorted feedstock that meets their feedstock specification tolerances.***

Challenges Identified from Market Survey	Emerging Technology that could address these challenges?	Estimated TRL status	So WHAT? What to monitor for future? Where relevant?
<ul style="list-style-type: none"> Multi-layer textiles 	<ul style="list-style-type: none"> No emerging technologies identified suitable for the challenge. Mitigation efforts are prioritised for the <i>initial</i> operation of an ATSP. 		<ul style="list-style-type: none"> As almost 10% of textile products are multi-layer, there needs to be a focused effort to mitigate problems in the recycling process from multi-layer textiles.
<ul style="list-style-type: none"> Carbon black dye and elastane identification 	<ul style="list-style-type: none"> Contact sensor Mid-infrared spectroscopy Machine learning models 	<ul style="list-style-type: none"> 1-3 7-9 7-9 	<ul style="list-style-type: none"> Trials to verify contact sensor capabilities Build database with relevant carbon black and elastane yarn structures to train machine learning models
<ul style="list-style-type: none"> Fabric structure identification 	<ul style="list-style-type: none"> Gelsight Tactile sensor Advanced Machine Learning 	<ul style="list-style-type: none"> 7-9 4-6 	<ul style="list-style-type: none"> More thorough research to quantify fabric structure needs for downstream recycling processes to determine most important properties to classify (e.g. yarn twist)
<ul style="list-style-type: none"> Verification of fibre-id system's accuracy claims 			<ul style="list-style-type: none"> Open-source lab-verified database to act as a baseline for comparison of different fibre-ID technologies

Size Reduction: Challenge

Challenges of Size Reduction : Downstream Condition of Supply

Feedstock size requirements vary across different recycling methods, with mechanical recycling requiring long fibre lengths to be preserved and chemical recycling requiring small cut swatches which are easier to feed via high-volume hoppers and break down chemically.

When researching the current state of the market for enabling technologies for an ATSP, size reduction processes and equipment proved to be difficult to advise on, as the requirements for supply of feedstock to downstream recyclers was unclear, and in many cases undefined – particularly in chemical fibre-to-fibre recycling as the technology is still developing.

Understanding the downstream condition of supply for physical feedstock size specification is mission critical for an ATSP's output.

There are many existing technologies capable of reducing the size of textiles, but none are versatile enough to produce optimal feedstock for the broad range of different fibre-to-fibre recycling processes. Technology providers for size reduction equipment believe they can calibrate or adapt their equipment to meet the physical size specifications required by recyclers, but lack of a common-accepted size specification to meet the economies of scale needed to justify CAPEX investment has hindered technology adoption in this step of the recycling process.

MTC intends to research downstream recycling processes to understand optimal condition of supply requirements that will enable collectors/sorters and future ASTP operators to design their systems in line with recycling process requirements. This work will increase the value and viability of the outgoing ATSP feedstock for recycling into the circular economy.



Shredded textiles

Source: trexproject.eu [2023]



Long swatches of Denim

Source: sourcingjournal.com [2023]

Disruptor Detection & Removal: Challenges

Disruptor Removal Overview:

To prepare the textiles for the recycling process, disruptors (hard trims and soft trims) need to be removed. Most textile products in circulation have not been designed for disassembly* so the removal of these trims is currently done by manual and labour-intensive methods, or automated but inaccurate/low material yield techniques.

Due to the variety and complexity of post-consumer NRTs that will be input into the facility, the ATSP needs to be able to sort and accommodate removal of a variety of disruptor types.

Some recyclers have zero tolerance for disruptors in their recycling process, making the detection step critical.

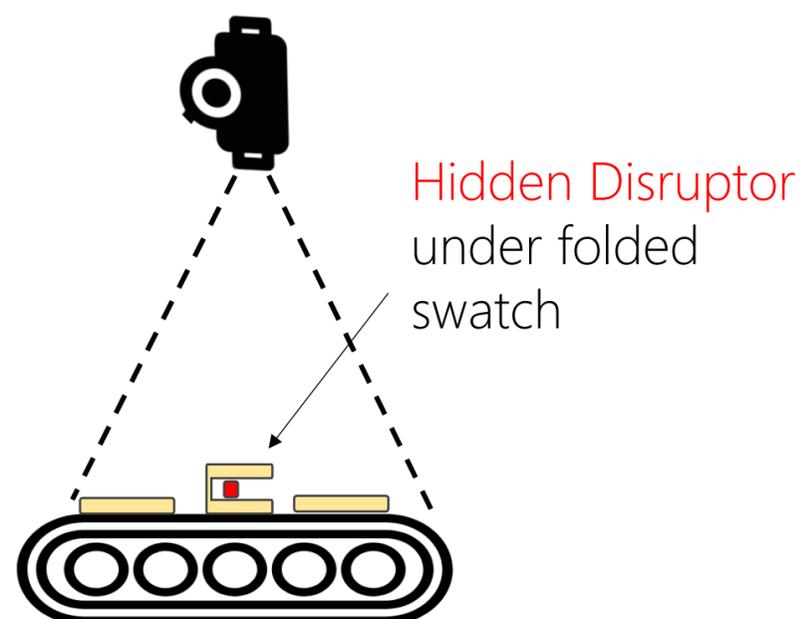
* emerging technology provider *Resortecs* have developed design-for-disassembly thread technology. More details in ['In Development Technologies' section](#)

Approximately
78%

of all clothing in recycling streams are made of different materials and/or have disruptors present such as zippers, buttons, beads etc. ^[16]

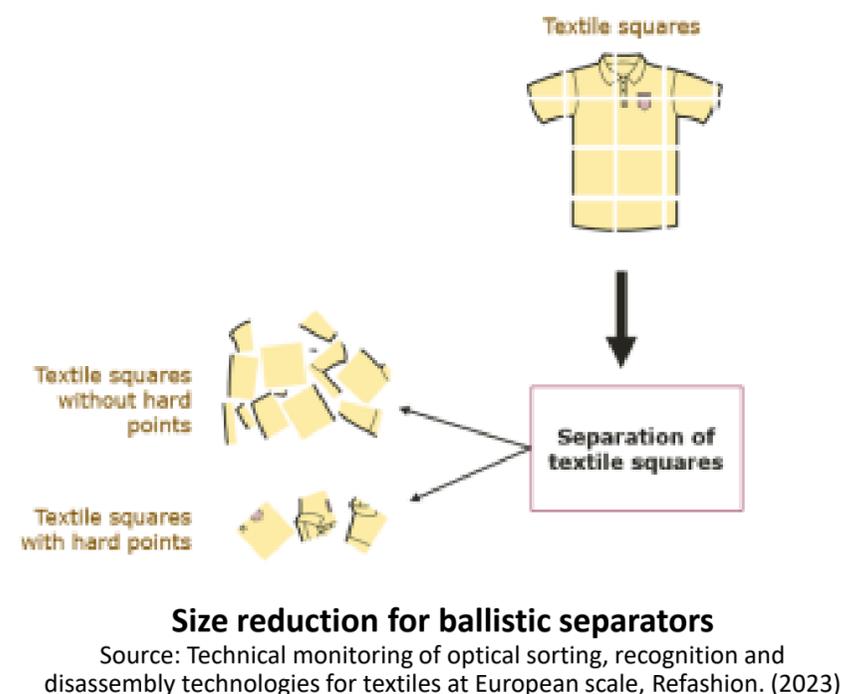
Disruptor Detection & Removal Challenges

Detection of Hidden Disruptors



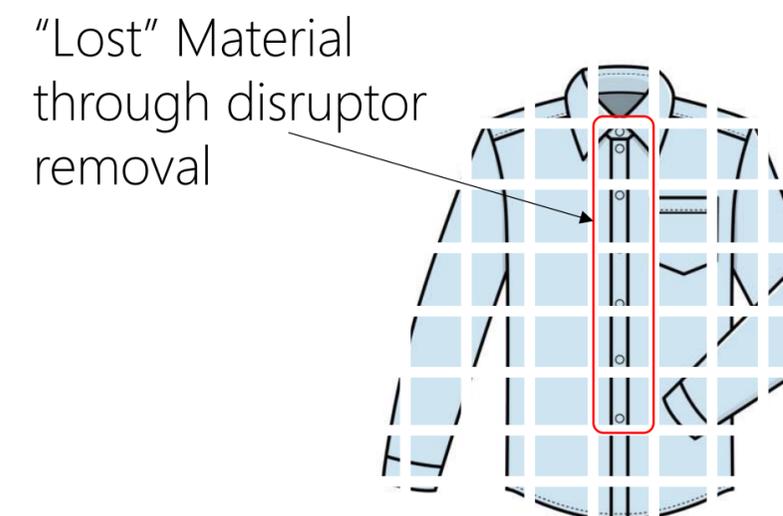
Current disruptor detection solutions rely on the disruptor being visible to the camera for identification and classification. The natural tendency for textiles to bundle and fold onto themselves can lead to disruptors being hidden from the camera, leading to potentially missed disruptors, or inefficiencies in the process as there would need to be multiple cycles of the same batch to ensure no disruptors are present.

Localised Disruptor Removal



At the time of writing this report, no solutions on the market offer localised disruptor removal. Ballistic Separators, commonly used in other recycling industries, require the textiles to be pre-processed into small swatches (Size Reduction) for disruptor removal. Swatches with a disruptor present are ejected into a separate aggregate bin away from other swatches.

Material Yield



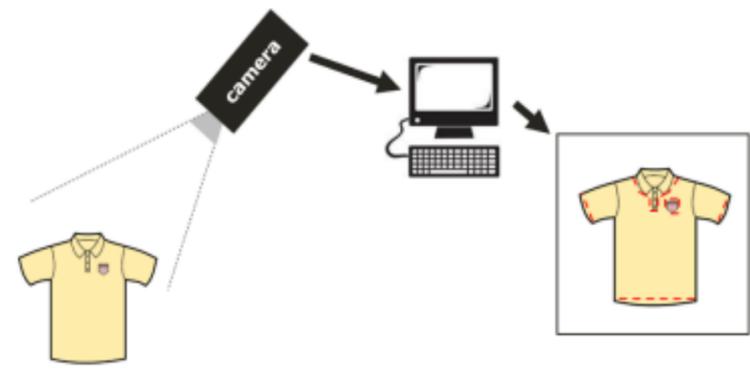
As ballistic separators for disruptor removal are reliant on smaller swatches for detection and removal, there is an inherent yield loss of textiles from the process. As textile recycles already operate on fine margins to make the process financially viable, it is critical that any material loss through the process is reduced to a minimum.

Disruptor Detection

Disruptor Detection is the step where identification and localisation of disruptors on various garments occurs. We have not found any specific publications in this territory, but we can leverage research efforts outside of the textiles manufacturing sector to understand how disruptor detection may work.

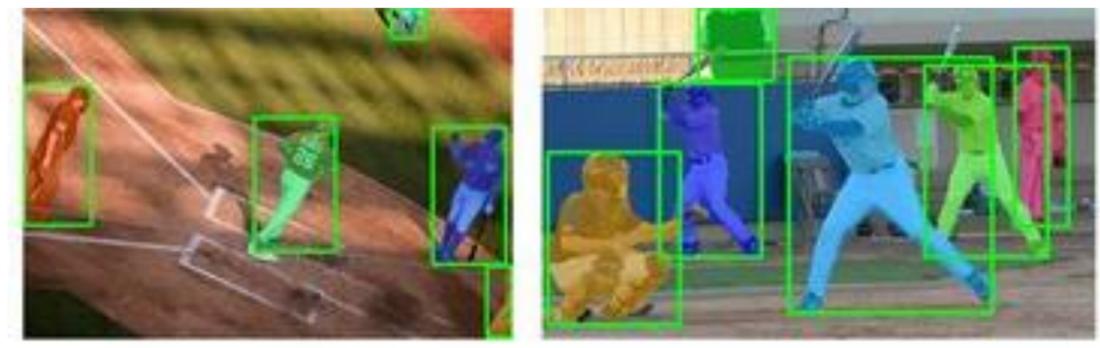
Currently, RGB cameras are coupled with machine learning techniques to identify disruptors and enable downstream processes to remove them. Object Detection and Instance Segmentation have been considered as the most promising types of machine learning techniques for localised identification of disruptors. Object detection identifies and localizes objects within an image or video and Instance segmentation distinguishes individual objects even when they are closely grouped or overlapping.

RGB cameras do not have penetrative qualities and are only able to detect what is visible on the surface of the garments. This can lead to disruptors moving through the process without being detected and reducing the purity of the feedstock produced by the ATSP.



Example of Potential Detection Technique

Source: Technical monitoring of optical sorting, recognition and disassembly technologies for textiles at European scale, Refashion. (2023)



Examples of Object Detection and Instance Segmentation used in other sectors

Source: Pose2Seg: Human Instance Segmentation Without Detection [2018]

Disruptor Detection: Potential Solutions

Multiple RGB Cameras



Multiple Cameras

Source: www.fdtimes.com[2015]

Multiple RGB cameras, when synchronized and positioned strategically, offer enhanced depth perception and spatial awareness. Their combined capabilities facilitate accurate colour capture and spatial mapping for a wide range of imaging tasks across a range of industries.

Multiple cameras would allow for the garment to be viewed from multiple angles and increase the likelihood of disruptor detection.

Terahertz

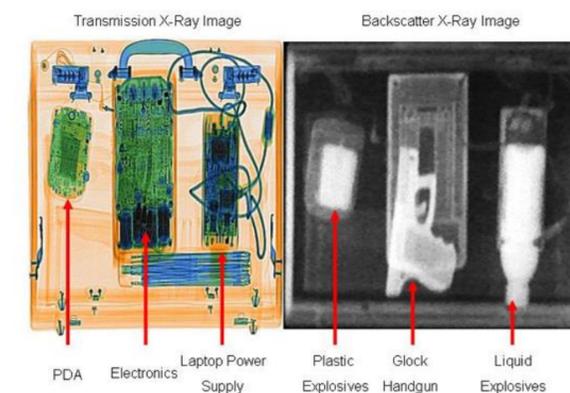


Optikan Terahertz Technology

Source: Optikan [2023]

Terahertz signals fall between the wavelengths of micro-waves and infrared in the electromagnetic spectrum. Terahertz waves are well-suited for penetrating beneath the surface of objects during scanning. The technology could be applied to identify disruptors on garments if combined with a machine learning model. [\[see further details of Optikan's technologies in 'In-Development Technologies section'\]](#)

X-RAY Backscatter



Transmission and Backscatter X-Ray Image For Screening

Source: www.d-tec-system. [2016]

X-ray backscatter is a technique that involves the scattering of X-rays by materials, with detection and analysis of the scattered radiation to provide information about the composition and structure of the target object. It is commonly used in security screening applications for the detection of concealed objects or substances.

Disruptor Detection

A summary table of the identified and reviewed technologies that could be suitable for disruptor detection below highlights the benefits and drawbacks of each sensor type:

	Multiple Cameras	Terahertz Scanners	X-Ray Backscatter
Benefits	<ul style="list-style-type: none"> • Additional perspectives for analysis • Well-known technology • Utilised by some disruptor removal technology providers • Range of cameras at different price points 	<ul style="list-style-type: none"> • Non-ionizing radiation • Penetrative qualities • Proven identification of Disruptors 	<ul style="list-style-type: none"> • Proven in other industries for penetrative object detection
Drawbacks	<ul style="list-style-type: none"> • Increased computational resource • Limited by what is visible to the cameras 	<ul style="list-style-type: none"> • In-development technology, not industrially ready • <i>Currently</i> not compatible with moving objects, however an inline scanner is in development 	<ul style="list-style-type: none"> • Ionizing radiation, requiring health and safety consideration • Expensive

Localised Disruptor Removal

Once disruptors have been detected and identified, the next step is the physical removal of disruptors from the garments. There are currently no automated industrially-ready solutions for localised removal of disruptors.

Commercially available technologies utilise Ballistic Separation which requires the garments to go through a size-reduction process to create separate swatches of material that may or may not have a disruptor present. If a disruptor is detected, the entire swatch will be ejected and as a result there is a lower yield in feedstock produced by the ATSP.

Start-up KAPDAA claim to be developing localised disruptor removal as part of their Ai4fibres project [\[see further details re: KAPDAA in 'In-Development Technologies' section\]](#).

*[Ai4fibres: "A pair of jeans will be processed through our system, which will read the composition (60% cotton fibres, 20% polyester, and 20% elastane) & blue colour. **The scanner will pick up the position of the rivets, zippers & button and send the information to the cutting arms.** Once the zipper etc are cut through with minimum wastage, the jeans will be sent to the allocated bay."^[17]]*

For any localised disruptor removal to be possible, garments must be presented to the system in such a way that the whole garment is accessible by the removal method [\[see research on flattening methods\]](#).

MTC have not found any [academic] publications relating to the localised removal of disruptors but can leverage research efforts in the textiles industry and outside of the sector itself.

[17] <https://kapdaa.com/pages/ai4fibres>. [Accessed: 2024].

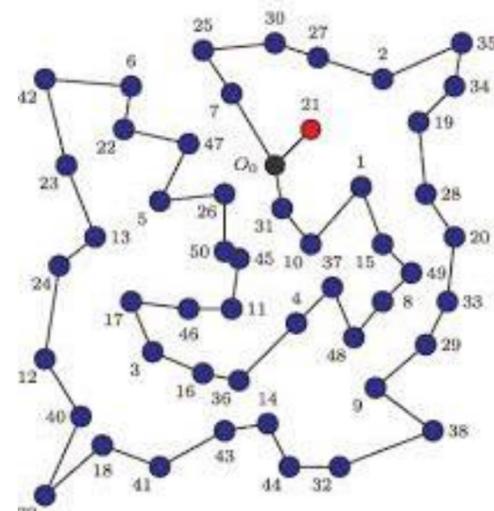
Localised Disruptor Removal

Potential Solution:

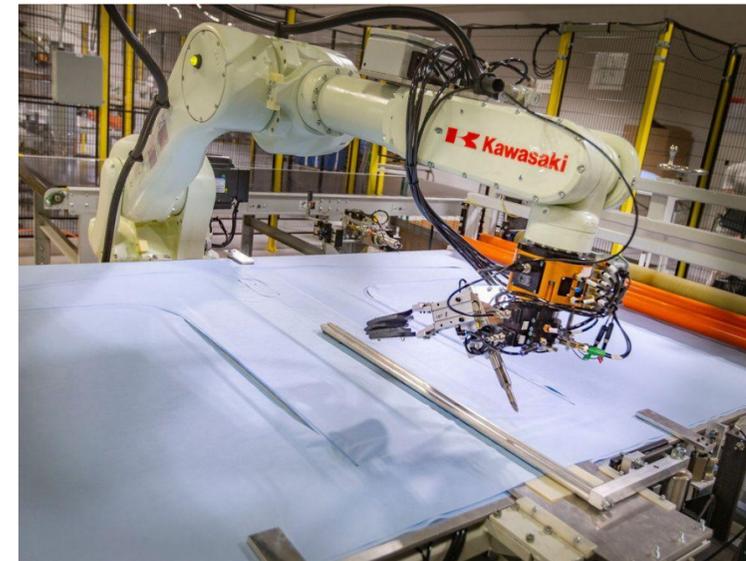
A robotic cutting system that utilises machine vision and complex path generation models to create cutting trajectories can enable the localised removal of disruptors whilst minimising the material loss.

Existing cutting technologies, such as laser and ultrasonic cutters can be used on a robot or CNC machine, whilst leveraging algorithms such as the Travelling Salesman Problem, which seeks the shortest possible route that visits every point in a set of locations just once^[18], to efficiently remove disruptors from garments. Other cutting techniques, such as conventional knife blades, either do not provide enough precision or require other technologies to maintain tension on the garment.

It is unlikely that one system like this alone would be able to complete this task at the throughput rate the ATSP requires, so multiple lines would likely be needed, incurring large investment and floorspace requirements which may make the solution financially unviable.



(a) Disruptor Cutting Pattern Generation
Source: Genetic and Ant Colony Algorithms to Solve the Multi-TSP [2021]



(b) Precision Cutting using device mounted on a robot
Source: windsorstar.com [2021]

[18] Kuo, M. (2024) *Algorithms for the travelling salesman problem (2024)*

Localised Disruptor removal

Laser Cutting



Laser Cutting Machine

Source: eubusinessnews.com [2021]



Close up of Laser Cutter

Source: newatlas.com [2019]

Laser cutting is a manufacturing process that uses a high-powered laser beam to cut materials such as metal, wood, plastic, textiles, and glass in a precise and versatile way making it a viable option for disruptor removal. Through a focused lens a laser beam is directed onto the material, melting, burning, or vaporizing it along the predetermined programmed cutting path. It is popular in industries ranging from automotive to fashion design because it offers high levels of accuracy, speed, and customization.

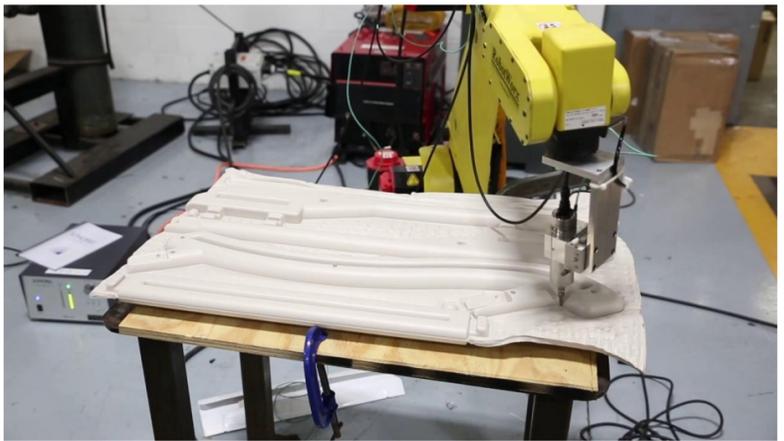
Laser Cutting	
Benefits	<ul style="list-style-type: none"> • High levels of accuracy and motion versatility allowing for the creation of complex shapes and designs. • It can cut a wide range of materials making it suitable for various industries and applications including textiles. • Faster than traditional cutting methods, enabling rapid production of parts making it a good fit for industrial automation.
Drawbacks	<ul style="list-style-type: none"> • Set up can be expensive, requiring an investment in equipment, training, and maintenance • While laser cutting is versatile, certain materials may emit toxic fumes. • Poses risks of fire, eye damage, and exposure to hazardous fumes if safety precautions are not followed diligently.

Localised Disruptor removal

Ultrasonic Cutting



Close up of Ultrasonic Cutter
Source: creno.com [2023]



Robotic Ultrasonic Cutting
Source: SONOTEC Ultrasonic Cutting Robot
www.youtube.com/ [2018]

Ultrasonic cutting utilizes high-frequency vibrations to cut through materials with precision and efficiency. A vibrating blade, typically made of titanium or steel, generates ultrasonic waves that create a clean, accurate cut without generating heat. Due to its ability to cut through various materials smoothly while minimizing material distortion this technology is commonly used in industries such as food processing, textiles, and plastics.

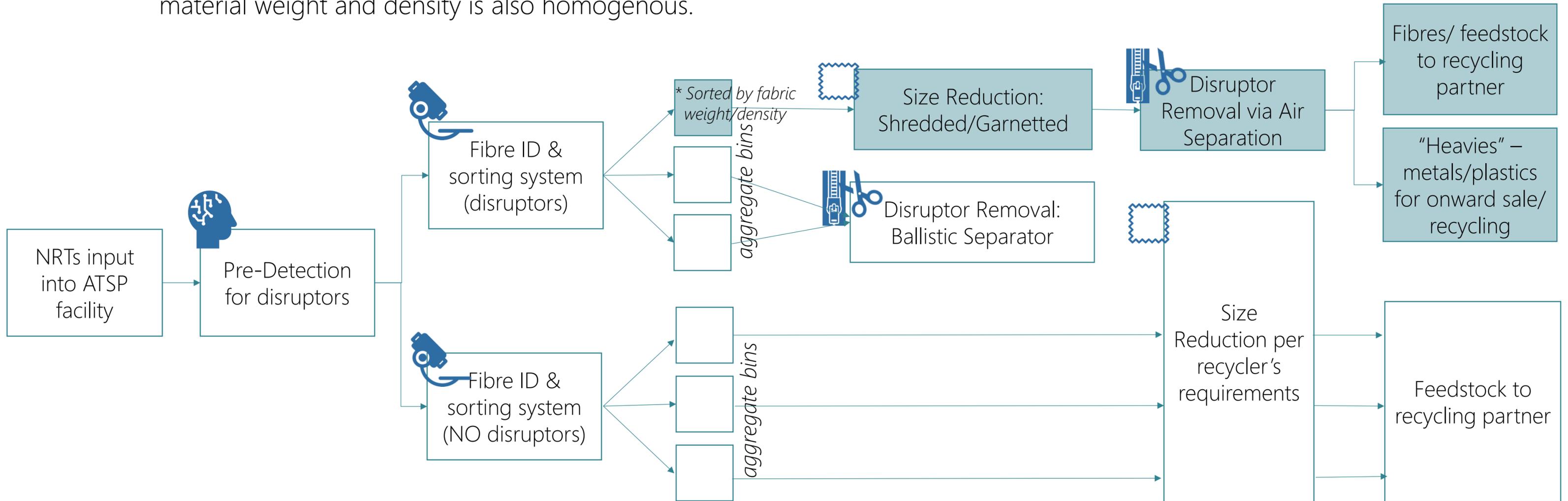
Ultrasonic Cutting	
Benefits	<ul style="list-style-type: none"> • Offers high levels of precision, making it useful for cutting complex shapes and delicate materials • Produces minimal heat, reducing the risk of material deformation or melting. • Can be used on a wide range of materials, including textiles making it a quite versatile tool across various industries.
Drawbacks	<ul style="list-style-type: none"> • Can have a relatively high initial cost, including the purchase of ultrasonic generators and specialized cutting tools • Less effective for cutting through thicker materials compared to other cutting methods. • Requires regular maintenance and upkeep to ensure optimal performance, including blade sharpening or replacement. Also, periodic calibration of equipment settings is needed.

Disruptor Detection & Removal: Complementary & Enabling Technologies

Disruptor Removal – Air-separation feasibility

Existing technologies take post-shredded used textiles (Ken Mills Engineering) or footwear materials ([Dr. Mike Lee research](#)) and can separate contaminants (metals, plastics, hard points) whereby the re-usable textile components are vacuumed via the top of the chamber and "heavies" (contaminants) fall to the bottom.

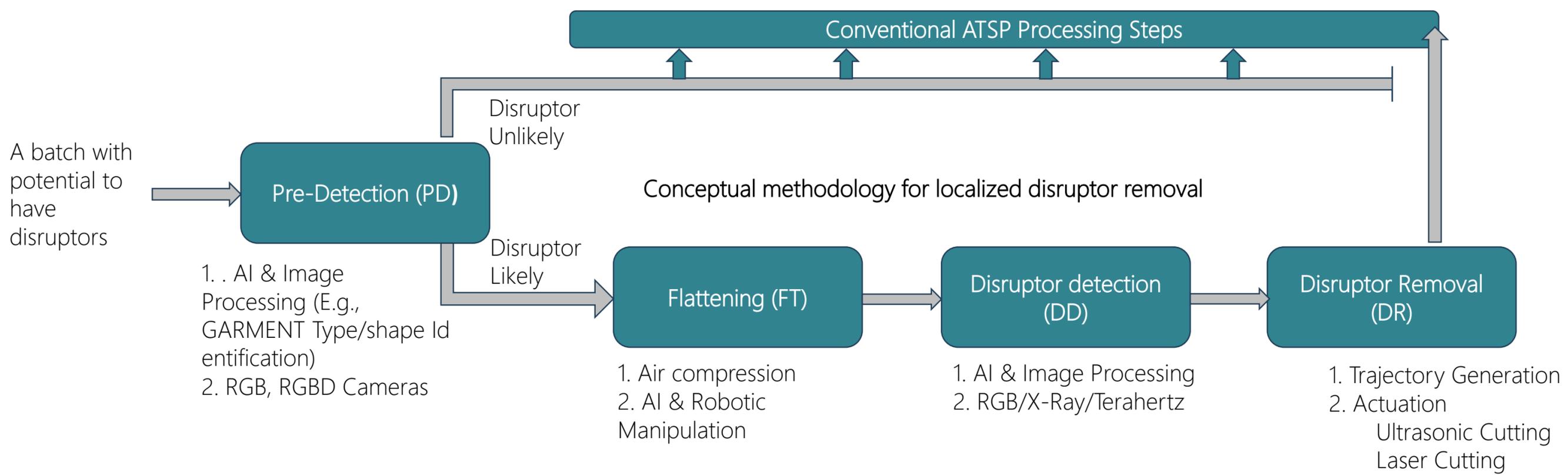
This process could be suitable for an ATSP if the outputs are proven to meet the demands of recyclers' feedstock. It is important that textiles inputted into this process are of similar weights/densities for the air-separation settings to be effective. This would necessitate accurate sorting upstream of this step to ensure that in addition to fibre type, material weight and density is also homogenous.



Pre-Detection of Disruptors

Localised disruptor removal is reliant on a garment flattening process and both processes would likely incur some additional challenges when looking at an industrial scale solution. The ATSP has an initial throughput target of 4.5 tonnes per hour, with future targets of 9 tonnes per hour. It is extremely unlikely that one disruptor removal system would be able to handle the estimated 78% of garments with disruptors present^[19] whilst meeting throughput requirements. To meet these throughputs, multiple processing lines would be required, increasing the floor space and financial requirements of creating an ATSP.

In an effort to reduce the demand on the localised disruptor removal system whilst still addressing the “Low Material Yield” challenge, a pre-detection step could be introduced to provide a high-level classification of the garment to determine which work stream should be used, reducing the overall load on the localised disruptor removal system.



[19] Characterisation study of the incoming and outgoing streams from sorting facilities, Refashion- April 2023.

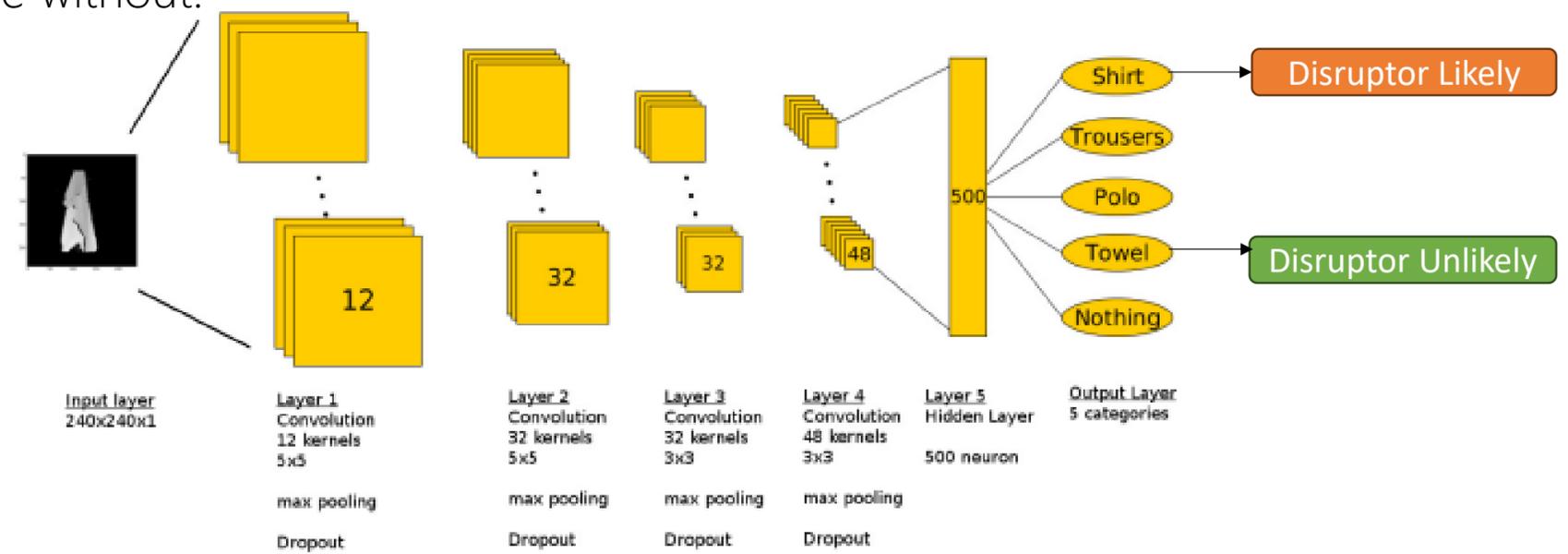
Pre-Detection of Disruptors: Emerging Technology

Key technologies for pre-detection have been identified in various textile research publications. Whilst these classification techniques only deal with identifying a clothing type (e.g. trouser, shirt, dress) they have potential to be further developed.

The likelihood of a disruptor being present on a garment can be inferred from data relating to the clothing type classifications.

There are a couple of places in the textile recycling process that this technique could be implemented to streamline the ATSP process:

1. Entrance to the ATSP: As described on the previous methodology slide, a pre-detection step could be implemented to determine the most suitable workstream for the garments. The existing methods researched are robotic-based, and unlikely that to meet the throughput requirements of an ATSP, as the textile manipulation techniques are time consuming.
2. Pre-ATSP, Sorters and Collectors: Utilise emerging AI-based technology (e.g. Technology developer Redivivum [[see further details in 'In Development Technologies' section](#)]). This could be implemented at the pre-sort stage to segregate NRTs into batches for those with disruptors and those without.

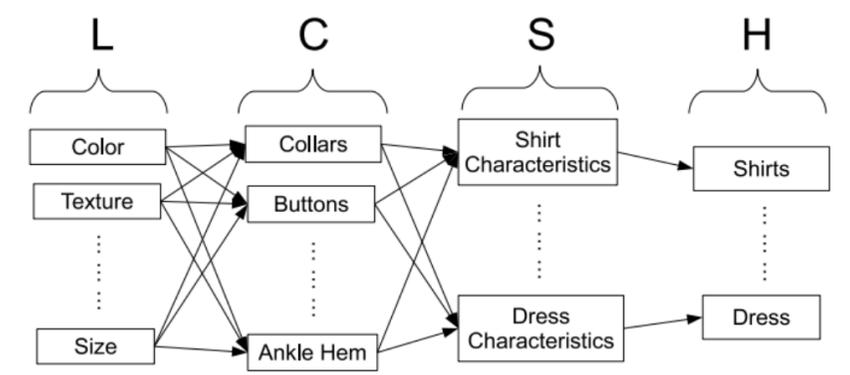


Example of AI based pre-detection methodology
Source: Robot-aided cloth classification using depth information and CNNs [2016]

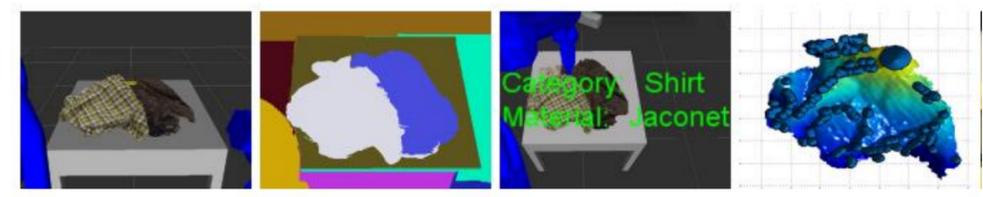
Garment classification techniques (1 of 3)

Five different classification and recognition approaches were identified in various research publications

- L-C-S-H classifier approach from a pile (2013) [1]
 - An approach for classifying items from a pile of laundry. The classification procedure exploits color, texture, shape, and edge information from 2D and 3D local and global information for each article of clothing using a Kinect sensor. The key contribution of this paper is a novel L-C-S-H classifier using characteristics and selection masks. Essentially, the method decomposes the problem into high (H), low (L) and multiple mid-level (characteristics(C), selection masks(S)) layers and produces "local" solutions to solve the global classification problem.
 - **Accuracy: 90%**
- Robot aided cloth classification (2016) [2]
 - A system to deal with the problem of classifying garments from a pile of clothes. This system uses a robot arm to extract a garment and show it to a depth camera. Using only depth images of a partial view of the garment as input, a deep convolutional neural network has been trained to classify different types of garments. The robot can rotate the garment along the vertical axis in order to provide different views of the garment to enlarge the prediction confidence and avoid confusions.
 - **Accuracy: 92%**
- Single shot category recognition (2017) [3]
 - A single-shot approach for recognising clothing categories from 2.5D features. We propose two visual features, BSP (B-Spline Patch) and TSD (Topology Spatial Distances) for this task. Integrated category recognition pipeline with a stereo vision system, clothing instance detection, and dual-arm manipulators to achieve an autonomous sorting system.
 - **Accuracy: 83.2%**



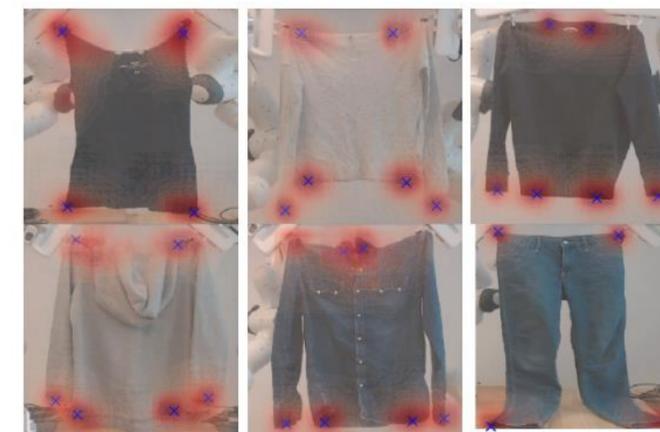
Source: Carme Torras [2016]



Garment classification techniques (2 of 3)

Five different classification and recognition approaches were identified in various research publications.

- Fashion landmark-based recognition (2020) [4]
 - Focus on techniques that can generalize from large-scale fashion datasets to less structured, small datasets collected in a robotic lab. Proposed training data augmentation methods such as elastic warping, and model adjustments such as rotation invariant convolutions to make the model generalize better using only RGB image dataset. Proposed a network architecture and training procedure on a large-scale fashion dataset DeepFashion.
 - **Accuracy:** 85 - 90%

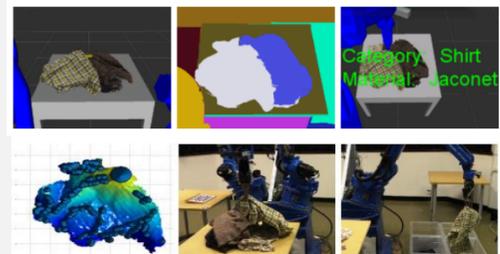
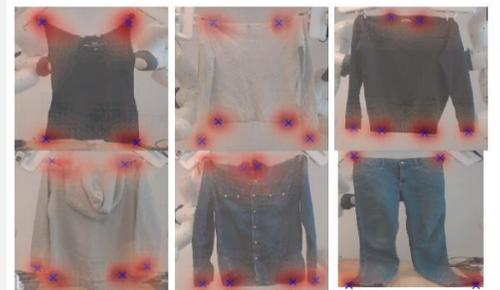


- Using shape estimation [5]
 - Segmentation and shape estimation of multiple deformed cloths stacked on a floor from an image using a CNN-based landmark detector and clustering. : (1) it can perform segmentation and shape estimation of multiple cloths of the same type or different types simultaneously by modeling a cloth as a grid of landmarks and estimating their positions and attributes, (2) it can correctly segment severely occluded or seemingly disjointed cloths by estimating and classifying landmark attributes including grid index, cloth position, cloth orientation, and cloth type.
 - **Precision:** 98.6%



The goal was to get an understanding of the different approaches and their effectiveness for classifying garments. To develop these classification techniques, further evaluation of the setup and configuration of the machine learning models is required to identify if they can be expanded to assess the likelihood of disruptors present on a garment, or if a custom model is required.

Garment classification techniques (3 of 3)

Image:	Publication:	Pros:	Cons:																				
 <table border="1" data-bbox="683 422 949 590"> <caption>Local and Global Features</caption> <thead> <tr> <th></th> <th>Shirt</th> <th>Dress</th> <th>Socks</th> </tr> </thead> <tbody> <tr> <th>Shirt</th> <td>58.64</td> <td>40.64</td> <td>0.72</td> </tr> <tr> <th>Dress</th> <td>4.32</td> <td>95.67</td> <td>0.02</td> </tr> <tr> <th>Socks</th> <td>37.10</td> <td>44.66</td> <td>18.24</td> </tr> <tr> <td colspan="4">Average TPR = 57.52%</td> </tr> </tbody> </table>		Shirt	Dress	Socks	Shirt	58.64	40.64	0.72	Dress	4.32	95.67	0.02	Socks	37.10	44.66	18.24	Average TPR = 57.52%				<p>[1] A New Approach to Clothing Classification using Mid-Level Layers(2013)</p>	<ul style="list-style-type: none"> • Each layer of the approach can be modified to include any type of learning Strategy and accuracy is 90% • Selection mask for collars, buttons etc. 	<ul style="list-style-type: none"> • Only 3 categories tested
	Shirt	Dress	Socks																				
Shirt	58.64	40.64	0.72																				
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Socks	37.10	44.66	18.24																				
Average TPR = 57.52%																							
	<p>[2] Robot-aided cloth classification using depth information and CNNs (2016)</p>	<ul style="list-style-type: none"> • Detection by hanging • Fast and Robust detection 92% accuracy • Detection from partial views 	<ul style="list-style-type: none"> • Only 3 categories tested 																				
	<p>[3] Single-shot clothing category recognition in free-configurations with application to autonomous clothes sorting(2017)</p>	<ul style="list-style-type: none"> • Robust to deformable shapes • Recognising clothing categories in random configurations based on high-quality stereo data 	<ul style="list-style-type: none"> • Slow and time-consuming process 																				
	<p>[4] Fashion landmark detection and category classification for Robotics</p>	<ul style="list-style-type: none"> • Trained on large category of clothes with up to 90% accuracy • Open-source code for further development. 	<ul style="list-style-type: none"> • Clothing needs to be somewhat flattened 																				
	<p>[5] Segmentation and Shape Estimation of Multiple Deformed Cloths Using a CNN-Based Landmark Detector and Clustering</p>	<ul style="list-style-type: none"> • Detection from a pile which has been verified on textured and folded clothes • Linked to robotic manipulation 	<ul style="list-style-type: none"> • Objects have similar shapes 																				

Summary & Conclusions

*Based on the feedback from textile recycler's spoken to, the most important aspect to them was to have very accurate fibre-sorted feedstock that **meets their feedstock specification tolerances.***

Challenges Identified from Market Survey	Emerging Technology that could address these challenges?	Estimated TRL status	So WHAT? What to monitor for future? Where relevant?
<ul style="list-style-type: none"> ▪ Detecting Hidden Disruptors 	<ul style="list-style-type: none"> ▪ Multiple RGB Cameras ▪ Terahertz Scanner ▪ X-ray Backscatter 	<p>7-9</p> <p>4-6</p> <p>7-9</p>	<ul style="list-style-type: none"> ▪ Penetrative sensing technology can improve efficiencies of current disruptor removal processes, although some development is still required for moving objects at industrial speeds.
<ul style="list-style-type: none"> ▪ Material Yield Loss & Localised Disruptor Removal 	<ul style="list-style-type: none"> ▪ Localised Disruptor Removal 	<p>1-3</p>	<ul style="list-style-type: none"> ▪ Localised disruptor removal is unlikely to be a direct replacement for current equipment in an ATSP. However, utilisation of these techniques spread across the textile recycling landscape (i.e. collectors & sorters) could reduce the demand on an ATSP.

*Localised Disruptor Removal remains a challenging area for technology development within pre-processing, primarily **due to the variation and material handling difficulties of post-consumer textiles products.** The advancement of supporting technologies that can repeatably manipulate the garments to expose key features is needed to enable precise analysis of garments and access to remove their disruptors.*

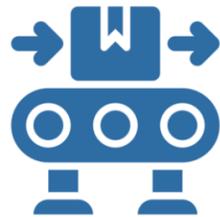
*Further trials are recommended to compare the energy consumption used and yields generated from existing technologies (ballistic separation, air separation) and a cost-benefit analysis completed to **assess if the potential improvements in material yield from localised disruptor removal warrant the development investments.***

Conclusions & Next Steps

Conclusions & Next Steps

Conclusion:

Through the exploration of the challenges identified in the previous report “Automatic Sorting for Circular Textiles: Technology Market Review”, emerging technologies and potential solutions have been identified. However, there remains some uncertainty surrounding the scale and criticality of the challenges for an ATSP, while the fibre-to-fibre textile recycling market is developing.



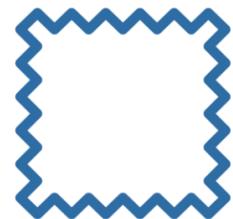
Material Feeding & Conveyance

- Automating item singulation and minimising the likelihood of garment overlapping is critical to efficient operations of an ATSP
- MTC are conducting robotic gripper trials to establish the most suitable option for textile feeding



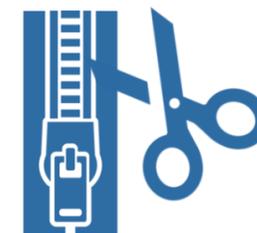
Fibre Identification & Sorting

- A Variety of further classification categories have been identified, along with possible solutions for identifying the characteristics required for classification.
- The commercial importance for further classification categories is unclear, and a “condition of supply” study would provide clarity.



Size Reduction

- There are no technologies versatile enough to produce optimal feedstock for the broad range of different fibre-to-fibre recycling processes.
- A “condition of supply” study would clearly define the physical specification of feedstock, enabling focused development efforts in this area.



Disruptor Removal

- Localised disruptor removal requires developments in a few key areas of robotics and machine learning. Although the throughput capacity of this technology has been rapidly increasing, it is still unlikely to satisfy the requirements at an industrial scale.
- An analysis of the cost of the material yield loss against development costs would be beneficial to inform further development efforts.

Next Steps:

In addition to the gripper trials in progress, the MTC intends to complete a “condition of supply” study in which an extensive group of post-ATSP processors (Chemical Recyclers, Mechanical Recyclers, etc.) are identified and interviewed to establish a consensus and guidelines for the downstream physical (Size, Fabric Structure, etc.) and chemical requirements (Dye tolerances, etc.) of feedstock for their processes. This activity will bring clarity and help focus future development of the ASTP to optimise output, in line with downstream recycling requirements to enable the textile circular materials economy.

In-Development Technologies



Fibre Identification

Conveyance/Material movement

Matoha

- UK-based start-up who have developed a range of plastic, textiles and carpet NIR-sensing devices – handheld, desktop, bench-mounted and sensing modules available
- Well-established with textile collectors and recyclers who use their devices sort textile waste and for quality checks for incoming goods - have sold 400+ devices in over 40 countries^[20]
- All Matoha devices are cloud-enabled, with the device able to report results to the cloud in real time. This supports traceability and allows the sorters to determine the composition of incoming and outgoing waste streams.
- Developing automated sorting system, combining their NIR sensor with robotics and AI to enable fibre identification and sorting/bin placement to be carried out in one action without human involvement.
 - Have created scaled demonstrator with £48k Innovate UK project - currently developing full-scale demonstrator
 - Potential to sort garments automatically with a small footprint, and low up-front cost through HaaS (Hardware as a Service)



Source: Matoha [2024]



Source: Matoha [2024]



Fibre Identification

Disruptor Removal



KAPDAA

UK-based company which started by working with designers and brands to create products from fabric offcuts in 2014. Partnerships with recyclers and brands with take-back schemes led them to develop their own fibre-sorting and trims removal technology completely in the UK.

Supported by Kingston University since 2022, KAPDAA has designed and developed a prototype of an automated textiles recycling machine Ai4FIBRES to identify & sort garments as per their composition, as well as detect and removing trims with minimum wastage.

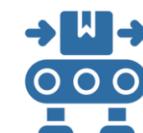
- Recipients of UKRI BridgeAI funding which starts in April to develop an industrial size prototype
- Commissioned by a UK interior brand to create a circular system from their waste
- Commissioned by a private European company that works within textile sorting to develop their AI-based disruptor removal system to integrate within their operations
- Ai4Fibres demonstrator will be accessible to brands / councils by September 2024 at Kingston upon Thames



[Video: Department of Science, Innovation and Technology](#)



System integrators



Conveyance/Material movement



Ken Mills Engineering

UK-based Ken Mills Engineering have over 40 years industry experience providing textile recycling solutions for multiple applications in the waste and recycling sector.

- [clients include](#) major textile recyclers and collector/sorters

KME have developed bale breaking and auto-feeding systems using series of spiked rollers and angled conveyor belts to singulate textile items (clothing, wiper rags), for passage under a metal detection system.

After an air-jet ballistic sort removes items with contaminants, materials are consistently fed on a conveyor ready for further sorting or baling.

*** An opportunity exists to trial this bale breaking and auto-feeding method with a preferred fibre-identification technology to test the accuracy and speed of textile items input in this way.*



[Video: Ken Mills Engineering](#)



[Video: Ken Mills Engineering](#)



Fibre Identification

Konica Minolta/Specim

Specim produces hyperspectral imaging devices covering range of spectra. Visual and NIR technologies were found useful for fibre and colour identification. The camera takes an image of the sample and produces a Spectrograph of the composition of the material, which can then be compared to a validated database to identify the material(s).

Specim cameras (such as FX17 – NIR region) operate in a line-scan mode, which means that the objects have to move to cover the whole space the textile (e.g. on the conveyer belt)

Hyper-spectroscopy aims to provide a continuous spectrum for each pixel (in the case of FX17 the camera covers 224 bands in the range of 900-1700 nm).

The NIR technology is currently used in most of the textile sorting solutions. It is however important to

- Identify the technology limits (some of them are indicted in the Fibre Identification Challenges section)
- Test if these limitations can be overcome with improved database and algorithms
- Compare with other potential technologies



Specim FX Series
Source: www.specim.com [2024]



SONY, UK

Tribo-Electric Sensor (TES)

The tribo-electric sensor (TES) that Sony is developing, measures the output voltages versus time of materials, enabling the creation of a tribo-electric signature for each material in the sensing geometry; furthermore, the collation of a database of triboelectric signatures – for different materials in different sensing geometries – is being developed to enable the identification of materials.

The TES technology requires direct contact between sensor and the object of analysis: the contact-interaction can be bouncing, tapping, or sliding over the sample being tested. It has been found under laboratory conditions to be able to identify and produce distinct data-clusters for differing fibre types such as polyester, cotton, viscous, wool or linen (and also for several blends thereof).

This technology could be used as complementary system that helps to identify fibre types; because its physical principles are different from NIR spectroscopy, it might be applicable in situations where NIR either fails or provides unclear results. However this is still low TRL technology, yet there exists some potential that it could be used to identify other fibre properties (such as thread type) – these would have to be investigated in future developments of the triboelectric material identification technology.



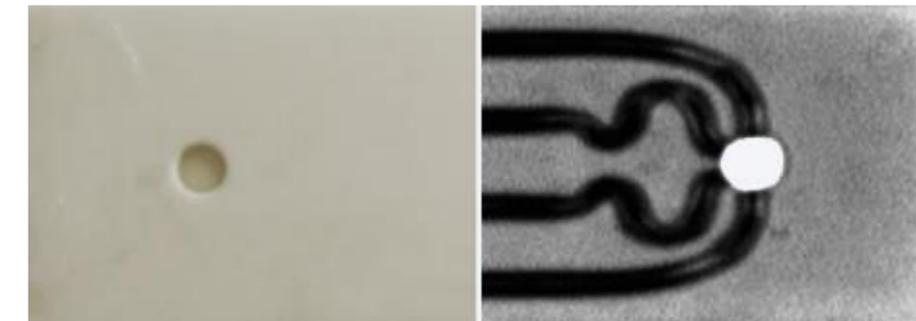
Fibre Identification

Optikan

Optikan produces non-distractive testing equipment based on Terahertz technology (T-rays). Terahertz radiation consists of electromagnetic waves of frequencies between 0.3 and 3 terahertz. This falls in between infrared and microwave radiation.

This technology is more penetrable than infrared and safer than X-ray. It allows detection of internal defects, internal analysis of materials, material sorting, and multilayer thickness measurements [21].

This equipment was investigated to be used for multi-layer detection of garments. The initial discussion with Optikan indicate that it might not be suitable for this purpose.



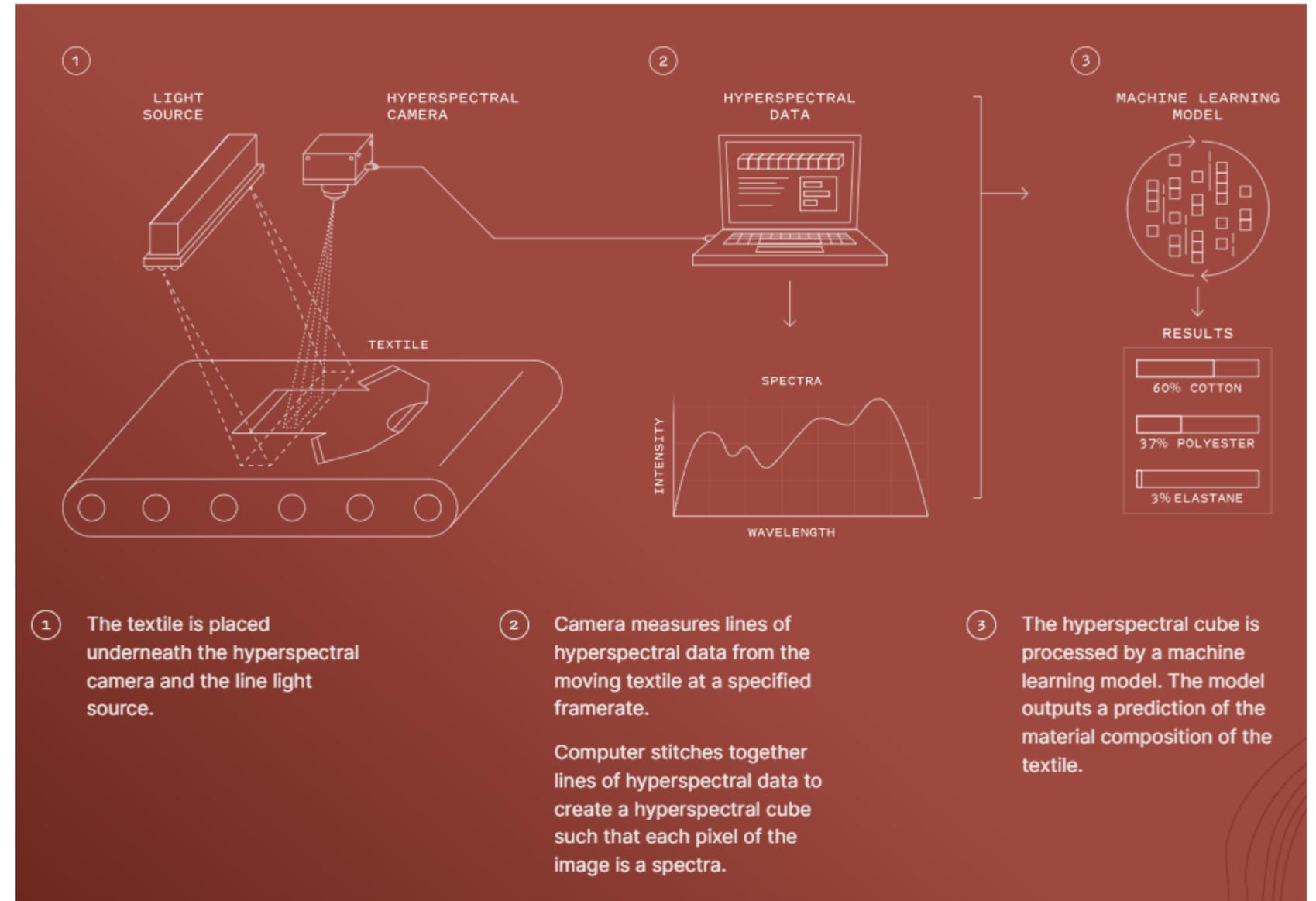
Visual and THZ image
Source: www.optikam.com [2024]



Fibre Identification

Refiberd

- US-based start-up; AI-based hyperspectral imaging technology provider.
- System has the ability to sort textiles based on fibre content within 2% accuracy.
- Their technology can be a tool for recyclers as a quality-control check to know what fibre composition fractions they are getting to better calculate their chemical usage quantities
- As of August 2024, are involved in several pilots in the US and EU with fibre-to-fibre recyclers, waste sorters, and fashion brands *(Refiberd could not disclose company names at time of interview, but hope to have news releases in the coming months)*



Refiberd AI-based hyperspectral technology
Source: [Refiberd](#) [2024]

 **Disruptor Removal**

In-Cycle – Dr. Mike Lee

- Researcher, founded In-Cycle in 2012
- Develops material separation and recycling technologies, largely for difficult to recover waste-streams, such as shoes, textiles and mixed plastics.
- Involved in a number of UK and [EU funded R&D projects](#) where bespoke recycling technologies are being developed. This includes the development of novel shredding, grinding, separation (mechanical and chemical) and moulding technologies
- Owns IP together with French company on an air separation technology
- Currently developing a novel air-based separator for shredded shoes separation- also applicable for shredded textiles to remove metals/hard points – will be available in future for small trials when machine is operational.



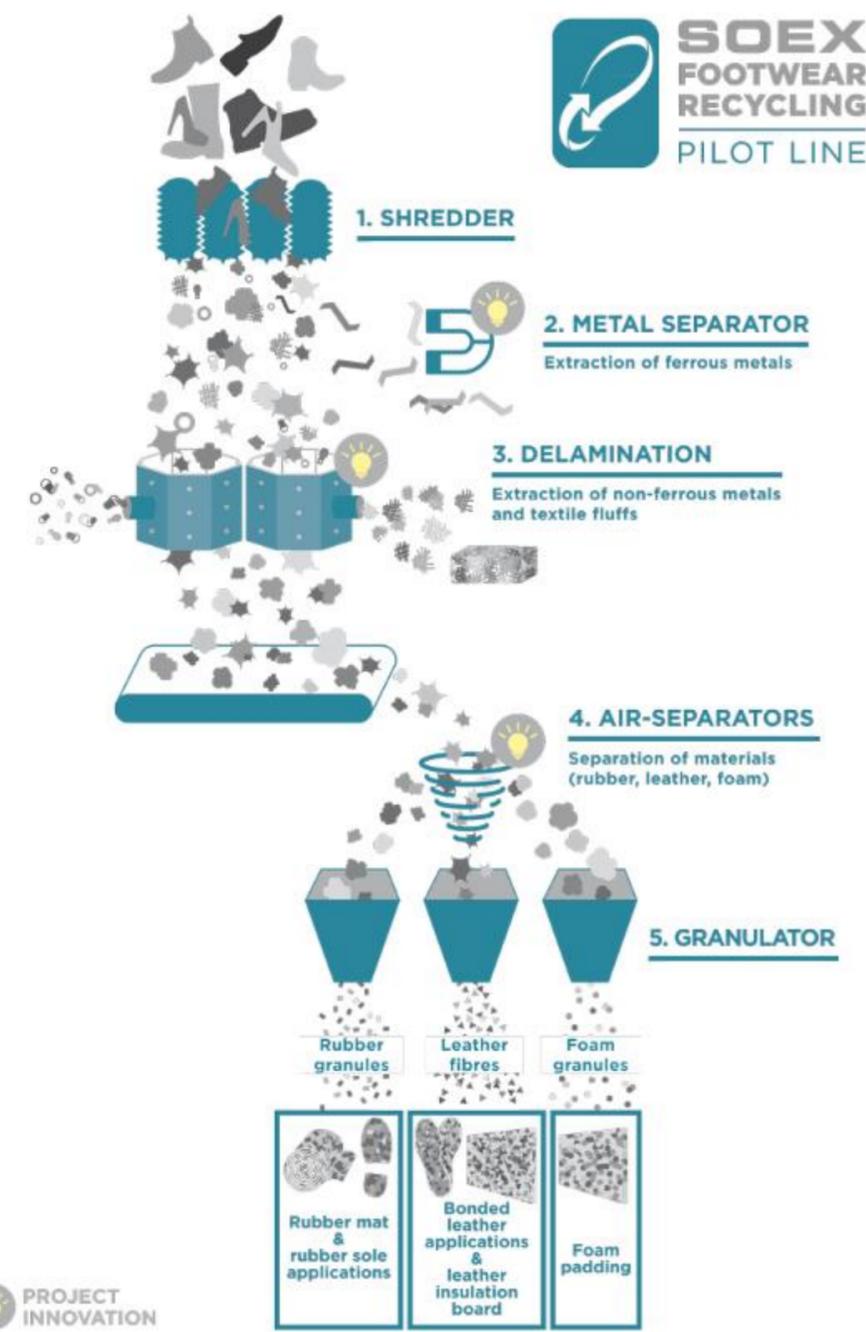
 [A novel separation process for recycling of post-consumer products](#)



 [An air-based automated material recycling system for postconsumer footwear products](#)

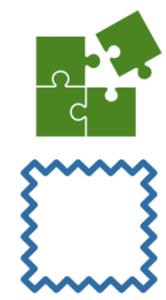


 [Development of an Economically Sustainable Recycling Process for the Footwear Sector](#)



SOEX Footwear Recycling Line

Source: [AIR coop](#) | [Footwear Recycling : from the idea to the demonstrator](#) [2024]



Complementary Tech

Size reduction

Upcycle Labs

Material science and technology company providing innovative upcycling services for fashion brands & retailers to convert their unwanted inventory into new high-quality décor products, store fittings and more.

- Are able to take entire garments and shred and granulate them into a powder granulate
- Granulate made from all components of garment – no need for trim removal - however machines which granulates lifts ferrous metals out so they can be aggregated and sold
- Add a plant-based resin to create a solution which can be moulded into any product (e.g, decoration shop fittings, tiles, bricks)
- Operate a circular business model in that they must have a customer willing to 'buy-back' the outputs (which can be bespoke moulded products of any kind) of their textile waste inputs



Source: [Upcycle Labs](#) [2024]

A potential option for any 'other'/generalisation categories of NRTs that get sorted in an ATSP without a fibre-to-fibre recycling route

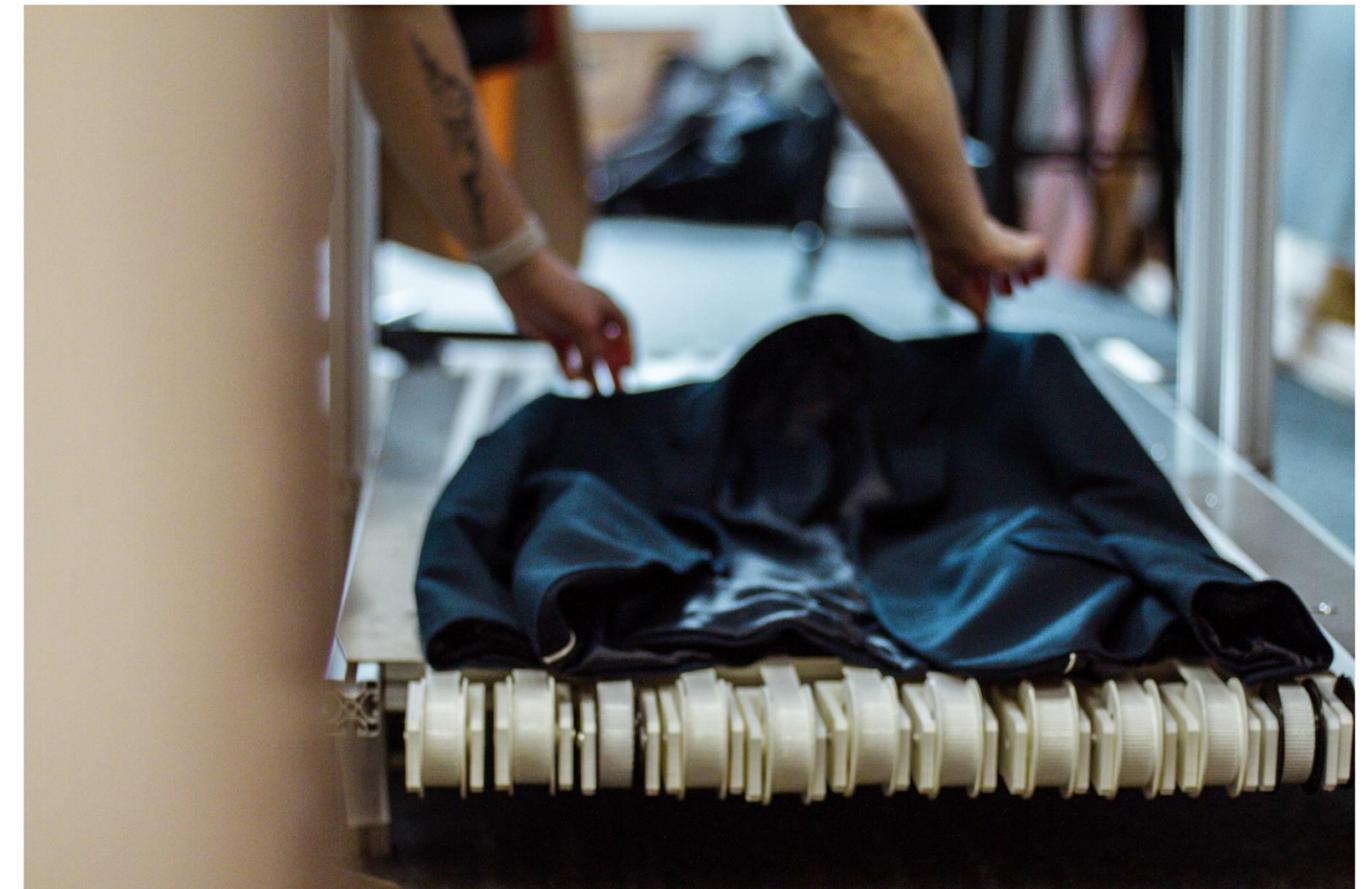


Complementary Tech

Fibre Identification

Redivivum

- German based start-up, working with UK-based collectors/sorters
- Have developed a Smart classification technology to automate & digitize pre-sorting RT from NRTs using a variety of artificial intelligence technologies to evaluate and sort used textiles based on their quality and condition.
- Categorises incoming garments (T-shirts, Jeans etc) and identifies additional parameters to determine reusability of clothing
- Small scale demonstrator completed February 2024
- Initial demonstration can identify garments with an average 80% accuracy
- Next development stage to focus on developing an automated feeding capability for pre-sorting lines



Source: Redivivum [2024]



Complementary Tech
Fibre Identification



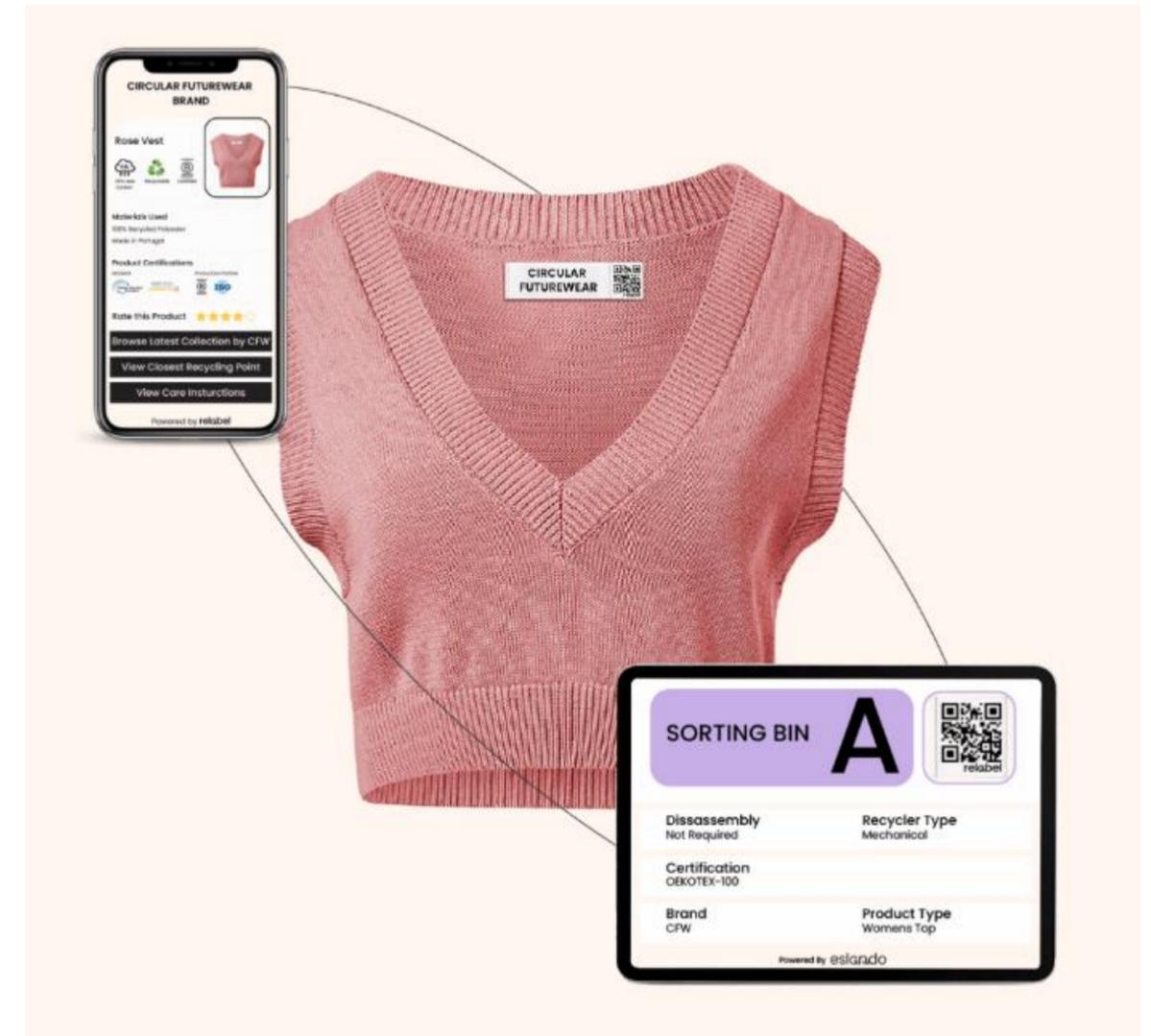
Eslando

UK-based start-up which has developed, Relabel, a Digital Product Passport (DDP)

- Have worked with brands to take their data and input into digital ID linked to QR code present on the garment
- Have worked with 35 recyclers to constantly update their dynamic system with the latest textile recycling guidelines

In theory, an ATSP with a DPP-reader could scan the QR code and automatically determine which sorting and pre-processing route to go down

- Recipient of UKRI Circular Economy for SMEs - innovating with NICER (National Interdisciplinary Circular Economy Research), round 2 funding
 - *Plan to have a minimum viable product demonstration system from June 2024 available for trialling*



Source: Eslando [2024]

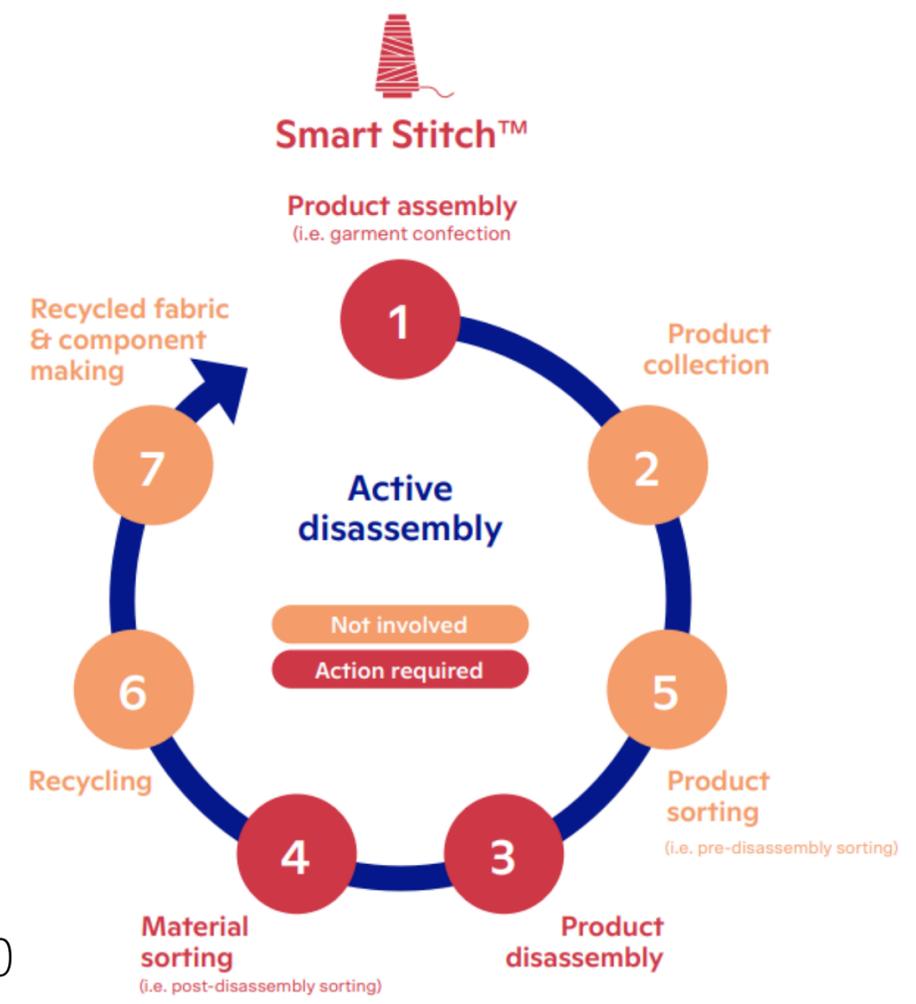
 **Disruptor Removal**

Resortecs

- Belgian-based technology provider which enables design-for-disassembly with complementary patented technologies:
 - **Smart Stitch™** - range of 16 heat-dissolvable threads-suitable for apparel to fire-resistant workwear
 - **Smart Disassembly™** - thermal disassembly system, low-oxygen chamber. In this system, heat is applied, and the heat-triggered Smart Stitch™ melts at a high temperature (> 150°C), automatically separating trims and different layers and materials of textile products—combines the quality of manual trim removal methods at up to 5x faster than manual disassembly.



Source: Resortecs [2024]



- Since 2021, both technologies have been piloted and technically validated by more than 50 brands. Some of the pilots resulted in products that were commercialized in over 60 countries.
- Already have established partnerships with workwear and mattress companies where collection eco-system is controlled, but foresee future consumer textile products could use their technology when assembled with washable RFID to signal to sorters that Resortecs Smart Stitch™ is present

Smart Disassembly™

Resortecs technologies for Active Disassembly occurs both at the end of the textiles product's life and during the textile product's design and production. This provides the advantage of controlling products and optimizing them for disassembly and recycling. On the other hand, it requires the involvement of more stakeholders in the process.^[22]

[22] <https://resortecs.com/from-waste-to-profit-unlocking-industrial-scale-textile-recycling-in-europe/> [Accessed: 2024]

Appendix

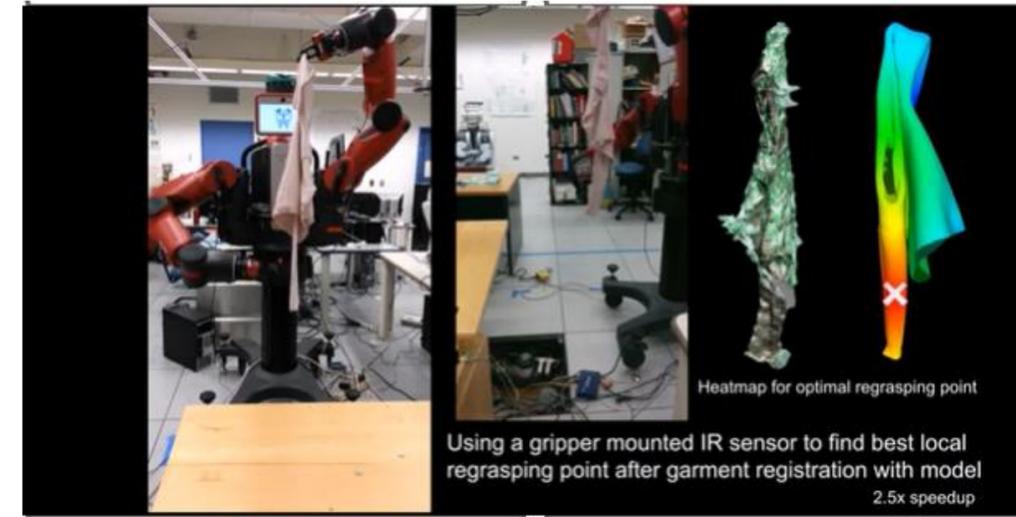
Garment Presentation: Flattening

Reviewed Publications:

1. Regrasping and Unfolding of Garments Using Predictive Thin Shell Modeling 2015

A method to teach a two-arm robot to efficiently track the states of a garment from an unknown state to a known state by iterative regrasping. A constrained weighted evaluation metric for evaluating the two desired grasping points during regrasping. Used simulated predictive thin shell models for garments to automatically create a large database of garments and their poses, which can be used in a learning algorithm to find object pose.

Accuracy: 80%



Pros	Cons
Two-stage deformable registration algorithm	Slow process
non-rigid registration method to minimize energy differences between source and target models	
centroid of the highest region as the starting point	
A semantically labeled garment database built with off line simulation that contains 37 different garments such as sweaters, pants, shorts, dresses, scarves, etc.	

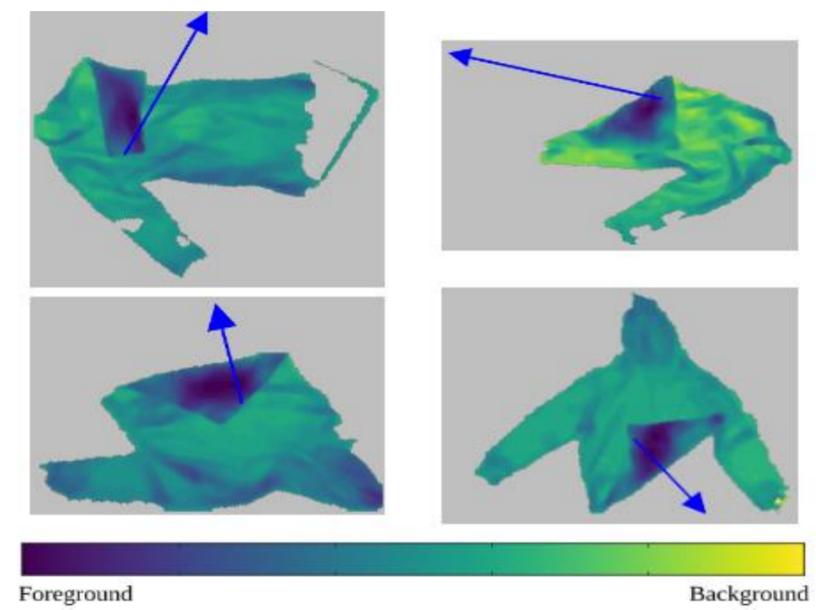
Garment Presentation: Flattening

Reviewed Publications:

2. Improving and Evaluating Robotic Garment Unfolding: A Garment-Agnostic Approach 2017

A garment-agnostic algorithm that requires no model to unfold clothes and works using only depth data. The algorithm presented is divided into 3 main stages. First, a Segmentation stage extracts the garment data from the background and approximates its contour into a polygon. Then, a Clustering stage groups regions of similar height within the garment, corresponding to different overlapped regions. Finally, a Pick and Place Points stage finds the most suitable points for grasping and releasing the garment for the unfolding process, based on a bumpiness value defined as the accumulated difference in height along selected candidate paths

Accuracy: 80%



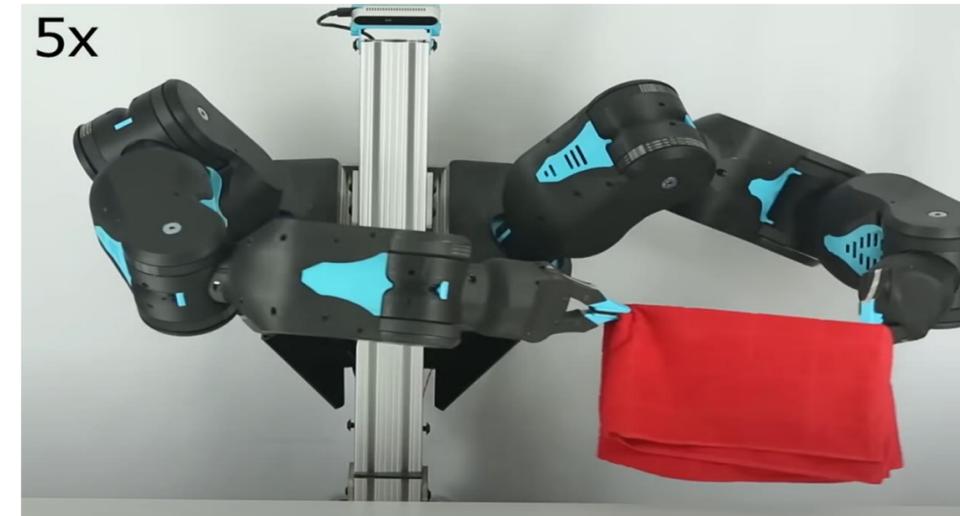
Pros	Cons
reconstructed point cloud is processed to obtain a depth map	Evaluated for simple folds and double folds only,
garment approximated as polygon	
centroid of the highest region as the starting point	

Garment Presentation: Flattening

Reviewed Publications:

3. Quasi-Direct Drive for Low-Cost Compliant Robotic Manipulation 2019

UC Berkeley have prototyped a new kind of robot arm design meant for the home and other human environments. Quasi-Direct Drive actuation as a capable paradigm for robotic force-controlled manipulation in human environments at low-cost. The prototype Blue is a human scale 7 Degree of Freedom arm with 2kg payload.



Pros	Cons
ROS package available	Specifically designed for household activities

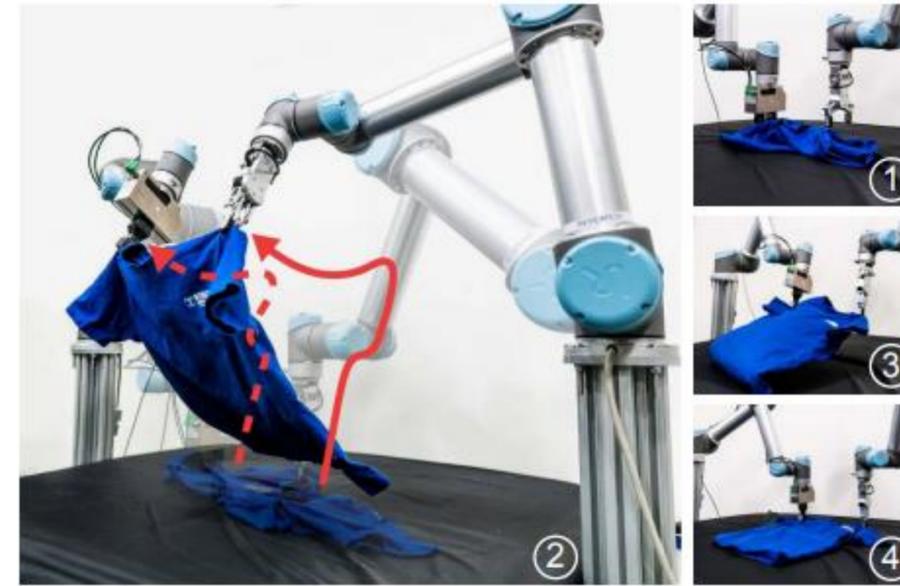
Garment Presentation: Flattening

Reviewed Publications:

4. FlingBot: The Unreasonable Effectiveness of Dynamic Manipulation for Cloth Unfolding 2021

Dynamic flinging actions for cloth unfolding using self supervised learning framework, FlingBot. approach learns how to unfold a piece of fabric from arbitrary initial configurations using a pick, stretch, and fling primitive for a dual-arm setup from visual observations

Accuracy: 80% within 3 actions to unfold



Pros	Cons
fling or throw actions can be useful for velocity driven trajectories that take acceleration into account.	generalizes to only T-shirts
Code, data, and simulation environment are available at https://flingbot.cs.columbia.edu have been open sourced.	
Generalizable for other testing and studies	

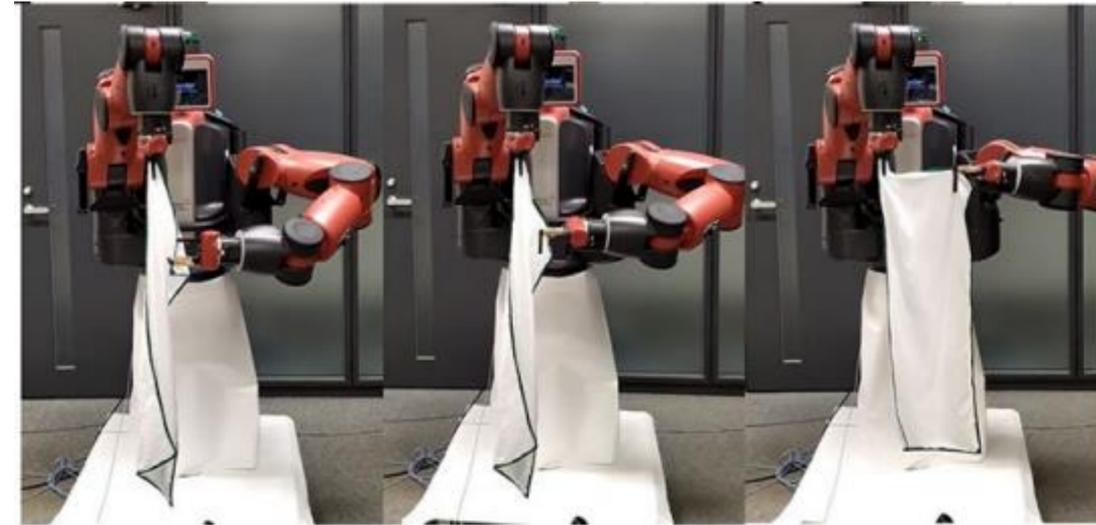
Garment Presentation: Flattening

Reviewed Publications:

5. Dual edge classifier for robust cloth unfolding 2021

Classifying the edges and corners of a garment by distinguishing between edges formed by folds and the hem or ragged edge of the cloth. Identifying the type of edges in a corner helps to determinate how the object is folded. This bottom-up approach, together with an active perception system, allows us to select strategies for robotic manipulation. Corroborated the method using a two-armed robot to manipulate towels of different shapes, textures, and sizes.

Accuracy: 80 -95% in unfolding



Pros	Cons
Identify corners of a cloth held in the air	Trained for rectangular cloths
	5 Robot actions defined because of rectangular cloth.

Garment Presentation: Flattening

Reviewed Publications:

6. SpeedFolding: Learning Efficient Bimanual Folding of Garments 2022

SpeedFolding, a reliable and efficient bimanual system, which given user-defined instructions as folding lines, manipulates an initially crumpled garment to (1) a smoothed and (2) a folded configuration. A novel neural network architecture that is able to predict pairs of gripper poses to parameterize a diverse set of bimanual action primitives is proposed.

Accuracy: 93%



Pros	Cons
Full github implementation available	Learning accuracy depends upon human annotation
Crumpled garment to smoothed	Textile patterns may be more challenging to detect and classify Correctly
Generalise to unseen garments	
t-shirt takes under 120 s	

Garment Presentation: Flattening

Reviewed Publications:

7. A Data-Centric Approach For Dual-Arm Robotic Garment Flattening 2022

Propose a data-centric approach to identify the known configurations of garments based on a known configuration network (KCNet) trained on the depth images that capture the known configurations of garments and prior knowledge of garment shapes. The known configurations of garments are the configurations of garments when a robot hangs garments in the middle of the air.

Accuracy: 92%



Pros	Cons
Perceives cloth motion trajectory to gain confidence in predicting shape	Source code not available
Crumbled garment to smoothed	Two camera-based recognition
On-the-fly strategy	pre-designed first and second grasping points
Sophisticated modelling for garments not required	Uses garments from only five shapes (Jeans, Shirt, Sweater, Towel, T-shirt)
	Unknown shape cannot be manipulated

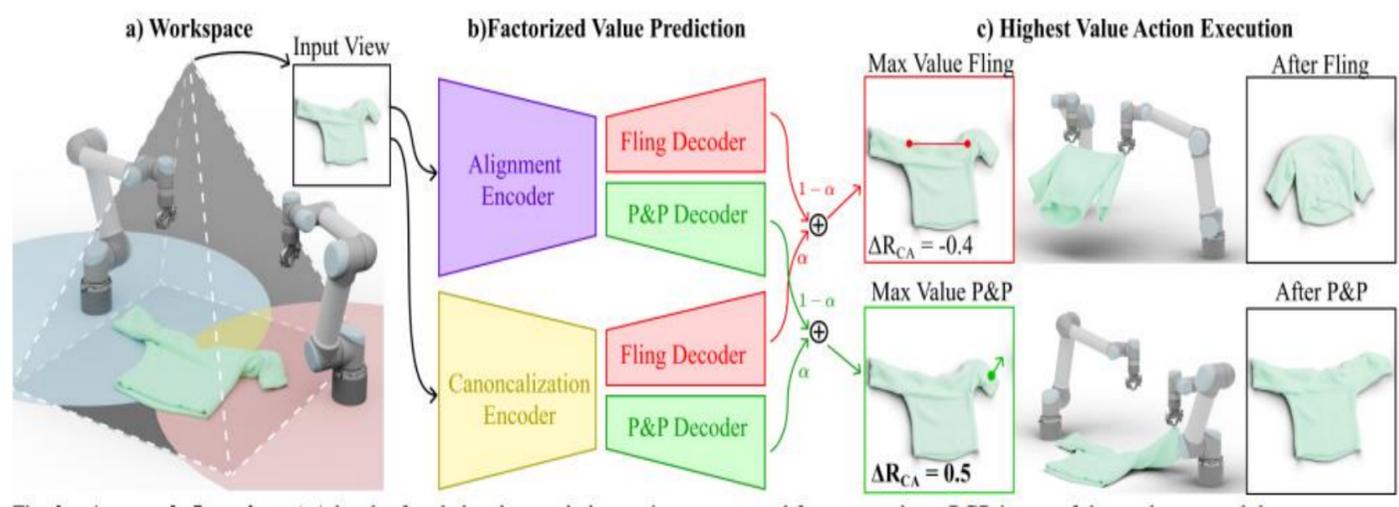
Garment Presentation: Flattening

Reviewed Publications:

8. Cloth Funnels: Canonicalized-Alignment for Multi-Purpose Garment Manipulation 2023

A “canonicalized-alignment” task for garment manipulation, where the goal is to transform a garment from its arbitrary initial state into a canonical shape (defined by its category) and align it with a particular 2D translation and rotation. This demonstrate that task-agnostic canonicalized-alignment can enable even simple manually-designed policies to work well where they were previously inadequate, thus bridging the gap between automated non-deformable manufacturing and deformable manipulation.

Accuracy: 80 - 87%



Pros	Cons
Robust task-agnostic canonicalization and alignment policy	Implementation code not available.
Crumbled garment to smoothed	
Generalise to unseen garments	

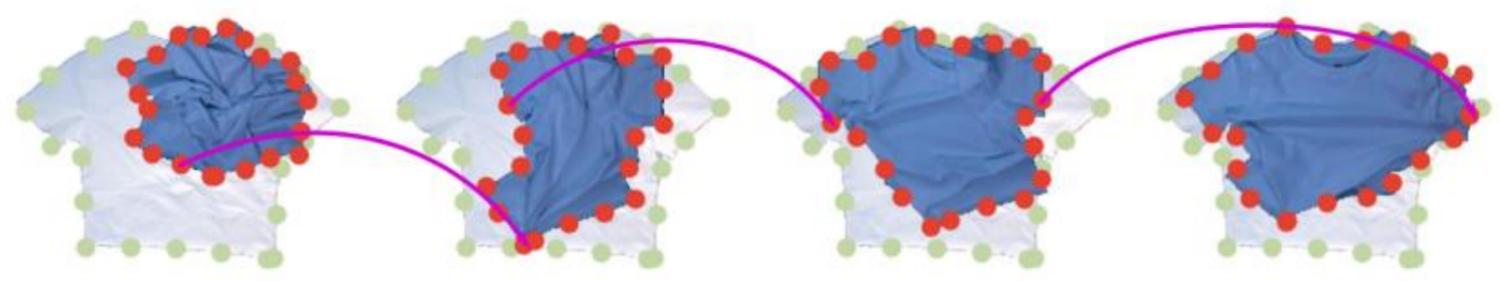
Garment Presentation: Flattening

Reviewed Publications:

9. Representing clothing items for robotics tasks 2022

Study the problem of clothing item representation. Focus on visual and graph representations, both extracted from images. Visual representations follow the current trend of learning general representations rather than tailoring specific features relevant for the task. Rely on a subset of DeepFashion2 dataset and study performance of developed representations in an unsupervised, contrastive learning framework using a downstream classification task. Visual representations are based on RGB images and graph representations are built from segmented and binarized RGB images.

Accuracy: 80 - 87%



Pros	Cons
Graph representation	Slow operation
Graphs are extracted from binarized RGB images, thus removing texture and color information.	
More suitable representations for robotic tasks requiring task and motion Planning.	

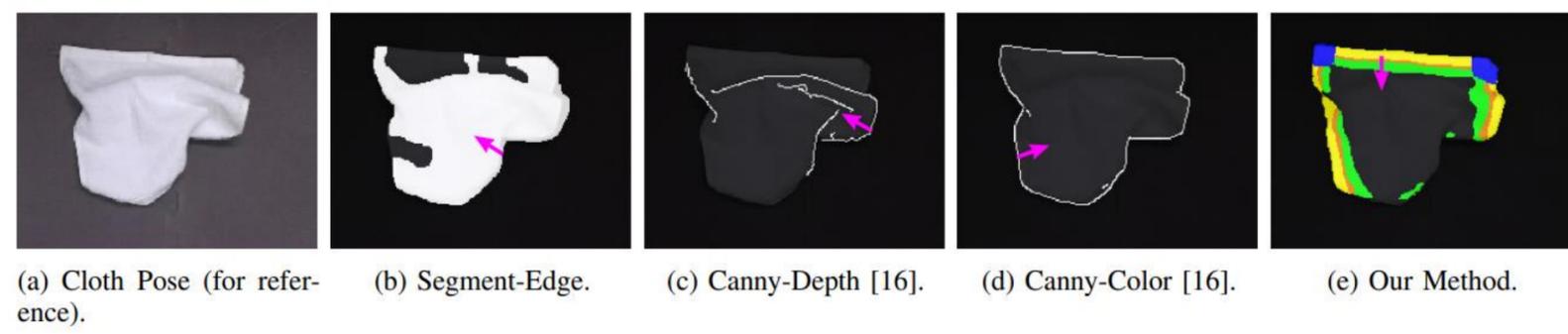
Garment Presentation: Flattening

Reviewed Publications:

10. Cloth Region Segmentation for Robust Grasp Selection 2020

Segmenting and grasping key regions. The approach trains a network to segment the edges and corners of a cloth from a depth image, distinguishing such regions from wrinkles or folds. Also, an algorithm for estimating the grasp location, direction, and directional uncertainty from the segmentation.

Accuracy: 70%



Pros	Cons
Github implementation available	Verified on small category of cloths
Simple and faster Edge and corner detection	
Robust to texture chnages	

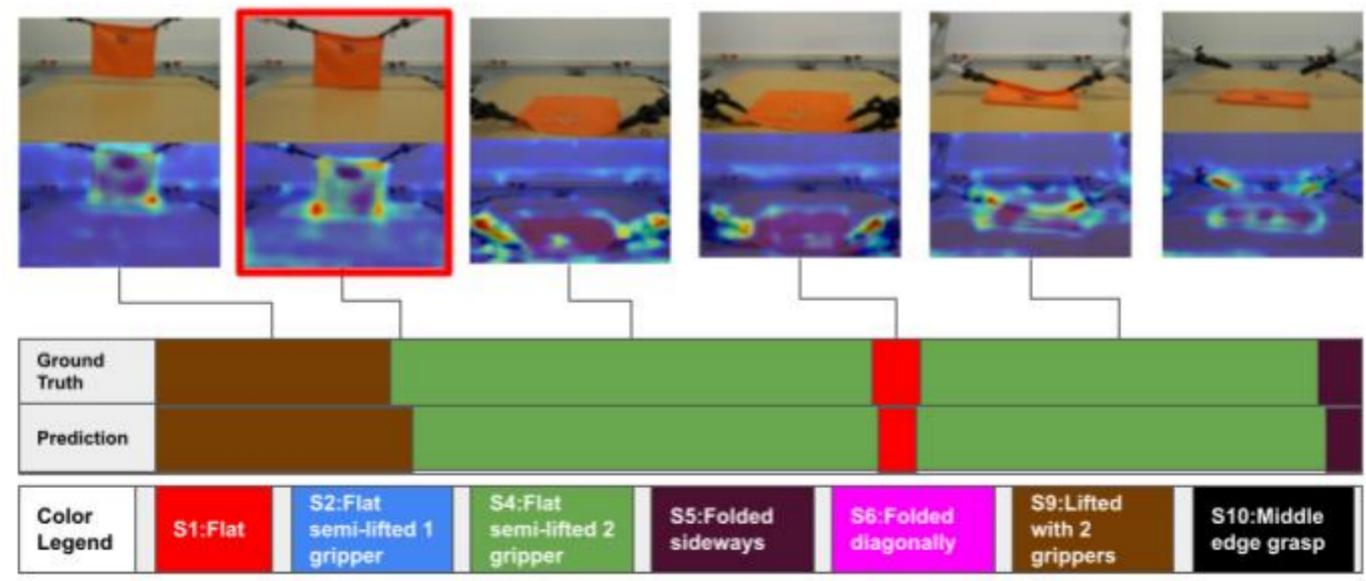
Garment Presentation: Flattening

Reviewed Publications:

11. Semantic State Estimation in Cloth Manipulation Tasks 2022

To solve the problem of semantic state estimation in cloth manipulation tasks. A new large-scale fully-annotated RGB image dataset showing various human demonstrations of different complicated cloth manipulations. Provided a set of baseline deep networks and benchmark them on the problem of semantic state estimation. A high-level semantic description of the cloth state which couples the cloth deformation type, the grasping state and the contacts with the environment.

Accuracy: 70%



Pros	Cons
Semantic state estimation in continuous cloth manipulation tasks in an end-to-end Manner	Performed on garment folding operation