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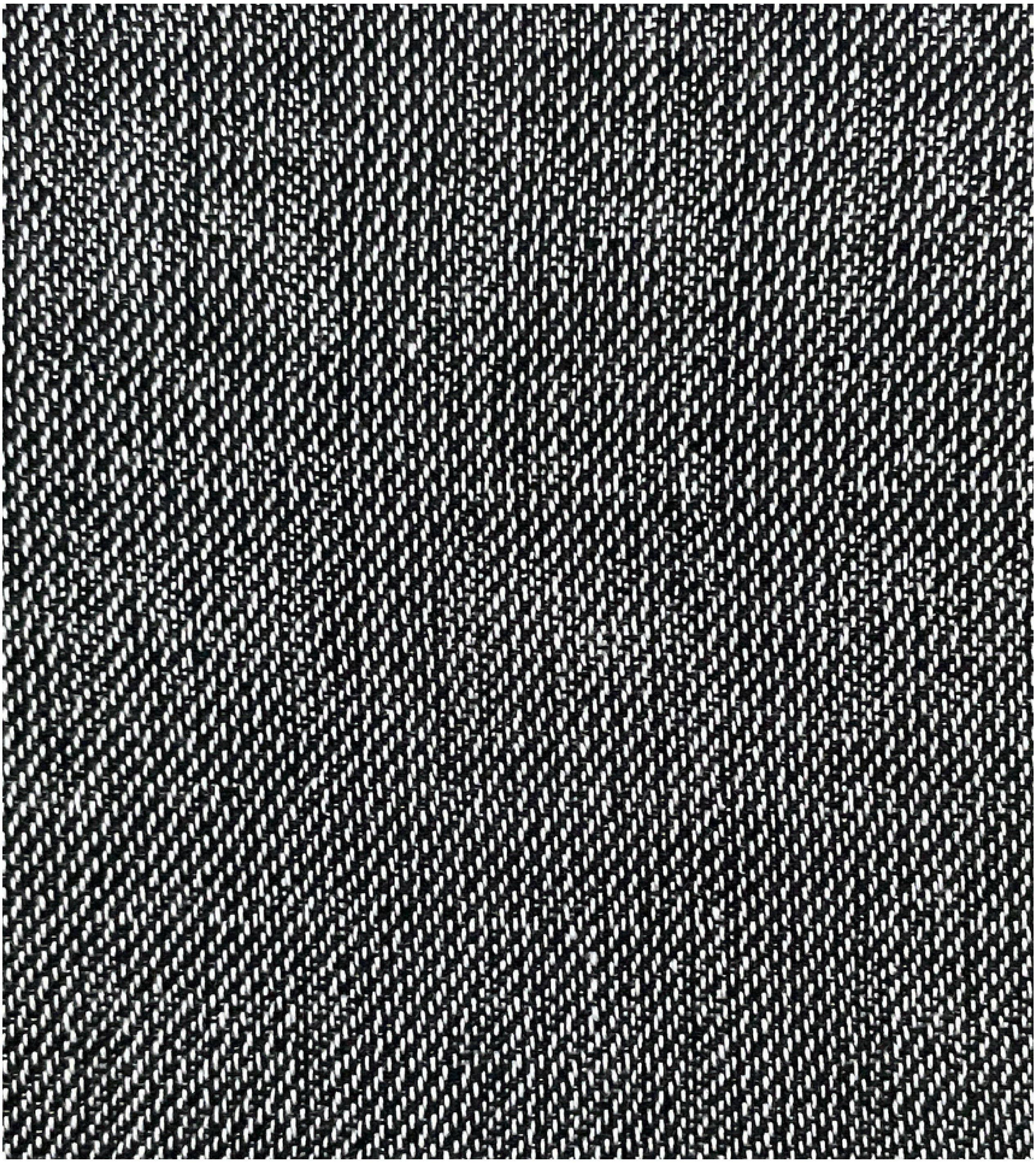

THESIS

WOVEN MEMORY: EMBEDDING INVISIBLE MARKERS TO ENHANCE DIGITAL TRACEABILITY

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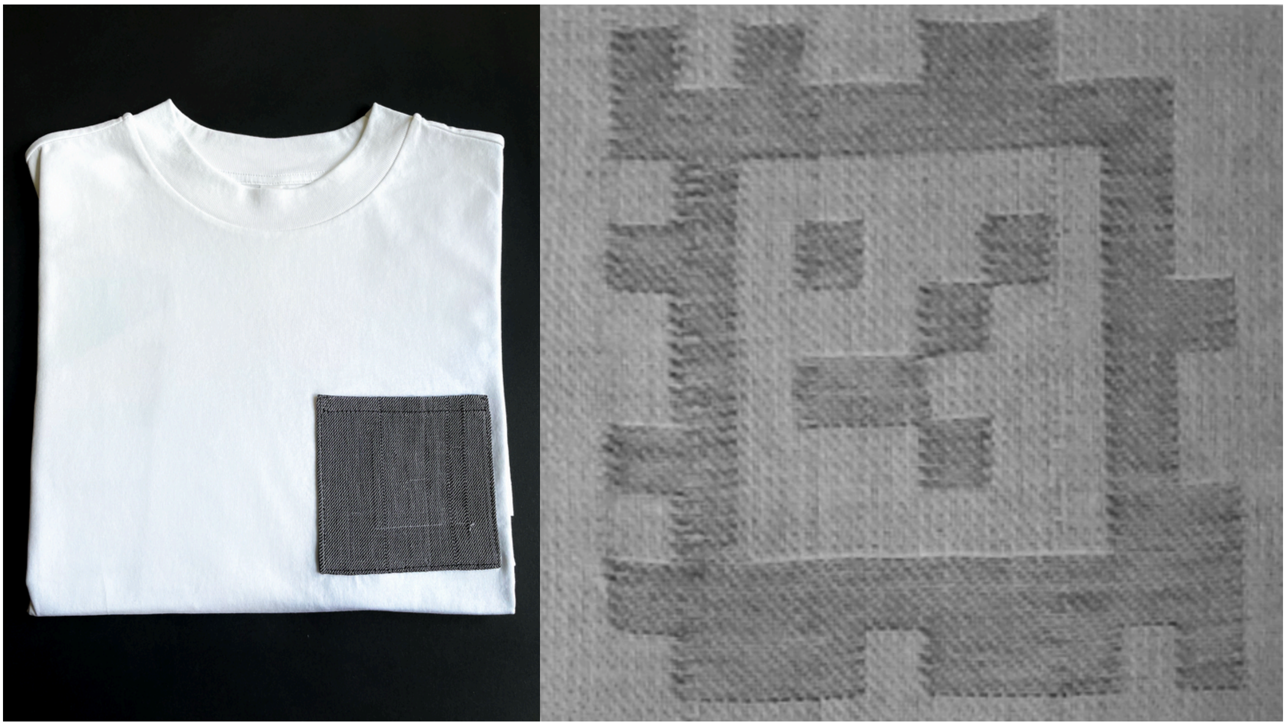


WOVEN MEMORY: EMBEDDING INVISIBLE MARKERS TO ENHANCE DIGITAL TRACEABILITY

Abstract

This research investigates how invisible data markers can be embedded into woven textiles and retrieved using near-infrared (NIR) imaging. It focuses on integrating machine-readable information without altering the textile's visible appearance, which is essential for traceability and compliance with emerging frameworks like the Digital Product Passport (DPP). The method follows a multi-stage approach, beginning with an analysis of material behavior and the combination of yarns with differing NIR absorption properties. Transparency and contrast serve as key evaluation criteria. Results demonstrate that specific yarn combinations in compound woven structures can be programmed with invisible markers that are detectable under NIR light yet remain invisible to the human eye. A final demonstrator validates the approach. This supports circular design by embedding product data within the material itself and contributes to human–computer interaction (HCI) by enabling non-electronic, material-based interfaces. The work advances research on embedded markers and tags, enabling machine-readable codes without additional hardware.

1.INTRODUCTION

Imagine a textile recycling facility where machines scan tags on garments and other textile products to identify fiber types and determine sorting categories. However, one batch of fabric passes through undetected because the information about its composition and provenance was printed on a label that was removed long ago. Without reliable data, the textile is downcycled or discarded, missing its opportunity to re-enter the production loop. This is not an isolated case. Across industrial textile systems, difficulties in identifying material content and the loss of attached product information lead to inefficiencies, material waste, and barriers to circularity.

This scenario reflects a central challenge facing the materials industry as it prepares for the European Union's Digital Product Passport (DPP) regulation. DPP requires traceable, standardized data to accompany products and materials throughout their lifecycle, from production to reuse and recycling. In response, research is increasingly focused on integrating machine-readable information directly into textile structures, where it cannot be removed, worn off, or lost.
At the core of this shift is the need to make data inseparable from the material itself.

If information is to remain available at every stage, from the factory floor to the sorting facility, it must move beyond tags, labels, and external codes. The textile must be able to carry its own data.

This study explores how markers that carry data can be structurally embedded into woven textiles using near-infrared (NIR) imaging. These markers are formed by layering yarns with distinct NIR absorption properties into compound weave constructions. The resulting patterns are invisible to the human eye under visible light, yet can be detected by sensing technologies under NIR.
From a human-computer interaction (HCI) perspective, this transforms the textile into a passive interface. Without relying on electronics, screen prints, or embroidery, the embedded markers enable machines to recognize and retrieve information directly from the material. The textile becomes part of a larger digital system, capable of storing and transmitting information structurally rather than digitally.

This approach reframes the textile as an active medium within applied sensing environments, contributing to both regulatory compliance for traceability and new interaction possibilities where information moves with the material by design.

1.1 Context and Motivation

Textiles are being reimagined not only as sociocultural signifiers or materials performing physical functions, but also as carriers of embedded data and information. This shift is unfolding across design, technology, and policy landscapes, where the textile is no longer seen as a passive material but as an active medium within connected systems.
Imagine a fabric that doesn't just clothe or cover but quietly holds information about its own composition, history, or intended future. In industrial and digital contexts alike, the ability to embed and retrieve such information opens up new possibilities. The integration of machine readable markers within woven fabrics enables identification, tracking, and automation in material handling processes, where knowing what a textile is, and where it came from, matters.
Previous approaches such as conductive yarns, fiducial markers, and AR codes have already shown that textiles can interact with digital systems (Poupyrev et al., 2016; Devendorf et al., 2019; Menon et al., 2023). Yet many rely on surface level techniques like printing and embroidery (Häkkilä et al., 2017; Liang et al., 2024), which are easily worn off and unsuited for long term or industrial use. The information they carry is often the first thing to fade, detaching from the material when it is needed most.

As regulatory frameworks like the Digital Product Passport (DPP) begin to take shape, the need for more integrated and resilient solutions becomes urgent.

The DPP requires that product specific data remains accessible beyond first use not just in retail or production, but through reuse, repair, and recycling. In response, researchers and designers are turning to the structure of the textile itself.

By embedding invisible markers within the woven structure, data becomes part of the material, not something added to it. These markers enable traceability without external tags or devices. Near infrared (NIR) imaging, already used in fiber detection and sorting technologies, offers a nonintrusive method for reading this information at any point in a textile's lifecycle.

In this way, woven textiles can carry not only their own weight and function, but also their own story ready to be read, recognized, and recirculated.

1.1.1 DPP and the Role of Data Embedded in Textiles

The Digital Product Passport (DPP) is more than a technical tool; it represents a turning point in how the textile industry thinks about accountability, transparency, and material flow. Introduced as part of the European Union's strategy for circular textiles, the DPP promises to follow a product throughout its lifecycle. From raw material sourcing to end-of-life recycling, it carries standardized data that supports visibility, compliance, and circularity at every step (Legardeur et al., 2024). Under the Ecodesign for Sustainable Products Regulation (ESPR), the DPP plays a critical role in promoting product durability, reparability, and recyclability (Figure 1) (Faraca et al., 2024).

But for that vision to become reality, it requires more than just policy. It depends on a robust digital infrastructure, one that is capable of tracking materials through production, use, repair, resale, and finally, disposal (Jensen et al., 2023). In practice, this presents major challenges. Not all textile producers operate on the same digital footing. While some companies automate data input from design and manufacturing tools, others still rely on manual entry, spreadsheets, or legacy systems. As Rosado da Cruz et al. (2024) point out, these variations introduce inconsistencies in data quality and raise doubts about reliability.

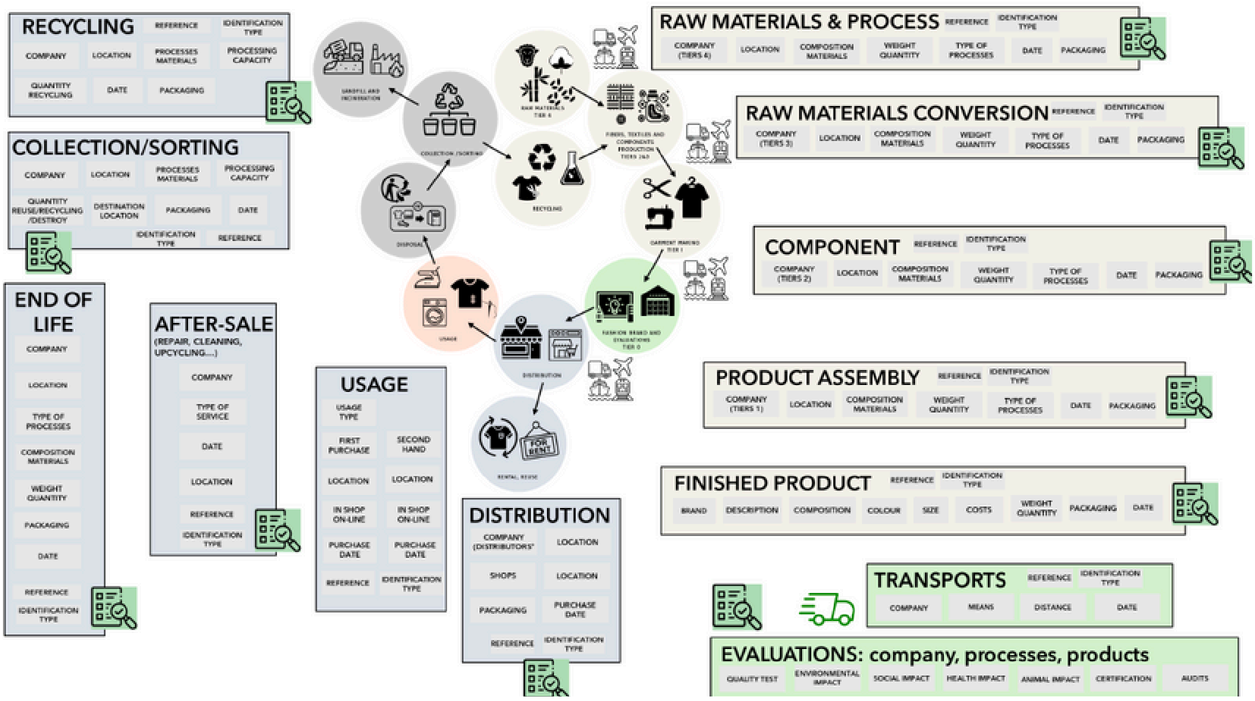


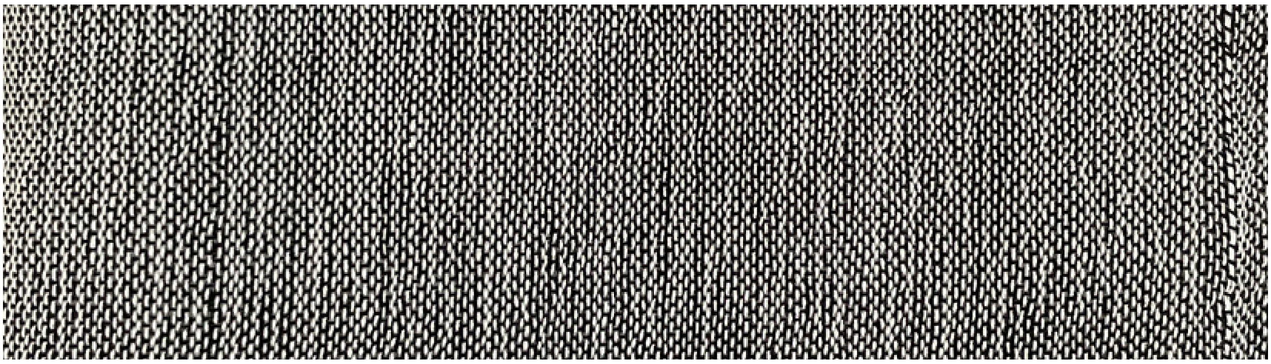
Figure 1. shows a generic Digital Product Passport model for textiles (EPRS 2024), outlining which data should be collected at each lifecycle stage, who can access it, and how unique product IDs support traceability, transparency, and circularity.

Blockchain has been proposed as one solution, offering a tamper resistant trail of material data (Alves et al., 2024), but even blockchain systems depend on consistent input (Figure 1).
Some technical pathways already exist. Embedded digital identifiers like woven RFID threads or conductive yarns have shown potential for storing and retrieving product data even after multiple lifecycle stages (Adisorn et al., 2021; Rukanova et al., 2024). These systems reduce dependency on external labels, offering more resilient tracking across use contexts such as recycling, repair, and disassembly.

The DPP is deeply aligned with broader EU goals, including the Circular Economy Action Plan (CEAP) and the European Green Deal. Yet implementing it across borders remains difficult. Regulations vary from country to country, and digital systems do not always speak the same language. To make the DPP truly work, standardized frameworks for data collection, interpretation, and sharing are essential (European Parliament, 2024).
According to McKinsey & Company (2022), embedding material specific data directly into textiles could revolutionize sorting and recycling processes, allowing machines to read what is inside a fabric and decide what to do with it. The vision is clear: smarter materials make for smarter systems.
The European Commission (2023) reinforces this point, emphasizing that standardized material data is a prerequisite for fiber to fiber recycling.

The question that remains is how to embed that data meaningfully so it lasts, scales, and integrates with DPP systems in practice.
This is where current research begins to reach its limits. While DPPs and embedded textile markers have been explored separately, their direct integration remains underdeveloped. We do not yet fully understand how standardized DPP data can be embedded into textile structures, nor what technologies offer the best balance between durability, accuracy, and cost. Interoperability between textile embedded markers and official DPP platforms remains uncertain, especially when considering cross border regulation and long term use.

As circular economy initiatives continue to expand, so does the urgency to bridge these gaps. Understanding how DPP related data can be structurally woven into textiles, and reliably retrieved at any point in their lifecycle, is a necessary step toward enabling the infrastructures of circularity to function smoothly, consistently, and at scale.



1.2 PROBLEM STATEMENT

To realize the full potential of the Digital Product Passport, data must remain with the material throughout its lifecycle. This raises a key challenge: how can that information be embedded in the textile itself rather than added externally?

A garment begins its life with a tag, printed, stitched, or embedded in a chip. That tag carries critical information: what the textile is made of, where it came from, and how it should be handled at the end of its life. But over time, the tag fades, detaches, or gets removed. The material remains, but the information disappears.

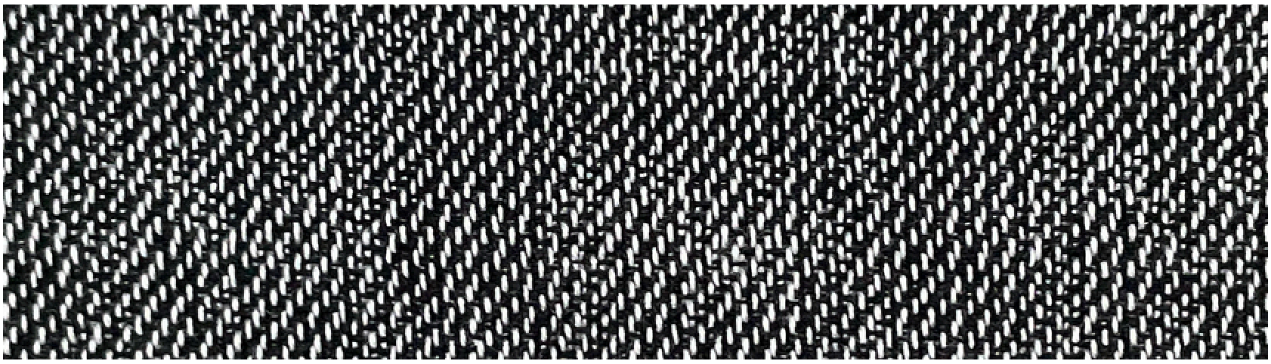
This is a common weakness in today's textile traceability systems. Labels, QR codes, and RFID tags are external elements, not part of the textile itself. They are easily lost, damaged, or altered, especially after repeated use and washing. As a result, materials become unidentifiable just when accurate data is needed most. This limits the effectiveness of automated recognition and reliable tracking in ndustrial and circular settings (Adisorn et al., 2021; Häkkilä et al., 2017).

Efforts to address this have largely focused on surface level solutions such as conductive yarns, printed sensors, and visible markers, but these approaches remain vulnerable to wear or require electronics that complicate production and recycling (Liang et al., 2024; Rukanova et al., 2024).

At the same time, technologies like near infrared (NIR) imaging have advanced in fiber detection and classification (Schmidt et al., 2022; Jensen et al., 2023). Yet their use in reading invisible, structurally embedded data within woven textiles remains largely unexplored. No method currently exists for embedding machine readable information into textiles in a way that is both durable and standardized. Critical questions persist: How do fiber types, dyes, and weave structures affect visibility under NIR? And how can patterns be designed to ensure consistent machine readability?

Without answers to these questions, the textile industry will struggle to meet the demands of regulatory frameworks such as the Digital Product Passport (DPP), which calls for persistent, product specific data across multiple lifecycles (European Commission, 2023; Legardeur et al., 2024). If information cannot stay with the material, it cannot support the data driven systems that circularity depends on.

The consequence is clear: missing data leads to missed opportunities. Without integrated traceability, the sector is limiting the potential to scale circular practices such as post consumer sorting, remanufacturing, and fiber to fiber recycling. The moment the label is lost, so is the chance to recirculate the material.



1.3 RESEARCH AIM

Building on these challenges, this research explores a material-based alternative to external tagging by embedding information directly into the structure of the textile itself. What if a fabric could hold information not on its surface, but within its very structure? Not with a label or a chip, but through threads arranged precisely so that only a machine could read them. The investigation focuses on how invisible, machine-readable data can be embedded in textiles using Jacquard weaving and retrieved through near-infrared (NIR) imaging.
It examines how fiber properties and weave structures influence NIR visibility and marker contrast, and how these factors can be controlled during the design and manufacturing process.

The aim is to identify yarn combinations that produce the highest contrast under NIR, while remaining invisible under artificial light.

This invisibility ensures the textile's surface remains visually and functionally unchanged, allowing information to be embedded without interfering with its use or appearance

The markers are designed to carry product-specific data such as fiber content, production origin, and processing history. This information is vital for traceability, post-consumer sorting, and alignment with regulatory frameworks like the Digital Product Passport (DPP). The research further explores how these yarns can be arranged through Jacquard compound weaving to encode information directly into the textile in a non-disruptive, integrated way.

A series of woven prototypes were developed to evaluate the feasibility of this approach, forming the basis for future work on structurally embedded markers that carry the data.

1.4 RESEARCH QUESTION

How can invisible, machine-readable markers be embedded and retrieved in woven textiles to enable the traceability of product-specific data?

Sub-questions are explored:

1. What yarn types and optical properties are suitable for embedding and retrieving machine-readable markers in woven textiles using near-infrared imaging?

2. What weaving methods can be applied to integrate machine-readable markers into woven textiles without affecting their visible appearance?

3. What technologies can be used to detect and interpret embedded machine-readable markers in woven textiles?

4. How do weave structures and yarn layering influence the visibility and retrieval of machine-readable markers under near-infrared imaging?

1.5 SCIENTIFIC CONTRIBUTION

Identification of contrast-generating yarns suitable for invisible NIR markers in textiles

- This study identifies yarns, including those made with recycled polyester, cotton, and wool, with the same colour expression under visible light (i.e., black under visible light) but contrasting behaviors under NIR imaging. Unlike previous work focused on conductive yarns or surface applied fiducials, this research evaluates yarns based on their intrinsic optical properties. This expands material options for embedding markers without altering textile aesthetics or requiring electrical functionality.

Embedding Data in Textile Weave Structures Using NIR-Responsive Yarn Combinations

- A novel method is proposed where data is embedded within weave structures by selecting yarns that differ in NIR reflectance and absorption. This approach avoids the use of external coatings, RFID tags, or printed elements, offering a durable, structure-integrated alternative for long-term data retention. It addresses the underexplored area of structural NIR marker embedding highlighted in studies such as Dogan et al. (2022) and Pouta et al. (2024).
- [MOU1]Weave structure - maybe that should be clearer in the title of this contribution?

Layered testing of yarn interactions under controlled light conditions

- The study introduces a four-stage experimental process that includes testing single yarns, two-layer combinations, and complex three-layer weaves. This multi-stage method provides a structured way to evaluate material behavior and optimize yarn positioning for marker contrast—an approach not documented in earlier textile-integrated AR or DPP-related marker systems.

Contribution to DPP-compliant textile traceability systems

- By embedding machine-readable identifiers at the textile structure level using ‘ordinary’ fibres and yarns, this method supports the development of reliable, passive data carriers aligned with the EU’s Digital Product Passport initiative. In contrast to printed QR codes or embedded RFID, which are vulnerable to wear or detachment, this woven solution is compatible with industrial sorting systems using NIR imaging and offers resilience during use, washing, and recycling.

2. LITERATURE REVIEW

To address the challenges of embedding invisible data in textiles and explore opportunities to overcome them, this literature review examines how machine-readable markers can be integrated into woven fabrics through structural, material, and optical strategies. It begins with research on e-textiles that leverage weave construction and yarn functionality to support interaction without external components. Studies on conductive yarns and layered weaves demonstrate how digital features can be embedded during fabric production. The review then explores how augmented reality markers and fiducial codes can be structurally incorporated into garments rather than applied to the surface. It also examines how near-infrared imaging can be used to detect hidden markers, depending on fiber type, weave structure, and dye properties. Finally, it addresses the technical and environmental factors that influence code readability, and how materials like polyester, cotton, and wool behave under NIR light. Together, these studies form the foundation for designing woven textiles capable of carrying invisible, machine-readable information.

2.1 Landscape of Woven e-Textiles in HCI

Pouta and Mikkonen (2022) survey of woven e-textiles in HCI consolidates two decades of work on loom-based interactivity, charting how weave structures, yarn choices and fabrication constraints translate into sensing, actuation and data-storage capabilities. By organising prior studies along the axes of mechanical patterning (plain, double-weave, jacquard), material functionality (conductive, thermochromic, shape-memory) and interaction purpose (touch input, visual feedback, on-fabric logic), the review exposes a clear design space in which textile behaviour can be “programmed” structurally rather than by attaching rigid electronics.

This framework is directly useful to the present project: it confirms that multi-layer weaving is an established route for embedding digital functions, highlights proven strategies for keeping the interactive layer hidden beneath an aesthetic façade, and most importantly, points out that optical encoding inside the cloth is still underexplored. The authors’ call for deeper, material-driven experimentation with jacquard looms therefore supports our decision to investigate near-infrared readable markers woven wholly from standard black yarns, positioning the study as a logical extension of and contribution to the structural e-textile research landscape articulated in their review.

2.2 Conductive Yarns and Touch-Responsive Textiles

When thinking about markers or codes that can carry hidden data, conductive yarns are often the first to come to mind. This is because they allow fabrics to transmit information and support tactile interaction, and they have been extensively explored in human–computer interaction (HCI). Textile-integrated markers enable garments and soft materials to support digital functionality while preserving their aesthetic and tactile qualities. Among the techniques examined in HCI, conductive yarns stand out because they can incorporate sensing, feedback, or logic functions directly at the yarn level.

Project Jacquard, led by Poupyrev et al. (2016), demonstrated the feasibility of weaving highly conductive yarns at industrial scale using standard production looms. The resulting capacitive-touch textiles embed gesture-responsive functionality without visible modifications, confirming that multi-layer weave structures can invisibly host interactive functionality (Figure 2).

Figure 2. From Left to Right. a) Project Jacquard: Interactive digital textiles at scale, b) Textile structure is similar to that of multitouch ca- pacitive panels used in tablets and mobile phones. Poupyrev, I., et al. (2016).

Ebb, developed by Devendorf et al. (2016), used conductive threads coated with thermochromic pigment to generate slow, ambient color changes when stimulated. Described as "ghostly and intimate," this work illustrates how yarn-level material responses can encode information without visible electronics (Figure 3).
Building on this foundation, Adapting Double Weaving and Yarn Plying Techniques for Smart Textiles by Devendorf et al. (2019) explored integrating actuation and sensing elements within the weave itself, focusing on crafting textiles that respond to touch. Their study demonstrated how weaving structures, such as partial double weaves and layered pockets, can hide electronics while maintaining textile properties (Devendorf et al. 2019)
Devendorf et al. (2020) showed that traditional weaving isn't just for texture or decoration but can itself become a programmable system. Over a six-week residency they worked hand-in-hand with a master weaver to embed logic- and response-like behaviors directly into the fabric's structure—no added electronics needed. By tuning layer sequences, yarn interlacing, and weave density, they programmed dynamic, interactive functions into soft interfaces.

This material-driven exploration not only preserved textile hand and durability but also demonstrated how artisanal craft skills can fuel high-tech innovation in digital systems.

Beyond industrial and computational textile innovations, craft-based techniques have also been explored to integrate digital interactivity into textiles. Crafted Logic, developed by Posch et al. (2016), examined how handwoven textiles could function as computational logic gates, demonstrating the potential for fabric-based digital processing and soft interfaces (Figure 4).

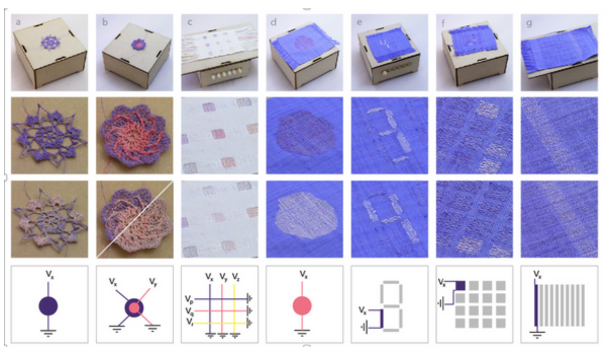


Figure 3. Example swatches from Ebb by Devendorf et al. (2016), illustrating variations in stitch density, multicolour crochet, woven colour-mixing patterns, graphic motifs, seven-segment displays, grids and stripes — included here as prior work, not as artefacts from the present study.

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The reviewed projects demonstrate that textile interactivity can be achieved through the structure and materiality of the fabric itself. Conductive yarns can be integrated into standard weaving processes to enable touch sensitivity, color change, and even logical computation without relying on external electronic components.

Multi-layer weaving and precise yarn placement allow complex behaviors to be embedded directly into soft materials while maintaining their tactile and visual qualities.

These examples show that the fabric's architecture can carry functional information, opening a broader design space for programmable textiles. However, the focus in these studies remains on electronic interaction and visible change. The potential of structural textile design for embedding invisible, machine-readable data, particularly through optical contrast, remains insufficiently explored.

This points to an opportunity to extend structural strategies from interactivity to identification and traceability using yarns selected for their optical properties.

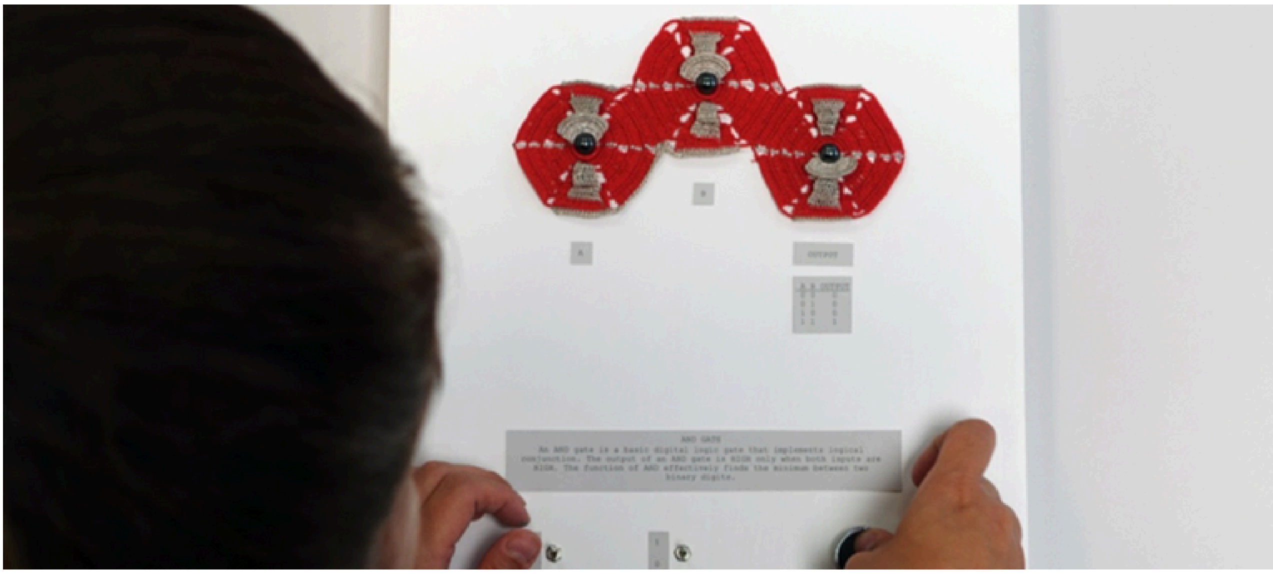


Figure 4. Interacting with the crochet AND gate: inputs A and B are set via switches, computation is triggered by a button, and outputs are displayed through crochet elements. Physical movement reveals the digital logic process. (Posch et al. 2016).

2.3 Multi-Layer Weaving for Embedded Functional Markers

While conductive yarns demonstrate how digital functionality can be introduced into textiles, they often remain visible or affect the fabric's surface. To address this, smart textiles offer the possibility of embedding machine-readable functions directly into the fabric structure using multi-layer weaving techniques. In the study by Pouta et al. (2024), double-faced and compound weaves were applied to organize different yarn types into separate layers.

This allowed conductive or sensor elements to be embedded in internal layers while preserving the outer fabric's flexibility, tactile quality, and visual aesthetics. Such structural separation enables the integration of functional systems without altering the garment's surface or requiring external tags (see Figure 5).

This approach is especially relevant for the current research, as it demonstrates how multi-layer weaving can conceal embedded information within textiles, without compromising the fabric's appearance. It supports the idea that machine-readable data—such as optical markers—can be integrated invisibly within a woven structure.

This expands the possibilities for creating textile-embedded codes that remain undetectable to the user, yet accessible through appropriate scanning systems. It also strengthens the case for working with jacquard looms to manipulate structure for data encoding rather than surface decoration.

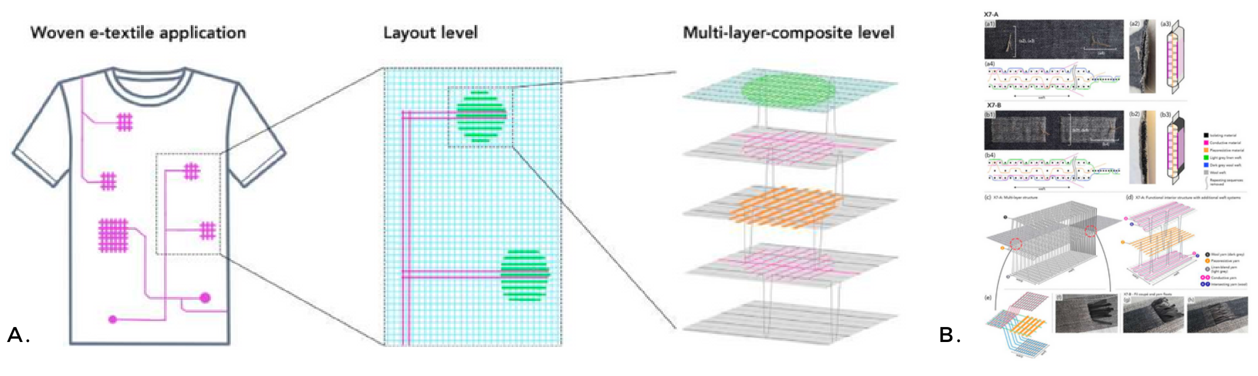


Figure 5. From left to right: a) Higher to lower levels of analysis: the textile, location-oriented composition, and layer-to-layer weave layout b) Exploration 7's samples for functional elements. (Pouta et al., 2024).

2.4 AR Markers: Structural Integration of Machine-Readable Codes

Previous work on conductive yarns and multi-layer weaving has shown how digital functions can be embedded into textiles, either on the surface or within internal layers. These methods have mainly focused on enabling touch-based interaction or embedding functions out of sight.

In comparison, augmented reality (AR) marker approaches use visible patterns in the textile to enable machine-readable recognition. AR is valuable for this research because it demonstrates how visible markers can be integrated into garments to allow users to access digital content through camera-based systems, illustrating how textiles can serve as interactive media.
Menon et al. (2023) demonstrated that AR markers can be embedded using plain, twill, and satin weaves with varied yarn colors. These woven markers were consistently detectable by AR systems, even when visual irregularities were present (see Figure 6).

The study confirmed that functional encoding is possible directly through textile construction, without relying on surface prints or attachments.

The project Clothing Integrated Augmented Reality Markers by Häkkilä et al. (2017) explored how augmented reality markers could be integrated into garments through printed and embroidered techniques.

The research demonstrated that such markers could enable users to view digital content overlaid onto physical clothing, using camera-based AR systems. These markers, while visible to the human eye, served as computer-readable elements to trigger content, interactions, or personal expression.

The study highlighted that integrating AR markers into garments allows the clothing to become an interactive medium, extending beyond its physical form. .

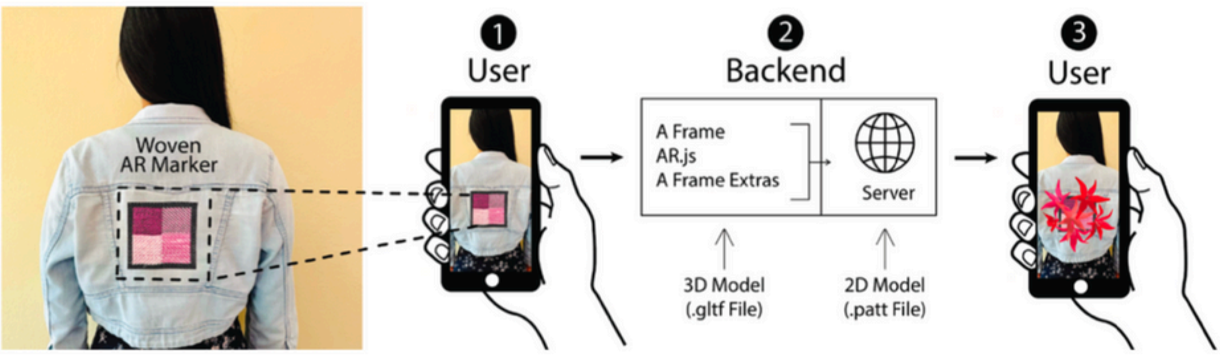


Figure 6. User interaction workflow: (1) scanning the woven marker, (2) invisible backend communication, and (3) display of the AR interface on the user's phone (Menon et al., 2021).

It also acknowledged the aesthetic and practical considerations in choosing between printed and embroidered methods, noting differences in flexibility, texture, and visual integration.

By experimenting with marker size, placement, and material constraints, the project offered early insights into wearable AR applications, emphasizing the potential for clothing to support digital interaction in a personalized and user-friendly manner (see Figure 7).

Together, these studies provide key insights for textile-integrated AR systems. Menon et al. demonstrate how woven structure alone can encode machine-readable information, while Häkkilä et al. show how material and design choices shape interaction quality and user experience.
However, both focus on visible markers and conventional surface treatments.

The potential of structurally embedded, invisible woven markers, detectable only through specific imaging systems, remains largely unexplored. This opens a gap for future research into embedded, optically encoded weave structures for unobtrusive integration into garments.

Another study by Roinesalo et al. (2016), Clothes-Integrated Visual Markers as Self-Expression Tools, explored the use of laser-cut and embedded AR markers in garments.
This research demonstrated how such markers can be used not only for identification or tracking but also for enabling personalized digital interaction—such as triggering animations or communication features via AR interfaces.
The study positioned visual markers as a medium for self-expression, expanding the role of clothing from passive aesthetic object to active digital interface (see Figure 8).

Figure 7. Using attachable visual markers for mobile AR interactions integrated into clothing (Häkkilä et al., 2021).

These studies collectively demonstrate the potential of AR markers to transform textiles into interactive and information-rich surfaces. They confirm that machine-readable patterns can be effectively integrated into garments using weaving, embroidery, or printing techniques.

These approaches emphasize the importance of contrast, pattern clarity, and material selection to ensure reliable detection in camera-based AR systems. While the focus remains on visible markers, the research highlights the feasibility of integrating digital identifiers directly into textile structures.

However, the explored methods rely on visual prominence, leaving the opportunity open for developing structurally embedded markers that remain invisible to the human eye but detectable through specific imaging technologies. This gap offers a promising direction for future textile research aimed at unobtrusive identification and interaction.

Figure 8. From Left to Right: a) Demo concept illustrating garment-embedded markers and the corresponding mobile AR interface, b) Reading a visual marker integrated into a garment. (Roinesalo et al., 2016).

2.5 Material-Embedded Fiducial and Invisible Markers

Building on the study of visible and structurally embedded AR markers, research into material-embedded fiducial and invisible markers expands the focus to embedding machine-readable information directly into textile materials using visual encoding and various fabrication techniques.

These markers may be partially visible or hidden from the human eye and are designed to be detected through camera-based scanning methods, including near-infrared imaging. Such approaches integrate data within textile structures using methods such as knitting, digital fabrication, or 3D printing, often without relying on external tags.

This research opens opportunities to apply and test similar encoding techniques in woven textiles while maintaining their aesthetic and functional properties.

The Threads of Traceability study by Haberfellner et al. (2024) demonstrates that machine-readable information can be embedded directly into textiles using visual encoding techniques. By knitting digital signatures into the textile design and applying a CRC-16 checksum system, the study achieves accurate detection and decoding of data through camera-based scanning. This offers a promising approach for linking physical garments to digital content such as sustainability and production transparency.

A key strength of the study lies in its ability to integrate data into the textile structure in a way that is visually coherent and requires no added hardware, making it compatible with existing manufacturing processes and relevant to Digital Product Passport applications. However, the technique relies on visible color contrast, making it sensitive to lighting conditions and surface wear. It is also limited to knitting, whereas the present project focuses on woven structures.

Moreover, because the markers are fully visible, they may not suit use cases where discretion or visual neutrality is required. The study provides a strong conceptual foundation for textile-based data encoding, but your research advances this by embedding machine-readable markers invisibly into multi-layer woven textiles using near-infrared detection, enabling a more discreet and structurally integrated solution. (Figure 9 and 10).

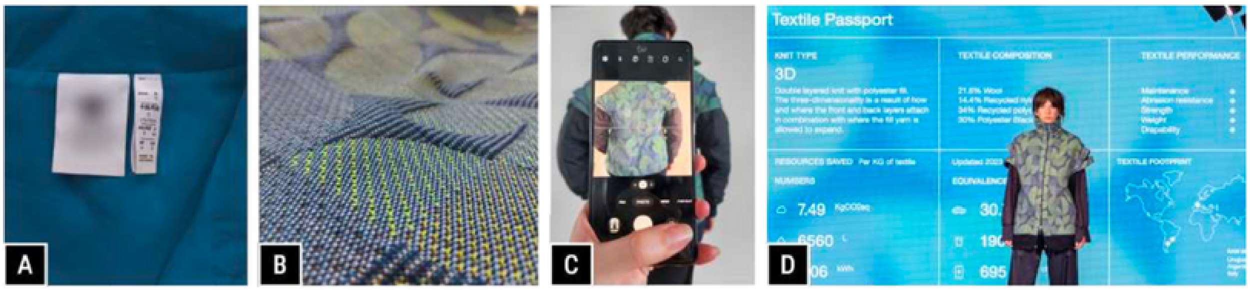


Figure 9. Threads of Traceability: (A) Traditional wash tag; (B) textile as a unique marker; (C–D) identification of the garment via integrated textile ID (Haberfellner et al., 2023).

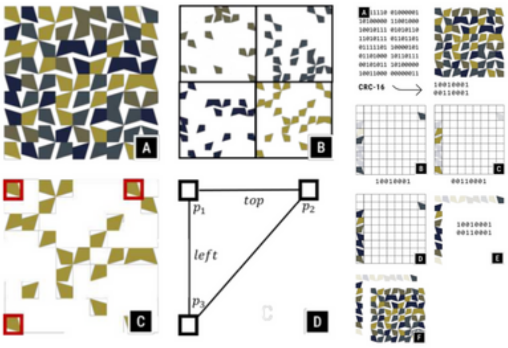


Figure 10. From Left to Right a) Marker detection process: (A) initial marker; (B) split into single-color markers; (C) anchor shapes identified; (D) parameters verified to confirm detection (Haberfellner et al., 2023). b) Marker encoding process using the CRC-16 algorithm: (A) checksum generation; (B–D) checksum embedded in marker matrix; (E–F) robust detection and decoding enabled by color and checksum data (Haberfellner et al., 2023).

Fiducial markers—computer-readable patterns used for object recognition and tracking—have been integrated into textiles to support wearable computing and interactive fashion. Chic-Marker: Fashionably Fusing Fiducial Markers into Apparel and Accessories, presented by Liang et al. (2024), introduced a method for embedding fiducial markers, such as AprilTags, into fashion garments.

By leveraging computational tools and digital fabrication, the researchers created functional garments that blend fiducial tracking with aesthetic appeal, allowing real-time motion tracking and object identification (Figure 11).

Material-embedded tags are an integral component of Human-Computer Interaction (HCI), facilitating object identification, tracking, and augmentation of physical interfaces.

Traditional fiducial markers, such as QR codes and barcodes, are widely used but are often visually obtrusive (Costanza et al. 2009). Recent research has aimed to develop markers that integrate into materials using fabrication techniques such as 3D printing, infrared imaging, and textile weaving. Material-embedded tags can be categorized based on visibility.

Figure 11. Red Herring poncho featuring a Pied-de-poule pattern integrated with AprilTag36h10 markers for posture tracking and garment identification (Liang et al., 2023).

Visible markers include printed QR codes and fiducial markers that maintain human and machine readability. Invisible markers remain undetectable to the human eye while being readable using specific imaging techniques.

CyberCode introduced a 2D-barcode system for augmented reality applications, providing a cost-effective solution for linking physical and digital environments (Rekimoto et al., 2000).

The d-touch system advanced this by allowing users to create aesthetically customizable fiducial markers for interactive applications (Costanza et al., 2009). Hand-crafted visual markers have also been explored, where designers manually create base designs that are algorithmically recombined into large-scale interactive surfaces, such as wallpapers with embedded markers (Preston et al., 2017).

InfraredTags embeds AR markers and barcodes inside 3D-printed objects using an infrared-transmitting filament. The markers remain undetectable to the human eye but are visible to infrared cameras. The system achieves this by leaving air gaps inside the printed structure, which can be detected due to their different infrared transparency.

The study demonstrates its application in object tracking, augmented reality (AR) interactions, and metadata embedding. A key advantage of this method is its low-cost fabrication using standard fused deposition modeling (FDM) 3D printers and a compact infrared imaging module for detection (Dogan et al., 2022) (Figure 12).

BrightMarker introduces near-infrared (NIR) fluorescent markers that remain undetectable under visible light but appear with high contrast when viewed through an NIR camera with a matching optical filter. This method enables robust real-time tracking, even in motion, overcoming previous limitations of low resolution and motion blur.

BrightMarker's fluorescent filament shifts the wavelength of incident light, allowing high-contrast detection while being embedded in colorful 3D-printed objects. Applications include motion capture wearables, object tracking on conveyor belts, and privacy-preserving night vision (Dogan et al., 2023) (Figure 13).

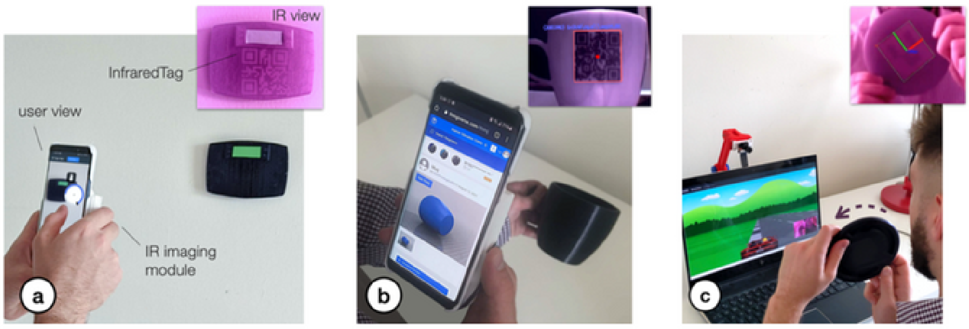


Figure 12. InfraredTags embedded in 3D-printed objects: (a) device identification and control in AR; (b) embedding metadata like 3D model URLs; (c) passive object tracking for tangible interaction (Dogan et al., 2023).

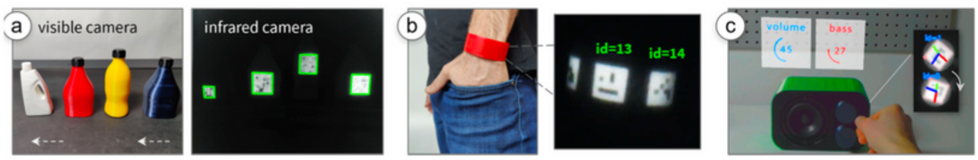


Figure 13. BrightMarkers embedded with NIR-fluorescent filament: (a) high-contrast tracking with NIR cameras; (b) custom wearables for motion tracking; (c) enhancing physical controls for mixed reality input (Dogan et al., 2023).

Hidden Interfaces explores a different approach by integrating passive-matrix OLED (PMOLED) displays into materials such as textiles, wood, and mirrors. This method enables digital interfaces to dynamically appear and disappear, blending interactivity into everyday materials without compromising their original aesthetic (Olwal et al., 2022) (Figure 14).

Beyond material-based integration, computer vision markers enable tangible interactions using camera-based detection. Research has explored fiducial markers embedded into different materials for interactive applications, reducing reliance on electronic circuits while enabling computer vision-based detection to track interactions across physical surfaces (Gyory et al.,2023).

These studies demonstrate that machine-readable information can be embedded within materials in a way that remains invisible to the human eye but detectable using near-infrared imaging (NIR). While much of the existing work focuses on rigid, 3D-printed forms, the underlying principles of structural integration and optical detection are highly relevant to textile applications.

For the present research, these approaches confirm the potential to embed data within woven textileswithout altering their surface appearance. They provide a foundation for developing textile-embedded markers that are visually undetectable yet accessible through appropriate scanning technologies.

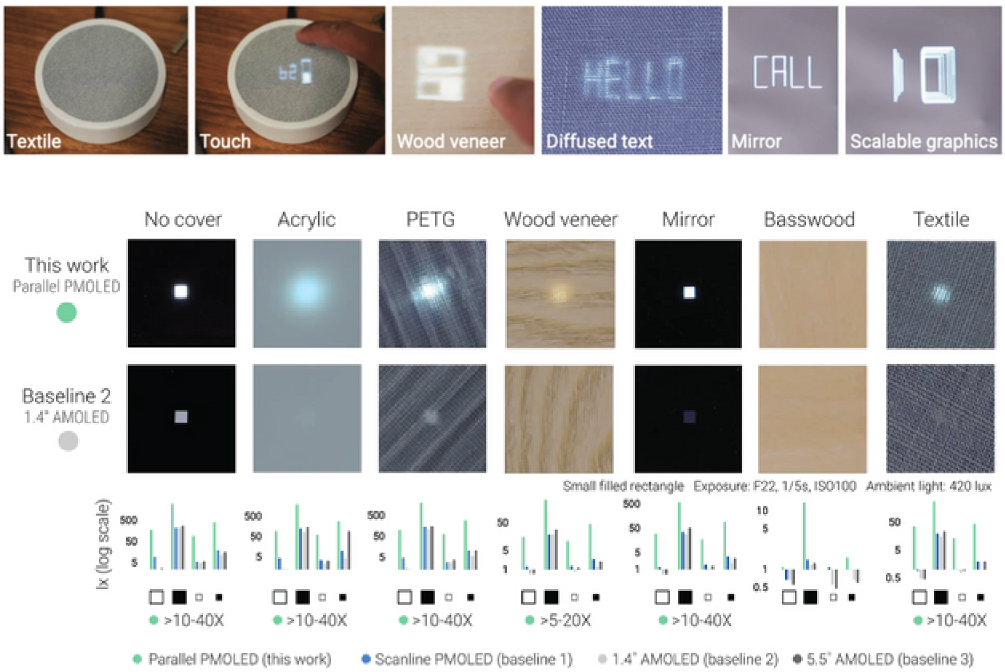


Figure 14. Concept sketches of hidden interfaces revealed through interaction: (left to right) touch-activated volume control, gesture-revealed dishwasher display, and proximity-triggered mirror temperature display; includes examples of displays under textiles, veneer, and mirrors using high-brightness visuals on low-cost matrix displays (Olwal et al., 2023).

2.6 Near-Infrared Applications and Integrated Technologies in Textile Identification and Tracking

The findings from BrightMarker show that near-infrared fluorescent markers, invisible under normal light, provide high-contrast detection with NIR cameras, enabling reliable real-time tracking even during motion (Dogan et al., 2023). This demonstrates the potential to apply similar techniques in this research for embedding and reading markers in woven textiles, which is crucial for maintaining the fabric's appearance while ensuring reliable detection.

Furthermore, advancements in Near-Infrared (NIR) spectroscopy have significantly improved textile applications such as fiber identification, material classification, and quality control. NIR spectroscopy allows non-destructive, rapid, and accurate differentiation of various fiber types, including natural, synthetic, and blended materials (Cleve et al., 2000).

This ability is essential for sorting and recycling processes that maintain textile quality and promote sustainability (Paz et al., 2024). Understanding these advancements supports the development of effective, machine-readable markers integrated within textiles.
Recent studies have demonstrated the effectiveness of NIR spectroscopy in distinguishing between different fibers.

For instance, machine learning models combined with spectral data have been utilized to enhance material classification accuracy in complex fiber blends, such as cotton-polyester mixtures (Zhou et al., 2019). Additionally, hyperspectral imaging has been applied to improve textile analysis, enabling real-time monitoring of fiber composition and textilestructure (Riba et al., 2022).

Automated textile sorting systems now utilize NIR-based detection methods to facilitate fiber separation, optimizing material recovery and reducing waste in textile recycling (Cura et al., 2021) (Figure 15).

However, certain challenges persist in the application of NIR spectroscopy within the textile industry. One issue involves textiles dyed with carbon black, a pigment that absorbs a significant amount of light in the NIR spectrum. This absorption can obscure the spectral data necessary for accurate fiber identification.

For example, black denim garments dyed with carbon black present difficulties in NIR analysis due to their high absorbance, which can mask the unique spectral signatures of the underlying fibers (Sagitto, 2023). To mitigate this, scanning the interior side of such textiles, where the effect of the dye is less pronounced, has been suggested as a potential solution.

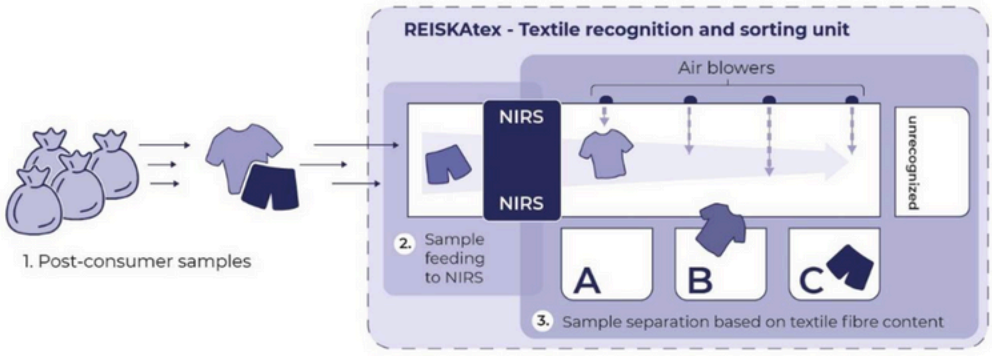


Figure 15. The REISKAtex recognition and sorting lab pilot using near-infrared spectroscopy for automated textile recycling (Cura et al., 2023).

For example, black denim garments dyed with carbon black present difficulties in NIR analysis due to their high absorbance, which can mask the unique spectral signatures of the underlying fibers (Sagitto, 2023). To mitigate this, scanning the interior side of such textiles, where the effect of the dye is less pronounced, has been suggested as a potential solution.

The concept of Near-Infrared (NIR) compliance in tactical clothing is also discussed. NIR refers to light just beyond the visible spectrum, with wavelengths ranging from 780 nm to 2,500 nm. Achieving NIR compliance involves selecting suitable textiles, rather than relying solely on camouflage patterns. The role of thermal signatures in combat zones and the significance of effective camouflage in various detection methods are further explored (UF PRO, 2021). NIR-compliant clothing is especially crucial in military settings, as these garments are designed to reduce visibility to NIR imaging devices, thereby improving camouflage effectiveness.

This is achieved by carefully selecting materials and treatments that exhibit low reflectance in the NIR spectrum, aligning the clothing's spectral properties with the surrounding environment (Hossain, 2023).

Furthermore, the integration of Radio Frequency Identification (RFID) tags with QR codes into garments represents a significant technological advancement in textile traceability and recycling. For instance, the fashion brand Hessnatur has piloted the use of in-garment RFID tags combined with QR codes to provide detailed product information, thereby facilitating recycling processes and promoting circularity within the textile industry (Trimco Group, 2024).

Additional research has explored fluorescent-based markers for textile tracking. The BrightMarker system, for example, integrates fluorescent materials into textiles, allowing NIR cameras to track embedded markers even in motion (Dogan et al., 2023).

Similarly, InfraredTags use low-cost NIR imaging and 3D-printed markers to encode machine-readable data within objects, demonstrating an application of NIR-based textile markers for authentication and augmented reality (Dogan et al., 2022). These approaches suggest new possibilities for textile tracking and authentication.
While NIR applications in textiles have advanced, gaps remain in achieving scalable fiber detection, accurate classification of blends, and efficient spectral data processing for industrial use.

2.7 The Code Readability: Technical and Environmental Considerations

Ensuring the readability of markers or codes is essential for reliable data retrieval, especially when embedded into woven textiles to support efficient traceability of invisible markers. For such systems to function effectively, the codes must remain scannable across different stages of a product's lifecycle, including production, reuse, and recycling.

For instance, several technical and environmental factors influence QR code readability. Tarjan et al. (2014) showed that increasing the amount of encoded data reduces the spacing between QR modules, making the code more crowded and less readable, particularly when printed at smaller sizes. Higher error correction levels improve resistance to damage but increase the code's complexity, which can negatively affect scanning performance if not balanced correctly.

In textile integration, where surface uniformity and lighting vary, readability challenges are amplified. Environmental conditions such as poor lighting, glare from reflective fibers, and inconsistent contrast can prevent scanners from correctly identifying the code. These aspects are especially critical in real-world conditions where textile products are used, washed, or exposed to variable surroundings.

Liu et al. (2021) further explored how printing quality impacts readability. They found that dot gain during printing can cause white modules to appear darker, leading to scanner errors. By modifying the microstructure of QR codes, specifically reducing the size of the printed dots, they showed improvements in readability without compromising visual aesthetics.
Environmental factors such as lighting conditions, reflections, and temperature fluctuations also significantly affect scanning performance. Glare from reflective surfaces or insufficient lighting can hinder a scanner's ability to read the code, making environmental management critical for ensuring consistent and accurate performance (Free Barcode, n.d.).
Recent work by Sancar (2025) highlights the importance of image quality in scannability. QR codes that suffer from low resolution, blur, or contrast loss often fail when processed by conventional scanners.

However, deep learning-based super-resolution models, particularly EDSR and VDSR, have proven effective in reconstructing such unreadable QR codes.
achieving detection rates above 90% even under significant visual degradation. This reinforces the necessity of preserving visual clarity in embedded QR codes, whether through textile structure, material contrast, or post-production enhancement (Figure 16).

Industry guidelines also stress the need for precision in QR code design. Cognex (2023) and QR Code Kit (2025) recommend using high-resolution graphics, maintaining proper scaling, avoiding lossy compression, and ensuring high contrast between the code and its background.

A clear margin, or "quiet zone," around the code is also critical for optimal scanning.

In summary, for QR codes embedded in textiles to fulfill their role in DPP systems, maintaining readability under varied physical and digital conditions is essential. This involves addressing technical parameters, material behavior, printing fidelity, and environmental exposure to ensure reliable and long-term data access.

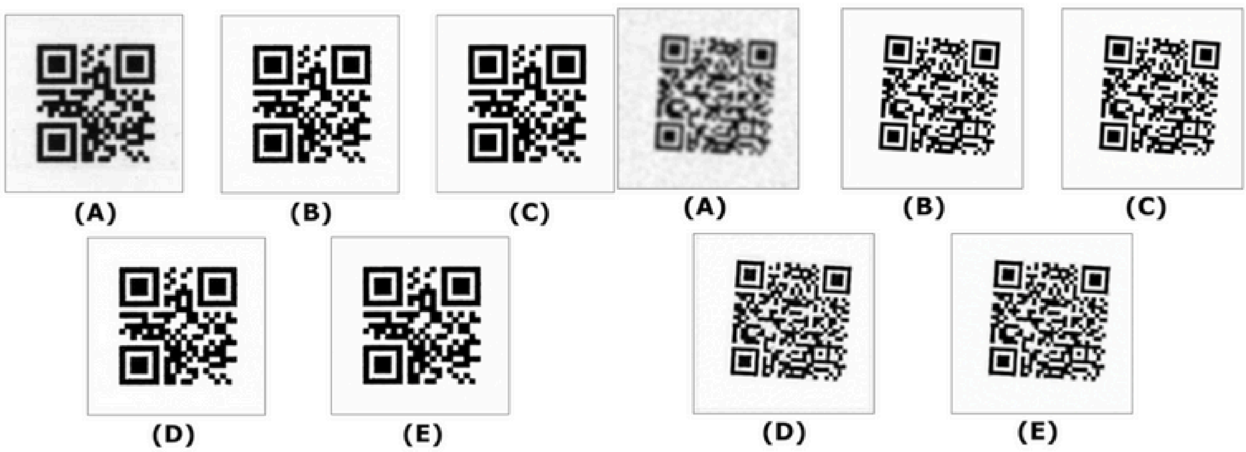


Figure 16. Examples of trained models enhancing scanned QR code images for improved readability (Sancar, 2023).

2.8 Near-Infrared Absorption and Reflection Properties of Polyester, Cotton, and Wool Textiles

The findings from BrightMarker demonstrate how fluorescent filaments can shift the wavelength of incident light to create high-contrast markers that are invisible under normal light but detectable with near-infrared cameras (Dogan et al., 2023).

This contrast mechanism, achieved by using different filament materials, highlights the potential for applying similar approaches to woven textiles, where yarns with varying compositions and treatments could produce distinct NIR responses for reliable marker detection.

Polyester (PET) exhibits strong NIR absorption due to its ester (C=O) functional groups, with absorption peaks between 1100–1680 nm (Becker et al., 2024). Absorption intensity is influenced by dye concentration, fiber density, and surface treatments. High concentrations of NIR-absorbing disperse dyes, such as azo and anthraquinone-based chromophores, enhance absorption and decrease reflectance (El-Shishtawy et al., 2007; Kaur et al., 2024). Fiber structure also plays a role, as tightly woven polyester textiles limit light penetration, increasing absorption (Becker et al., 2024).

Surface coatings further modify polyester's NIR properties. Metal oxide coatings (TiO_2, Cu-based films) and plasma treatments enhance absorption by altering reflectance properties (Lu et al.,, 2024; Zhou et al., 2019). In contrast, high-reflectance pigment finishes or metallic coatings increase reflectance, reducing heat absorption (Almetwally et al., 2024).

Dyeing processes impact reflectance, as some dyes maintain high NIR reflectance, allowing polyester fabrics to remain visible under infrared detection systems (Becker et al., 2024).

Cotton and NIR Absorption and Reflection

Cotton, composed of cellulose, shows moderate NIR absorption, primarily influenced by its hydroxyl (-OH) groups (Quintero Balbas et al., 2022). The application of natural and reactive dyes with strong chromophores increases absorption by modifying fiber interactions with infrared radiation (Hossain, 2023; Kaur et al., 2024). Cotton's hydrophilic nature enhances absorption when moisture is present, shifting NIR spectral properties (Quintero Balbas et al., 2022).

Cotton typically exhibits higher NIR reflectance than polyester, but dyeing and surface treatments alter this property. Light-colored cotton textiles reflect more NIR radiation, while NIR-absorbing pigments and coatings, such as carbon-based dyes and TiO_2 films, reduce reflectance (Hossain, 2023). Cotton-polyester blends modify reflectance, with polyester content increasing absorption and reducing visibility under infrared scanning (Quintero Balbas et al., 2022).

Wool and NIR Absorption and Reflection

Wool's keratin structure, rich in amide bonds, results in strong NIR absorption, with key absorption bands attributed to peptide vibrations (Mattiello et al., 2022). Dyeing has a significant impact, as mordant and infrared-absorbing dyes enhance absorption and decrease reflectance, making wool less detectable under infrared scanning (Bruni et al., 2011). Wool's ability to retain moisture further increases NIR absorption, as water molecules interact with infrared wavelengths (Thiébaud & Kneubühl, 1983).

Reflectance in wool is lower than in cotton but varies based on fiber modifications and dyeing methods. Wool-polyester blends show altered reflectance, with polyester content increasing infrared reflectance, while wool-dominant blends enhance absorption (Bruni et al., 2011). Surface coatings and nano-treatments provide additional control over NIR absorption and reflection (World Intellectual Property Organization, 2009).

Dye chemistry plays a key role in shaping the near-infrared (NIR) absorption and reflection properties of textiles. Polyester exhibits strong absorption, particularly when treated with disperse dyes and metal oxide coatings, whereas cotton and wool demonstrate more variable absorption levels influenced by dye type, fiber morphology, and moisture retention.

The dyeing process further modifies reflectance, determining how textiles interact with NIR radiation and influencing their visibility under infrared detection systems.

2.9 RESEARCH GAPS IDENTIFIED

Most existing approaches to embedding data in textiles focus on surface-based methods, such as printing, embroidery, or attaching external labels. These are visible, often temporary, and do not use the full potential of woven structures. The idea that data can be structurally embedded, woven directly into the textile so it becomes part of the textile itself, has been largely overlooked. This gap is especially relevant when the data needs to remain invisible to the user but still machine readable.

Reading such structurally embedded data using near infrared (NIR) imaging is another area that remains underdeveloped. Although NIR is widely used for fiber classification and recycling, little work has been done to explore how it could detect patterns intentionally woven into textiles for identification or tracking. The relationship between textile variables such as fiber type, weave density, yarn treatments, and dye absorption and their impact on NIR visibility has not been systematically studied.

One key reason this remains unexplored is the complexity of aligning such encoding with existing production workflows. Industrial weaving is optimized for speed, efficiency, and visual outcomes, not for embedding machine readable information. Embedding codes without altering texture, color, or performance poses both technical and manufacturing challenges.

Furthermore, while fiducial markers and machine-readable tags have been successfully used in rigid or 3D-printed materials, their adaptation to flexible, stretchable textiles is still missing. These materials behave differently during use and under scanning conditions, especially when codes are hidden within layers or subjected to motion, wear, or distortion. There is a lack of research into how to make such embedded codes reliable and readable over time in real-world conditions.

Finally, while Digital Product Passport (DPP) initiatives require product-level traceability throughout a lifecycle, there is no solution yet that embeds data directly into the textile in a way that is scalable, durable, and compliant with automated scanning systems. Most current solutions rely on detachable elements or external carriers that can be lost or damaged.

This research addresses these gaps by exploring how invisible, structurally woven markers can be designed and detected using NIR imaging, without compromising the textile’s appearance or interfering with existing industrial weaving processes. It aims to demonstrate a method that makes identification permanent, discreet, and manufacturable at scale.

3. RESEARCH THROUGH DESIGN METHOD

RQ: How can invisible, machine-readable markers be embedded and retrieved in woven textiles to enable the traceability of product-specific data?

Sub-questions:

1. What yarn types and optical properties are suitable for embedding and retrieving machine-readable markers in woven textiles using near-infrared imaging?

2. What weaving methods can be applied to integrate machine-readable markers into woven textiles without affecting their visible appearance?

3. What technologies can be used to detect and interpret embedded machine-readable markers in woven textiles?

4. How do weave structures and yarn layering influence the visibility and retrieval of machine-readable markers under near-infrared imaging?

This research follows a Research through Design (RtD) methodology within a practice-based framework. The aim is to explore how invisible, machine-readable data can be embedded into and retrieved from woven textiles using near-infrared (NIR) imaging.

Knowledge is generated through making, testing, and iterating, allowing materials and structure to inform the direction of the research.

The process is organized into progressive stages, beginning with open-ended exploration and evolving toward controlled, repeatable tests. Parallel prototyping played a key role in the early phases: low-fidelity trials involved wrapping yarn and layering textiles to understand fundamental interactions between fiber types, weave densities, and NIR detection. These quick material studies helped establish baseline insights into light absorption, reflection, and concealment.

High-fidelity prototyping followed, using jacquard weaving to produce functional textile samples. These woven trials were designed to test how yarn type, layering strategy, and weave geometry affect the legibility of embedded markers under NIR imaging. Each iteration was informed by observational feedback, imaging results, and structural analysis, allowing the design variables to be refined over time.

This RtD approach supports a deeper understanding of how textile materials can serve as both visual and data-bearing media, and how their structural properties can be manipulated to embed invisible information while maintaining functional and aesthetic integrity.

All samples were technically characterised experiments were conducted under consistent laboratory conditions.

Lighting and imaging setups were standardized, and parameters such as yarn composition, thickness, and density (yarns/cm) were documented. The yarns were evaluated based on their response to artificial light (AL) and NIR, and were classified into four visibility categories:

Transparent: NIR light goes through the yarn easily. These yarns look bright in NIR images because they don’t block the light.

Translucent: Some NIR light goes through the yarn, but not clearly. The yarn lets light through in a soft or blurry way.

Opaque White: The yarn does not let light through but sends it back toward the camera. These yarns look bright white in NIR images.

Opaque Black: The yarn blocks or absorbs the NIR light. These yarns look dark or black in NIR images.

These optical classifications served as a framework for selecting yarns and constructing woven samples throughout the research.

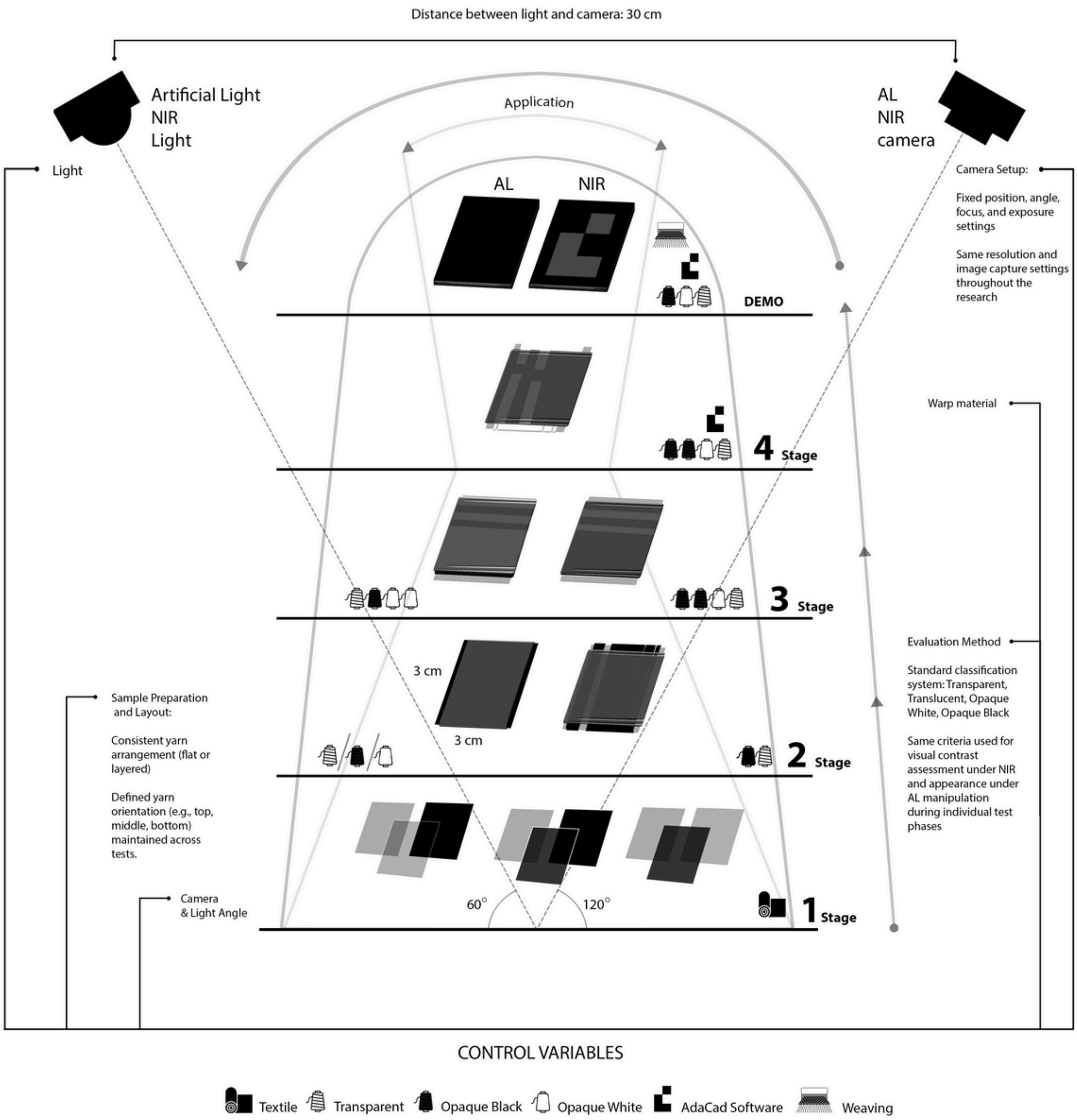


Figure 17.

The visual (Figure 17) presents a complete overview of the experimental framework used in the research. It combines the four research stages and the Demo, the technical test setup, the control variables, and the flow of material testing. It shows the progression from initial exploratory analysis to final demonstrator development.

The setup for data collection is clearly indicated: the light source is positioned at a 60˚ angle, and the NIR camera is positioned at a 120˚ angle relative to the sample surface. These angles were kept constant during all measurements to ensure consistency in lighting and imaging conditions.

The visual also defines which samples were tested in each stage and what variables were fixed or varied, including how the middle layer served as a control point in comparative evaluations.

Crucially, the diagram shows a loop from the final demonstrator back to the first stage, emphasizing that the process is iterative. This feedback loop highlights that the demonstrator serves not as an endpoint, but as a foundation for future development—allowing the research to return to Stage 1 with new materials, structures, or settings to continue exploration and refinement.

Stage 1 – Exploratory Research
The first stage involved open-ended exploratory testing. Using low-fidelity textile samples, the researcher examined how different yarn types and simple weave constructions responded to NIR and artificial light exposure. This phase helped define visibility criteria and guided the development of a classification system based on NIR optical behavior. It also served to identify useful variables for structured testing, such as yarn thickness, layering, and density.

Stage 2 – Intermediate Testing: Individual Yarns
The second stage focused on the individual testing of 13 black yarns made from polyester, cotton, and wool. Each yarn was evaluated under both artificial light and NIR exposure. Key material parameters—including fiber type, thickness, and density—were recorded.
The primary objective was to assign each yarn to one of the four visibility categories and determine its suitability for use in layered structures. The outcomes of this stage informed the selection of yarn combinations for the next level of testing.

Stage 2 – Layered Combinations: Two-Layer Structures
This stage introduced structured layering to test yarn interaction. Four two-layer woven samples were developed using different combinations of selected yarns. Each sample consisted of a top and a bottom layer, arranged to test how optical contrast could be achieved when materials with distinct NIR behaviors were layered. This stage assessed whether specific material pairings could generate a visible pattern detectable only under NIR imaging.

Stage 3 – Intermediate Testing: Three-Layer Structures
The third stage expanded to three-layer woven structures. Two test samples were developed with a top, middle, and bottom layer. Each layer was constructed using yarns pre-classified in earlier stages. This configuration was used to study the influence of material placement and interaction within the structure, particularly how a middle layer behaves when enclosed between two layers with differing NIR responses.

Stage 3 – Multi-Layer Interwoven Structures

In this stage, two advanced samples were woven with interwoven multi-layer constructions. These designs introduced two different yarns into the middle layer, combined within a single structure and framed by top and bottom layers. This stage simulated more complex layout patterns and explored how combinations of opaque, translucent, and transparent yarns could encode invisible markers in a textile surface.

Stage 4 – The Demo Prototype: Woven Sample with Embedded Data

This stage focused on validating the final concept through a wrapped thread sample and contrast evaluation using NIR imaging. Based on the results, a weaving file was developed in AdaCAD for the demo prototype. The final woven sample was produced and analyzed, showcasing three variations of embedded data that become visible under NIR light while remaining hidden under normal conditions.

4. EXPERIMENTAL SETUP

To evaluate material responses under near-infrared (NIR) light, a test setup was developed using a USB camera module and a dedicated NIR light source. The camera, equipped with an OV9732 sensor, records at 1280×720 pixels with a 72° field of view. It includes an IR-CUT filter, enabling switching between visible and infrared modes. This functionality allows the system to detect differences in optical behavior that are not visible to the human eye.

An 850 nm infrared illuminator (NEWZEROL) was used to provide stable and consistent near-infrared lighting. The 850 nm wavelength falls within the NIR spectrum (760–1500 nm), which lies just beyond the visible range. NIR light has a longer wavelength than visible light, allowing it to interact with materials in a way that makes certain surfaces appear more or less transparent.

Depending on the fiber composition, thickness, and dye treatment, materials such as cotton or polyester can reflect, absorb, or transmit NIR radiation differently (Quintero Balbas et al., 2022; Paz & Sousa, 2024).

To ensure consistent measurements, the camera was positioned at a 120° angle relative to the sample surface, and the light source was positioned at a 60° angle. The distance between the camera and the light source was fixed at 30 cm.

These parameters were kept constant throughout all tests to provide coherent lighting and observation conditions.

These variations in material behavior were captured by the NIR-sensitive camera, which recorded differences in brightness and transparency. Materials that strongly absorb NIR appeared darker, while those that transmit or reflect NIR appeared brighter. This selective visibility enabled detection of contrasts within multi-layered or visually uniform textiles. It was essential for identifying hidden structures or evaluating material performance under specific lighting conditions (Dogan et al., 2023) (Figure 18).

4.1 Stage 1 – Exploratory Research

The first stage of the research was exploratory and aimed to test whether contrast and visibility under near-infrared (NIR) light could be achieved using common textile materials. This initial phase focused on how black textiles made from different fiber types respond to NIR radiation, and whether clear optical contrast could be created by varying the material type, textile thickness, and layering. Black textiles were used to eliminate visible color differences under artificial light (AL), allowing the focus to remain on NIR-specific behavior.

To establish a baseline, three widely used fiber types—cotton, wool, and polyester—were selected, each in spun yarn form with 100% fiber content. Although many textiles are made from blended fibers, these pure materials were chosen to simplify the analysis and test whether standard yarns can already produce enough contrast to be reliably identified under NIR imaging. The goal was to classify each material based on its ability to transmit, reflect, or absorb NIR light when used in layered woven structures (Figure 18).

H_0: The visibility of black fabrics under NIR does not differ based on material type, thickness, or layering order.

H_1: The visibility of black fabrics under NIR varies depending on material type, thickness, and layering order.

Independent Variables
- Fabric material: polyester, cotton, wool
- Fabric weight: lightweight or medium-weight
- Layering order: top/bottom arrangement of different fabrics

Dependent Variable
- NIR visibility classification: transparent, translucent, opaque black, or opaque white

Control Variables
- Lighting angle and intensity (constant artificial and NIR light sources)
- Camera setup: fixed angle, focus, and distance
- Background: neutral, non-reflective surface
- Sample size and shape: consistent fabric squares

Method
Three fabric types were selected—cotton, polyester, and wool—and each was tested in two weights: thin and medium.

Polyester A:
A1 – lightweight (approx. 90 gsm)
A2 – medium-weight (approx. 170 gsm)
Wool B:
B1 – lightweight (approx. 165 gsm)
B2 – medium-weight (approx. 275 gsm)
Cotton C:
C1 – lightweight (approx. 100 gsm)
C2 – medium-weight (approx. 160 gsm)

Fabrics were sourced from commercial suppliers and were all black in color. Selected fabric combinations were manually layered, with different yarns placed above and below one another to observe interaction through physical stacking. Samples were assessed under both artificial light (AL) and near-infrared (NIR) using a fixed camera angle, lighting direction, and neutral background (Figure 18).

In addition to black fabrics, white versions of the same materials were also tested under the same conditions to assess whether their reflectivity could provide useful contrast under NIR. Although the tests were documented, they did not produce meaningful results (see Appendix 1A).

Based on the observed behavior, fabrics were classified into four categories:

- **Transparent:** NIR light passes through the fabric
- **Translucent:** NIR light is partially transmitted and scattered
- **Opaque White:** NIR is reflected from the surface of the fabric
- **Opaque Black:** NIR is absorbed or blocked by the fabric

Figure 18.

Additional Observation during the experiment

In this experiment, some black fabrics made from the same fiber composition (100% cotton, polyester, or wool) appeared differently under near-infrared (NIR) imaging. This suggests that NIR readability is influenced not only by fiber type but also by at least one additional factor.

This factor is suspected to be either the dye used to color the fabric black or a finishing treatment applied during production or recycling. While the fiber itself is known to affect NIR absorption and reflection due to its structure and density, the material's surface reflectance and spectral response can be further influenced by the dye chemistry.

For example, disperse dyes on polyester and vat dyes on cotton have been used to tailor NIR reflectance for camouflage applications, and studies show that even small changes in dye formulation can significantly impact reflectance properties (Degenstein et al., 2021).
Similarly, NIR transmission tests through dyed fabrics indicate that chemical differences between dyes can influence transmission levels, even when the base material is the same (Saleem et al., 2013).

However, in many cases, the exact dye formulations are proprietary or undisclosed be the supplier, limiting the ability to draw precise conclusions about their specific contribution to NIR behavior.

As a result, although both yarn composition and dye/finishing treatments are likely to affect NIR readability, the lack of accessible dye information about the latter introduces uncertainty in interpreting experimental outcomes.
Due to this combination of factors effecting NIR readings, the yarn variable relating to fiber type and (unknown) dye/finishing treatment of yarns will from here on be referred to as "yarn composition".

Result:

This experiment confirmed H_1. Although all fabrics appeared equally black under normal lighting, they reacted differently under near-infrared (NIR) light. The visibility under NIR depended on the fabric material and its weight. For example:

- Lightweight polyester (A1, approximately 80–100 gsm) appeared more transparent under NIR than the medium-weight polyester (A2, approximately 160–180 gsm).
- Wool samples showed lower NIR transparency overall, with medium-weight wool (B2, approximately 250–300 gsm) remaining the most opaque.
- Cotton fabrics also varied, with lightweight cotton (C1, approximately 90–110 gsm) allowing more NIR transmission than medium-weight cotton (C2, approximately 150–170 gsm).

Layering also influenced results: placing more transparent fabrics over more opaque ones affected how much contrast could be seen. These patterns were consistent across test samples.

***Result of the Test with White Fabrics Under NIR Imaging**

The test with white textiles failed to produce useful contrast under near-infrared (NIR) light. They reflected too much light, which flattened the image and made them unsuitable for contrast-based data embedding. For full test details, see Appendix 1A.

Conclusion

This experiment demonstrates that near-infrared (NIR) visibility in woven textiles is influenced by both the fiber type and the weight of the fabric. While all samples appeared uniformly black under artificial light, their response under NIR imaging revealed substantial differences in how they transmit, reflect, or absorb light—critical factors when embedding invisible, machine-readable patterns into textiles.

Lightweight polyester (A1, approximately 90 gsm) consistently allowed the most NIR transmission and appeared bright under imaging. Medium-weight polyester (A2, approximately 170 gsm) was less transparent but still permitted significant NIR passage. When placed over wool or cotton, both polyester samples maintained their brightness, but layering polyester A1 over wool B2 (medium-weight, approximately 275 gsm) produced the highest contrast.

This pairing proved optimal for creating invisible yet machine-readable contrast in woven patterns.

Wool fabrics, both lightweight (B1, approximately 165 gsm) and medium-weight (B2), absorbed NIR light and appeared dark or black under imaging. Their low reflectivity and opacity make them ideal as the base layer beneath more transparent fibers. The heavier wool enhanced this effect, making it especially effective when used beneath NIR-transparent polyester.

Cotton samples presented intermediate behavior. Lightweight cotton (C1, approximately 100 gsm) was partially transparent under NIR, while the medium-weight variant (C2, approximately 160 gsm) reflected more light and sometimes appeared white.

The contrast created by layering polyester over cotton was moderate and less consistent than with wool, making cotton a less reliable substrate for predictable contrast.

The layering order had a significant impact on NIR readability. When transparent fabrics such as lightweight polyester were layered on top of opaque or reflective materials like wool or heavier cotton, the contrast under NIR became more pronounced.

This confirms that combining materials with contrasting NIR properties in a specific arrangement is a viable method for constructing hidden, machine-readable structures.
In addition to fiber and weight, the experiment showed that other variables likely play a role.

Some samples with identical fiber content exhibited different NIR responses, suggesting that dye composition or finishing treatments also influence visibility. Since this information is often proprietary or undisclosed by fabric suppliers, the combined influence of these factors is referred to as “yarn composition” in this study.

These findings confirm hypothesis H_1 and provide a foundational insight: by strategically combining common textile materials of known weights and optical behaviors, it is possible to construct layered woven structures that embed scannable data invisible to the human eye.

This approach can be integrated into standard weaving processes without altering surface appearance or tactile properties, making it a promising pathway for applications such as Digital Product Passports and automated traceability in the textile industry.

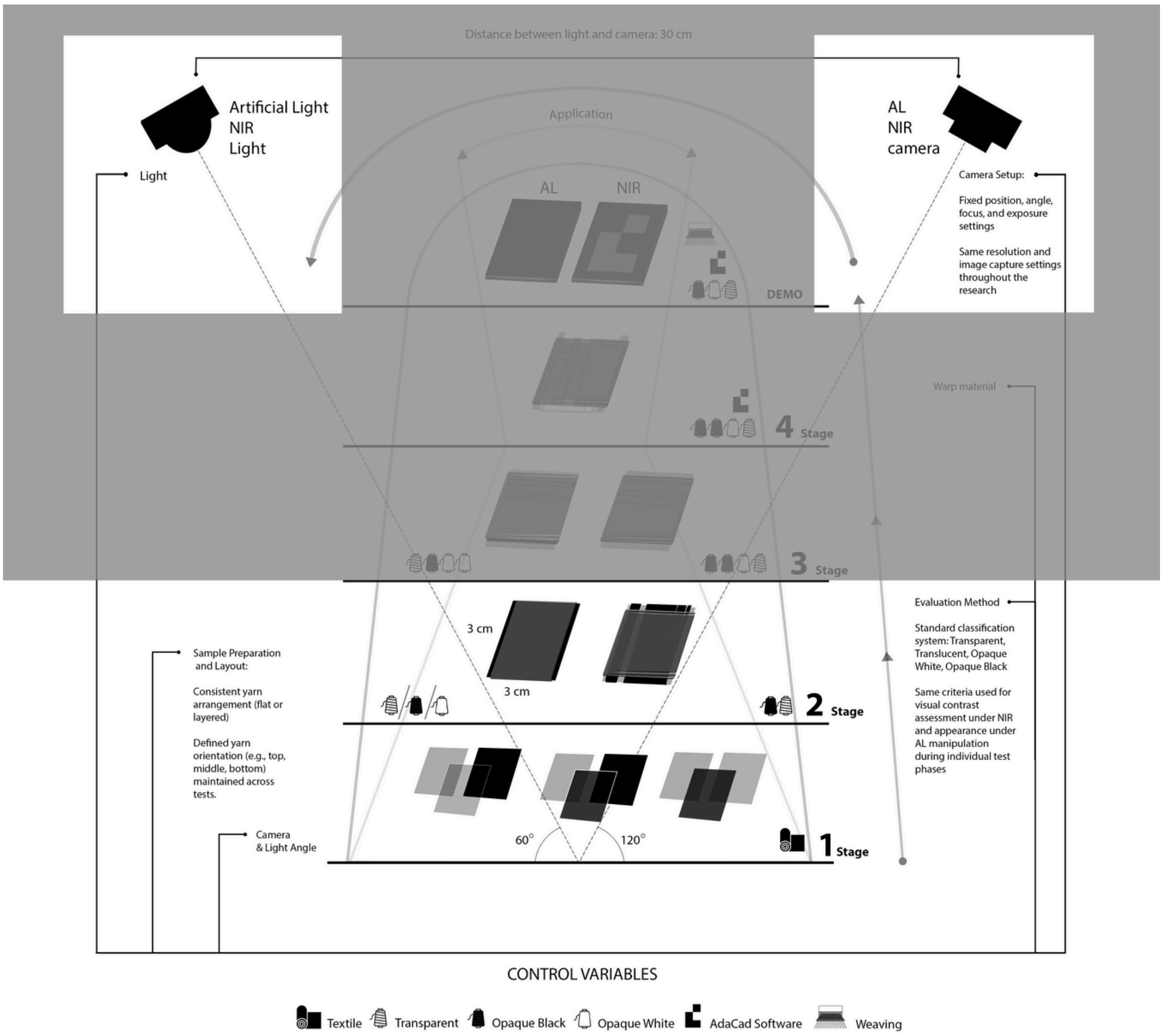


Figure 19.

4.2 Stage 2 – Intermediate Testing: Individual Yarns

This stage aimed to systematically examine how individual black yarns including polyester, wool, and cotton respond to artificial light (AL) and near-infrared (NIR) radiation (Figure 19). Unlike earlier tests that focused on layering existing woven fabrics, this experiment assessed yarns wrapped around 3×3 cm squares to observe their natural interaction with NIR light, specifically their ability to transmit, reflect, or absorb it (Figure 20).

The artificial light source used was a 10W LED bulb, providing consistent ambient illumination. The goal was to classify the yarns based on these optical responses. This classification is key to identifying yarns with distinct behaviors that can later be combined to create hidden contrast zones within woven structures.

The aim was to classify individual black yarns by their optical behavior under AL and NIR, and to identify how differences in yarn composition, yarn weight, and yarn density influence their classification into visibility categories.

This foundational dataset would support the selection of yarns for controlled two-layer and woven contrast structures in subsequent stages (Figure 21).

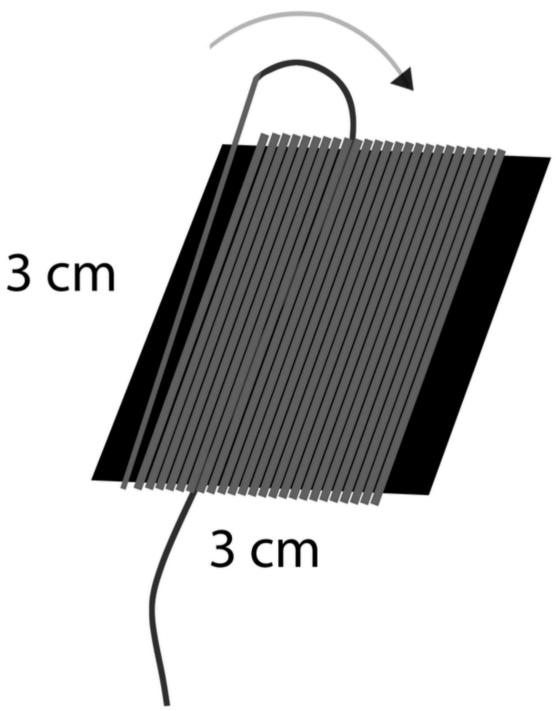


Figure 20

H_0: All black yarns, regardless of material, show similar visibility under NIR.
H_1: Black yarns differ in NIR visibility based on material, thickness, and density.

Independent Variables:
- Yarn material (polyester, cotton, wool)
- Yarn thickness
- Yarn density

Dependent Variable:
- NIR visibility classification (quantified)

Control Variables:
- Background black carton
- Lighting
- Camera setup

Method
Thirteen commercially available black yarns were selected to represent a diverse range of fiber types and structural characteristics:

Polyester yarns (including recycled polyester): 3 types
Wool yarns: 4 types
Cotton yarns: 6 types

Each yarn varied in:

Fiber type (100% polyester, wool, cotton)
Weight/Thickness
Density (yarns/cm – the number of yarns positioned side by side per centimeter)

Each yarn sample was tested on its own, placed flat on a neutral, non-reflective surface. There was no weaving, layering, or stretching, so the test would show the yarn's behavior in isolation.
The testing was done under two types of light:

Artificial Light (AL): to see how the yarn looks to the human eye. A 10W LED bulb (warm white, approx. 3000K) was used to provide consistent ambient lighting conditions during these observations.

Near-Infrared (NIR): to see how the yarn reacts to light that is invisible to the eye but detectable by infrared cameras.

The test environment was controlled to ensure consistent comparison across samples. All photographs were taken using the same lighting setup, camera angle, distance, exposure settings, and background. The samples were not manipulated between tests, and all were evaluated in a static state.

Each yarn's optical behavior under NIR was classified into one of the following four categories:

Transparent – NIR light passes through with minimal obstruction
Translucent – NIR light is partially transmitted and scattered
Opaque White – NIR light is reflected, producing a light-toned image
Opaque Black (Opaque B) – NIR light is absorbed

These classifications were used to identify the range of optical behaviors present in the selected yarns and to establish a visibility logic for selecting contrast-effective material combinations in later experimental stages.

These results support a strategic material selection for layered weaving:

Top layer: Polyester #1 or #2 (transparent under NIR)
Black Middle layer: Polyester #3 or Cotton #6 (opaque black under NIR)
White Middle layer: Reflective cottons (opaque white under NIR)

The observed behaviors were linked to physical properties. Thinner, smoother yarns were more likely to transmit NIR; thicker or tightly spun yarns tended to absorb it. Loosely constructed or rough-surfaced yarns scattered NIR, increasing reflectivity and contributing to translucent or white opaque appearances under NIR.

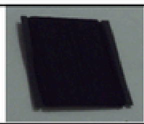
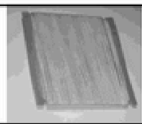
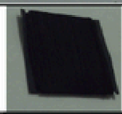
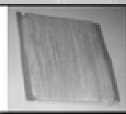
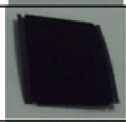
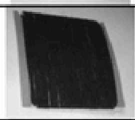
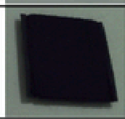
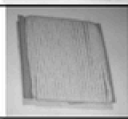
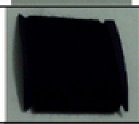
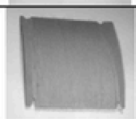
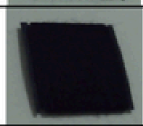
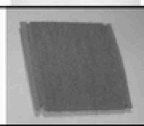
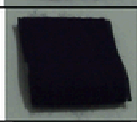
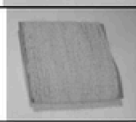
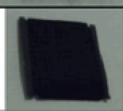
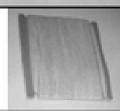
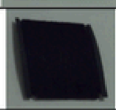
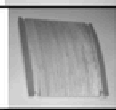
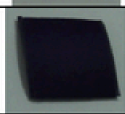
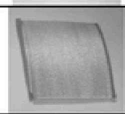
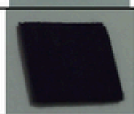
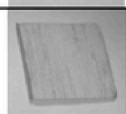
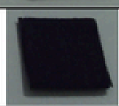
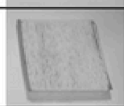
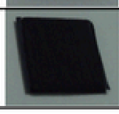
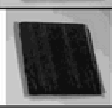
Material	Thickness	Yarns per cm	Artificial Light (AL), photo	Near Infra Red (NIR) photo	NIR Visibility
Polyester#1	70/2	36			Transparent
Polyester#2	70/2	36			Transparent
Polyester#3, R-PET	34/1	36			Opaque Black
Wool#1	8/2	8			Opaque White
Wool#2	64/2	30			Translucent
Wool#3	28/2	16			Translucent
Wool#4	20/2	16			Opaque White
Cotton#1	70/2	36			Opaque White
Cotton#2	50/3	36			Opaque White
Cotton#3	34/2	26			Opaque White
Cotton#4	28/2	20			Opaque White
Cotton#5	6.7	14			Opaque White
Cotton#6	34/1	18			Opaque Black

Figure 21

Result:

This experiment supported H_1. Although the yarns were all black and looked visually identical under artificial light, their behavior under near-infrared (NIR) imaging varied depending on their material, thickness, and structural density.

Polyester yarns generally allowed more NIR transmission and appeared brighter in the images. Wool yarns, especially those with higher density or loosely spun construction, tended to absorb more NIR and appeared darker. Cotton yarns showed mixed behavior, with some yarns appearing semi-transparent and others more absorptive.

The differences in NIR visibility were consistent across repeated tests, indicating that yarn-level characteristics—such as fiber type and physical structure—systematically affect how light interacts with the material under NIR.

Conclusion:

This stage successfully classified black yarns according to their visibility under near-infrared (NIR) light. The yarns' optical behavior was influenced by material type, as well as structural factors such as thickness and how tightly the yarn was spun. Yarns that exhibited translucent behavior—neither clearly transparent nor clearly opaque—were excluded from further testing, as they did not contribute to usable contrast when layered with other materials.

The yarns that showed distinct NIR responses (either strong transmission or strong absorption) were selected for the next stage, where they were combined in layered configurations to evaluate their ability to produce high visual contrast under NIR.

4.3 Stage 2 – Tests 1 to 4: Controlled Two-Layer Material Combinations

Following the classification of black yarns in Stage 2 Intermediate, this stage examined how selected yarns—classified as NIR-transparent, opaque white, and opaque black (NIR-opaque)—behave when layered in two-yarn configurations. The primary aim was to determine which combinations create strong visual contrast under near-infrared (NIR) illumination while preserving a consistent black appearance under artificial light (AL).

These contrast behaviors are fundamental for embedding machine-readable information into woven textiles without any visible interference on the surface.

To explore and validate two-layer yarn combinations in which material contrast—based on their NIR transparency, reflectance, or absorbance—produces detectable contrast under NIR imaging, while maintaining a consistent visual appearance under AL.

This test aimed to identify optimal material pairings that enable invisible information encoding through structural layering alone (Figure 22).

H_0: Layering transparent yarns over opaque yarns does not affect contrast under NIR.

H_1: Layering transparent yarns over opaque yarns significantly enhances contrast under NIR.

Independent Variables:
- Top yarn material (e.g., Polyester #1 or #2)
- Bottom yarn material (e.g., Polyester #3 or Cotton #6)

Dependent Variable:
- Contrast under NIR (measured using Michelson contrast)

Control Variables:
- Yarn alignment
- Weave tightness
- Lighting angle

Method

Four two-layer combinations were created using black yarns that had previously been categorized in Stage 1.

These included:

- Top yarn candidates (NIR-transparent): Polyester #1 and Polyester #2
- Bottom yarn candidates (NIR-opaque): Polyester #3 (R-PET) and Cotton #6
- Control combinations: Cotton #1 and Cotton #2 (non-transparent) over Cotton #6

Each sample was assembled with one yarn on top and one on the bottom, then photographed under both artificial light and NIR light using a controlled setup. Visibility was classified into one of four categories: Transparent, Translucent, Opaque White, or Opaque Black (Opaque B), (Figure 22).

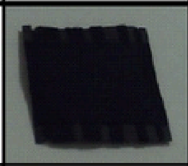
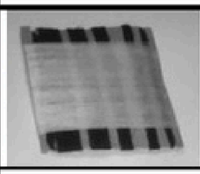
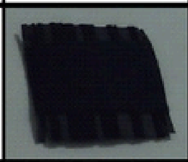
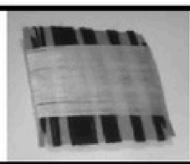
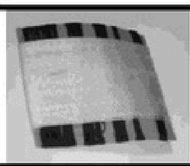
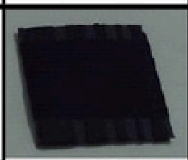
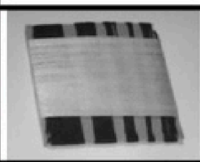
Test	Material	Order of Threads	Artificial Light (AL), photo	Near Infra Red (NIR) photo	NIR Visibility
Test #1	Polyester#1	Top			Transparent
	Polyester#3, R-PET	Bottom			Opaque Black
Test #2	Polyester#2	Top			Transparent
	Polyester#3, R-PET	Bottom			Opaque Black
Test #3	Cotton#1	Top			Opaque White
	Cotton#6	Bottom			Translucent
Test #4	Cotton#2	Top			Opaque White
	Cotton#6	Bottom			Translucent

Figure 22

Result:

This series of tests confirmed H_1. Among the combinations tested, the highest contrast under near-infrared (NIR) light was achieved when Polyester #1—a yarn classified as NIR-transparent—was used as the top layer, and Cotton #6—a yarn classified as NIR-opaque—was used as the bottom layer. In this configuration, the top layer allowed NIR radiation to pass through with minimal interference, while the bottom layer blocked or absorbed the NIR signal, creating a clear contrast between light and dark zones in the resulting image.

Other combinations involving less distinct yarns, especially those with partial translucency, produced weaker or inconsistent contrast and were excluded from further use.

Conclusion:

Stage 2 confirmed that layering yarns with opposing NIR properties—specifically, a transparent yarn on top and an opaque black yarn underneath—can create contrast zones that are invisible under normal lighting but clearly visible under near-infrared (NIR) imaging. The most effective and consistent combinations were Polyester #1 or #2 layered over Polyester #3 or Cotton #6, which produced stable, repeatable contrast across multiple tests.

These results establish a reliable design method for embedding hidden visual information within woven textiles and serve as the technical basis for the layered structures developed in the next phase. This contrast behavior is illustrated in Figure 23, which shows the visual difference between low-contrast and high-contrast two-layer combinations under NIR.

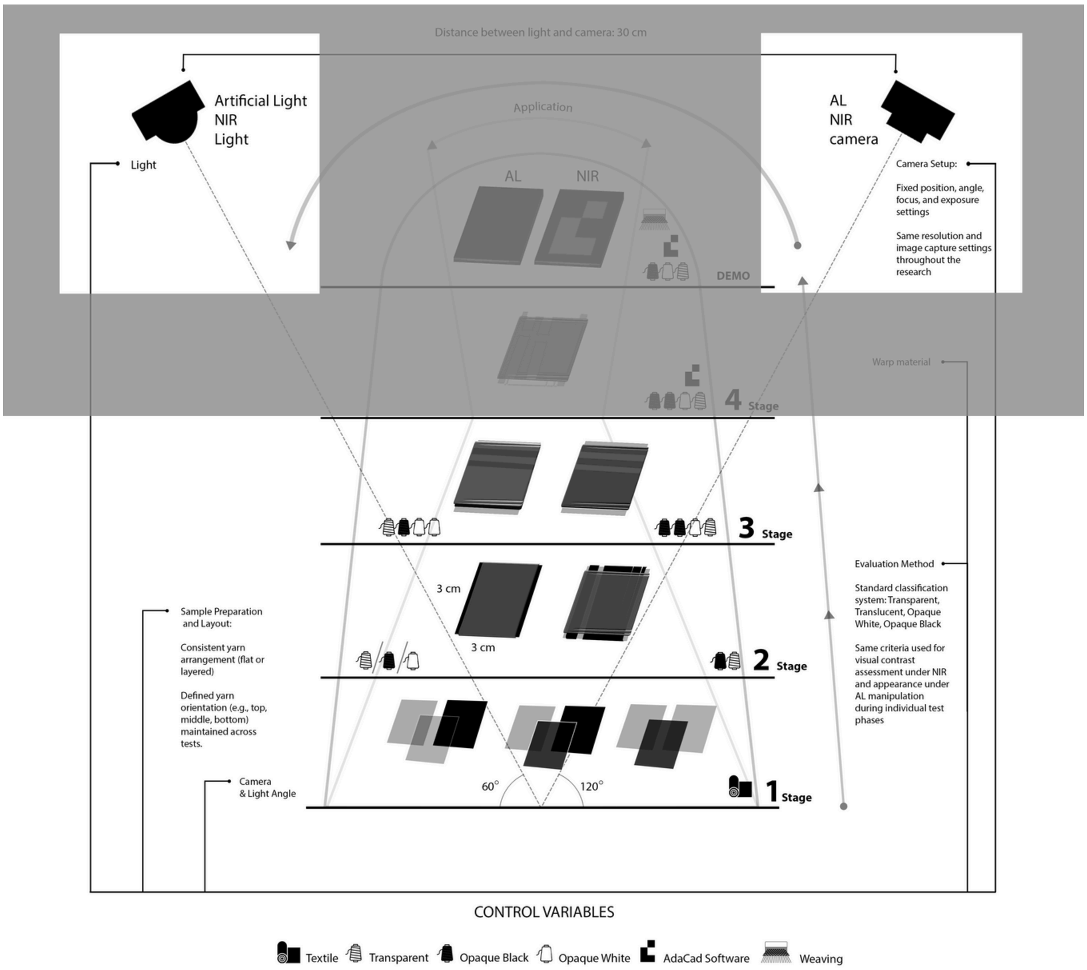


Figure 23.

4.4 Stage 3 (Intermediate): Evaluation of Opaque Black and Transparent Yarn Combinations

After identifying yarns with reliable optical behavior in Stages 1 and 2, Stage 3 focused on verifying their performance in a structured three-yarn configuration. This setup aimed to test whether data could be hidden by placing a yarn classified as opaque black under NIR (Polyester #3 or Cotton #6) between two yarns classified as transparent, making it invisible under artificial light (AL) but detectable under NIR imaging (Figure 23).

The test specifically examined the interaction between transparent and opaque black yarns under NIR conditions.
The goal was to confirm that this material arrangement produces high contrast under NIR while maintaining a uniform black surface under AL. This structure reflects real woven textile constraints, where yarn positioning is determined by construction rather than visible design.

The evaluation centered on using transparent yarns (Polyester #1) as the top and bottom layers, with an opaque black yarn at the center, to assess contrast visibility under NIR and whether the center layer remains hidden under AL (Figure 24).

$\underline{H_0}$: Adding an opaque black middle layer between transparent top and bottom yarns does not affect internal contrast under NIR.
$\underline{H_1}$: An opaque black middle layer between transparent yarns produces internal contrast under NIR.

Independent Variable:
- Middle yarn type (Polyester #3, Cotton #6)

Dependent Variable:
- Internal contrast visibility under NIR (evaluated qualitatively and via brightness difference)

Control Variables:
- Top and bottom yarn: Polyester #1
- Imaging conditions

Method
To evaluate the interaction between NIR-transparent and NIR-opaque yarns, a controlled material layering test was conducted using a three-yarn configuration. Each sample was constructed by wrapping yarns around a 3 × 3 cm square of matte black cardboard to ensure a neutral, non-reflective background. In all cases, the same yarn classified as NIR-transparent (Polyester #1) was used for the top and bottom layers to maintain consistency.

The middle layer varied between two yarns previously identified as NIR-opaque: Polyester #3 and Cotton #6.
Yarns were applied manually under moderate tension to ensure surface consistency without excessive compression. Each yarn layer was aligned and pressed flat to ensure contact between fibers. Two test groups were created:

Test 5: Middle layer Polyester #3 (R-PET)
Test 6: Middle layer Cotton #6

Samples were imaged under identical lighting and camera conditions used in prior experiments. Artificial light (AL) and near-infrared (NIR) sources were applied sequentially, and high-resolution photographs were taken from a fixed position.

Each sample was evaluated based on its appearance under AL and NIR imaging, focusing on the detectability of internal contrast caused by the middle layer. Visibility was classified using four predefined categories: Transparent, Translucent, Opaque White, and Opaque Black. This process allowed for qualitative and brightness-based comparison across test samples.

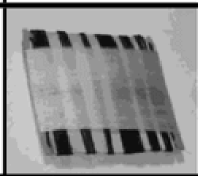
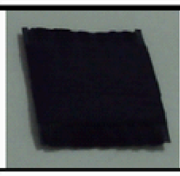
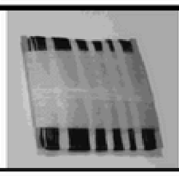
Test	Material	Order of Threads	Artificial Light (AL), photo	Near Infra Red (NIR) photo	NIR Visibility
Test #5	Polyester#1	Top			Transparent
	Polyester#3, R-PET	Middle			Opaque Black
	Polyester#1	Bottom			Transparent
Test #6	Polyester#1	Top			Transparent
	Cotton#6	Middle			Opaque Black
	Polyester#1	Bottom			Transparent

Figure 24

Result:

This experiment supported H_1. In both Test 5 and Test 6, the use of an NIR-absorbing yarn in the middle layer, enclosed between two transparent layers, created a clearly detectable internal contrast under NIR imaging. Under artificial light, the samples appeared visually uniform and black, showing no contrast. Under NIR, the middle yarn blocked light transmission, while the top and bottom layers allowed light to pass through. This produced a well-defined contrast region within the woven structure. Both Polyester #3 and Cotton #6 demonstrated consistent NIR-blocking behavior across multiple samples.

Conclusion:

Tests 5 and 6 confirmed the effectiveness of a three-layer configuration composed of transparent top and bottom yarnswith an opaque black middle yarn to generate hidden contrast zones visible only under NIR. Polyester #1 functioned reliably as an NIR-transparent yarn, while Polyester #3 and Cotton #6 acted as stable NIR-blocking components. This combination produced an internal contrast effect without altering the textile's appearance in visible light. The outcome demonstrates that visual contrast can be embedded structurally using controlled material layering alone.

This result supports the continued use of this layering logic in further development. In the next step, a fourth yarn will be introduced to evaluate whether the contrast effect can be enhanced or selectively modulated. The contrast behavior demonstrated in this stage is shown in Figure 24.

4.5 Stage 3 – Tests 7 and 8: Multi-Yarn Middle Layer Contrast Evaluation

This stage expanded upon the findings of earlier configurations by testing whether combining multiple yarn types in a single layer could produce detectable internal contrast under near-infrared (NIR) imaging.

The goal was to evaluate whether a contrast-encoded structure, created by placing one opaque black and one opaque white yarn side by side in the middle layer, would yield higher NIR contrast. The top layer was fixed as a NIR-transparent yarn to enable optical transmission, while the bottom layer was alternated between an NIR-absorbing black yarn and an NIR-reflective white yarn to assess how base reflectivity influences visibility. (Figure 25 and 26).

H_0-1: Combining black and white yarns in the middle layer does not produce internal contrast under NIR imaging.

H_1-1: Combining black and white yarns in the middle layer produces internal contrast under NIR imaging.

H_0-2: The bottom yarn type (black or white) has no effect on the visibility or strength of internal contrast under NIR.

H_1-2: The bottom yarn type influences the visibility or strength of internal contrast under NIR.

Independent Variables
- Middle yarn composition: Alternating black and white yarns (contrast-encoded)
- Bottom yarn material: Black or white (NIR-absorbing or reflecting)

Dependent Variable
- Internal contrast visibility under near-infrared (NIR) imaging
- (qualitatively assessed through brightness separation and contrast clarity)

Control Variables
- Top yarn: Polyester #1 (NIR-transparent)
- Imaging conditions: Fixed lighting intensity, camera position, and exposure settings
- Sample size and weave structure: Consistent across tests

Method
Two test groups were created, each consisting of a woven three-layer configuration. The top layer in both cases was Polyester #1, classified as NIR-transparent. In the middle layer, two yarns—Polyester #3 (classified as NIR-opaque black) and Cotton #2 (classified as NIR-reflective white)—were placed side by side in a consistent weave sequence. The bottom layer differed across the two tests:

Test 7: Bottom yarn — Polyester #3 (NIR-absorbing black)
Test 8: Bottom yarn — Cotton #2 (NIR-reflective white)

All yarns were woven into a controlled three-layer swatch using a plain weave structure. Imaging was conducted under fixed near-infrared illumination and artificial light. Samples were evaluated visually and documented using NIR-sensitive camera equipment.

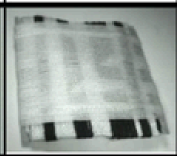
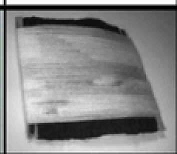
Test	Material	Order of Threads	Artificial Light (AL), photo	Near Infra Red (NIR) photo	NIR Visibility
Test #7	Polyester#1	Top			Transparent
	Polyester#3, R-PET	Middle			Opaque Black
	Cotton#3	Middle			Opaque White
	Polyester#3, R-PET	Bottom			Opaque Black
Test #8	Polyester#1	Top			Transparent
	Polyester#3, R-PET	Middle			Opaque Black
	Cotton#3	Middle			Opaque White
	Cotton#3	Bottom			Opaque White

Figure 25

Result

The experiments supported both H_1-1 and H_1-2.
The use of alternating black and white yarns in the middle layer successfully created detectable internal contrast patterns under NIR, confirming that coded contrast can be embedded at the yarn level.
The bottom yarn material influenced the visibility of the contrast: using a black bottom yarn enhanced contrast by absorbing stray NIR light, while a white bottom yarn reduced overall contrast by reflecting excess light, slightly flattening the visual difference between the black and white elements in the middle layer.

Conclusion

Tests 7 and 8 demonstrated that internal contrast can be enhanced by combining multiple yarn types within the middle layer, using alternating absorptive and reflective materials to encode visual differences under NIR. The bottom yarn layer also plays a critical role: absorptive black yarn improves contrast clarity, while reflective white yarn can reduce its effectiveness. This stage confirms that material-based contrast encoding can be fine-tuned not only through layer separation but also by varying within-layer composition and underlying support layers, offering increased control over embedded visual data structures in woven textiles.

4.5.1 Iterative Development Process

After identifying the challenge of embedding and retrieving invisible data within textiles, a After identifying the challenge of embedding and retrieving invisible data within textiles, a dedicated research process was developed to systematically address the problem. This process is visualized in the graphic titled Iterative Development Process.

It began within fabric by examining how commonly used fibers such as polyester, cotton, and wool behave under near-infrared (NIR) light. The initial focus was on how material characteristics such as thickness and color influence the textile’s optical response under NIR imaging. All samples in this phase were woven, ensuring a consistent fabrication approach for material testing (Figure 26).

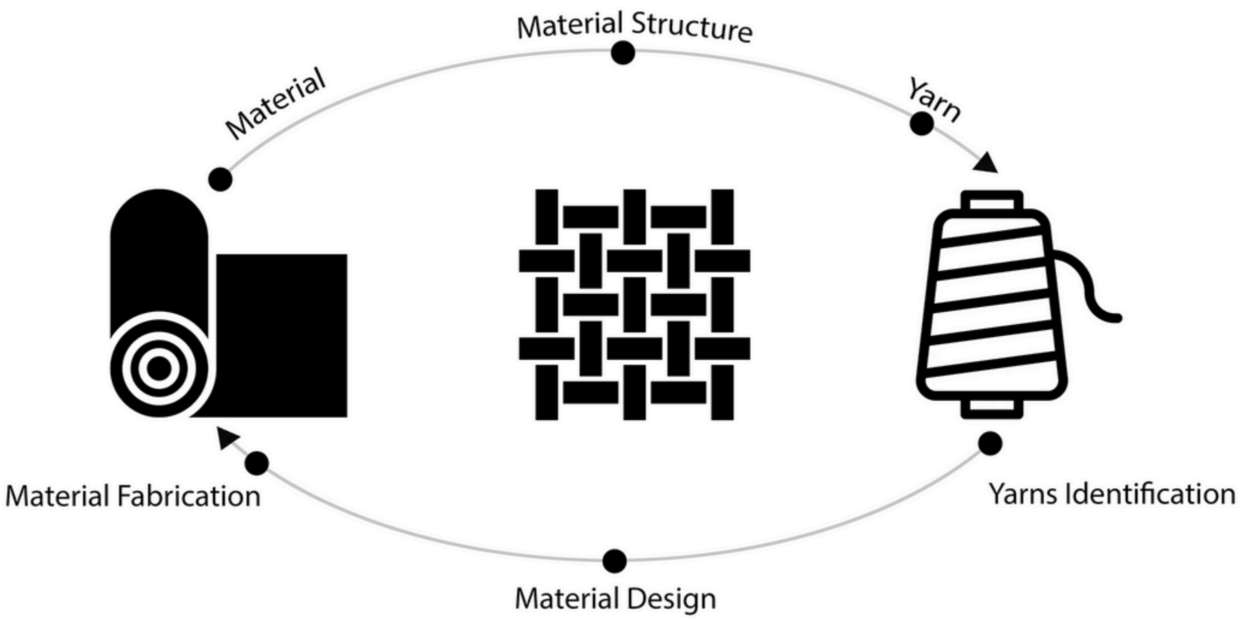


Figure 26

As the investigation progressed, attention shifted to the yarn level. Individual yarns were tested and classified based on their fiber composition and visibility under NIR, specifically how they transmitted, reflected, or absorbed light. This step enabled the identification of yarns that provided high contrast under NIR conditions.

Building on these findings, yarn combinations were developed and arranged in layered woven samples. These combinations were selected to maximize contrast while maintaining a visually consistent appearance under artificial light. In the final stage, these configurations were applied in textile fabrication, resulting in samples designed to embed and reveal data when viewed under near-infrared conditions.

After fabric samples were woven, the process continued by evaluating the visibility of embedded data. This included testing combinations of yarns and how they interacted in layered woven configurations.

Through this, the iterative process was formed by refining material choices and layering strategies step by step to develop textiles capable of encoding and retrieving invisible data under NIR imaging.

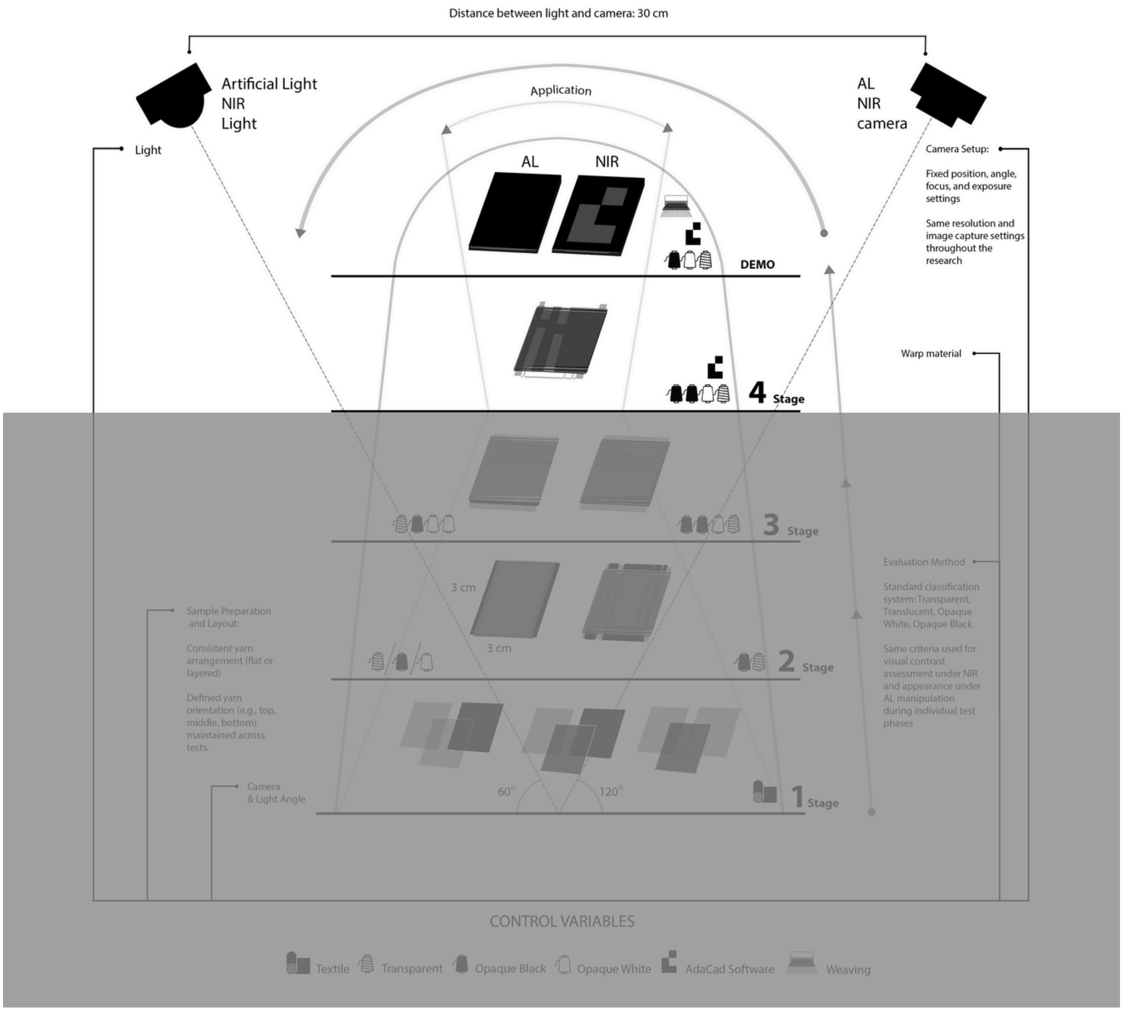


Figure 27

4.6 Stage 4 – NIR-Readable Demo Prototype

This stage focused on developing a 3×3 cm textile sample, following the same wrapping method used in previous stages. In this case, the warp was fixed to 100 percent mercerized cotton due to TC2 loom limitations, as the cotton yarn was already pre-installed for educational use. After assembling the sample, it was tested under both artificial light and near-infrared (NIR) imaging to assess internal contrast.

Digital filters were applied to the captured NIR images to enhance visibility and support material evaluation. Based on these results and confirmation that the selected yarns produced high contrast, the structure was designed in AdaCAD. Finally, the demonstrator was woven to validate the selected material configuration and assess its performance for embedding invisible data under both lighting conditions (Figure 27).

4.6.1 Sample Construction and Layering Setup

A 3×3 cm textile sample was constructed by manually wrapping the warp and interweaving the weft in three layers. The warp (vertical threads) was fixed to 100% mercerized cotton due to the limitations of the TC2 digital loom, which was pre-threaded with cotton for educational purposes. This yarn was selected because previous tests showed it appeared opaque white under near-infrared (NIR) light, making it a suitable background for NIR-based contrast.

The sample was designed using the following layer configuration:

Warp (fixed): 100% mercerized cotton (opaque white under NIR)

Top weft layer: Polyester #1 – black under artificial light, transparent under NIR

Middle weft layer: Polyester #3 and Cotton #3 – black and white under NIR, respectively
Bottom weft layer: Polyester #3 – black under NIR

This layered structure was intended to hide any internal contrast under artificial light while making it selectively visible under NIR imaging (Figures 28, 29, 30).

<u>H_0:</u> A textile structure composed of selected yarns (transparent top, contrast-coded middle, black bottom) will not produce measurable contrast under NIR.

<u>H_1:</u> A textile structure composed of a transparent top layer, a coded middle layer (black and white yarns), and a black bottom layer will produce measurable and readable contrast under NIR, without visible appearance change under artificial light.

Independent Variable
- Yarn selection and layer configuration: Transparent top layer (Polyester #1), Coded middle layer (alternating black and white yarns), Absorbing bottom layer (black yarn)

Dependent Variable
- NIR contrast measurement using the Michelson contrast formula

Control Variables
- Warp yarn: fixed white yarn
- Imaging conditions: constant lighting, camera settings, distance, and background
- Weave structure: consistent yarn tension and positioning
- Sample size and format: standardised demonstrator layout

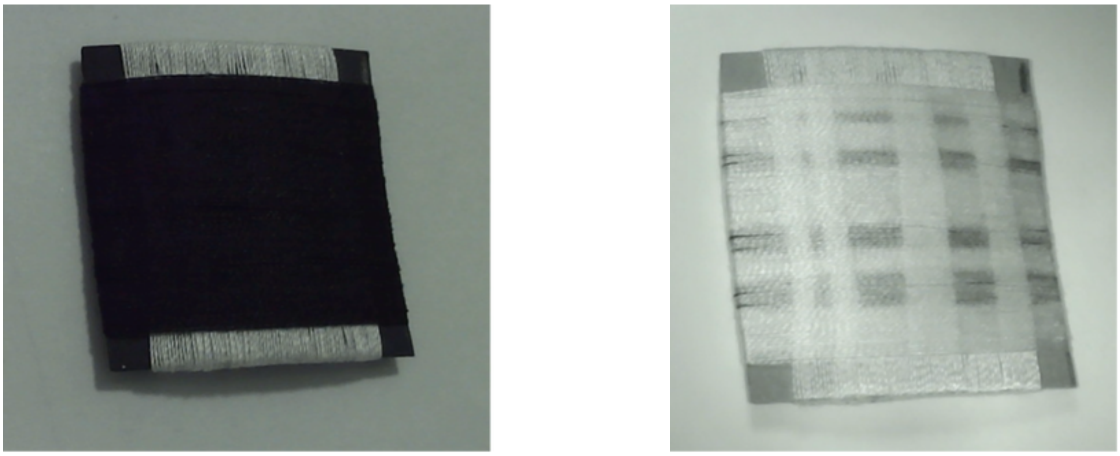


Figure 28. Selected Yarns combinations test. From Left to Right: a) Sample under Artificial Light, b) Sample under NIR

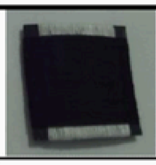
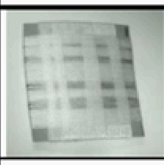
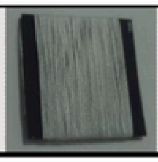
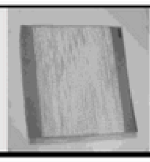
Material	Order of Threads	Artificial Light (AL), photo	Near Infra Red (NIR) photo	NIR Visibility
Polyester#1	Top			Transparent
Polyester#3, R-PET	Middle			Opaque Black
Cotton#3	Middle			Opaque White
Polyester#3, R-PET	Bottom			Opaque Black
Cotton 100%	Warp Fixed in the Lab			Opaque White

Figure 29

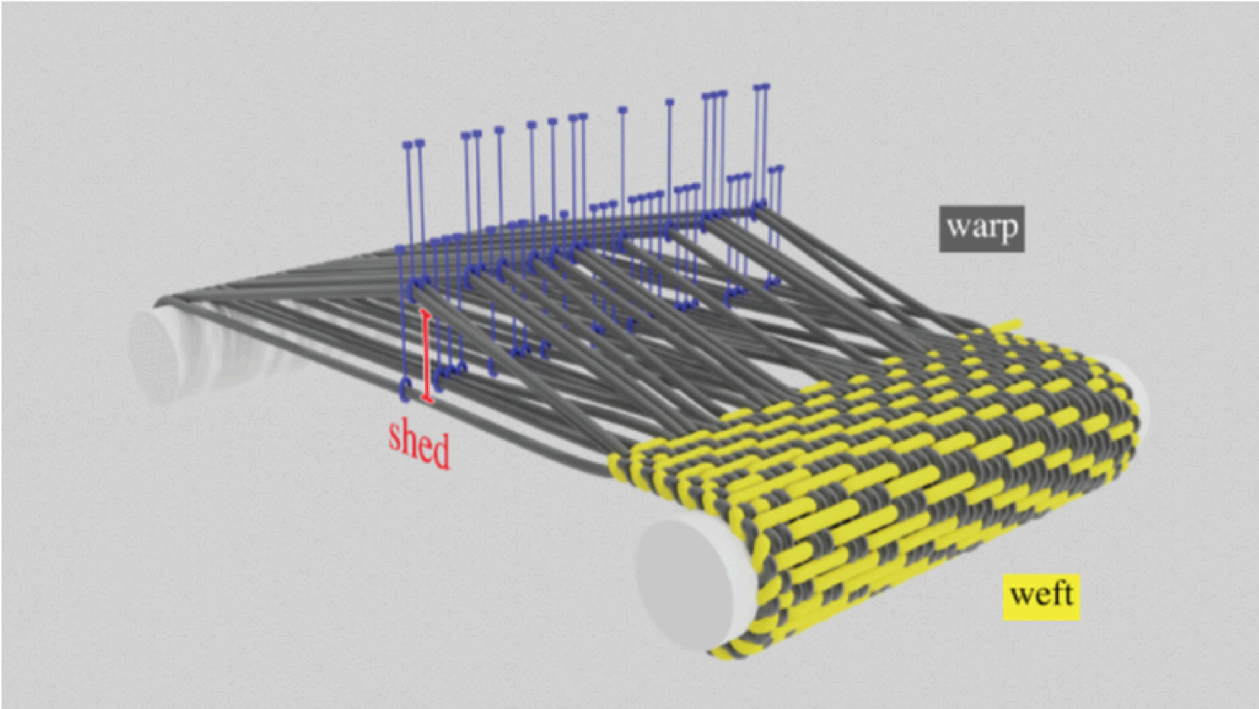


Figure 30. Warp threads set on a Jacquard loom, illustrating how the warp is fixed during the weaving process. Image from Enabling Personal Computational Handweaving with a Low-Cost Jacquard Loom by Albaugh et al. (2021).

4.6.2 Contrast Enhancement Using Digital Filters and Post-Processed Contrast Evaluation

To support the evaluation of internal contrast, simple image filters were applied to the NIR photographs using Adobe Photoshop.

This process enhanced the visual distinction between black and white zones and helped confirm which yarn combinations delivered the clearest result (Figure 31).

Steps Applied:

NIR photo capture
Hue/Saturation adjustment
Levels adjustment
Brightness and contrast refinement
Final levels adjustment
The processed image (Figure 31) provided a clearer view of contrast zones, improving decision-making in the material selection phase.

Figure 32 shows the sample under three conditions:

a) artificial light,
b) NIR imaging,
c) post-processed with digital filters.

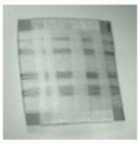
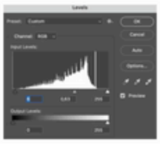
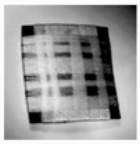
1. NIR photo	**2. Adobe Photoshop Hue/Saturaiton**	**3. Adobe Photoshop Levels**	**4. Adobe Photoshop Bright and contrast**	**5. Adobe Photoshop Levels**	**6. Final NIR Image After Contrast Enhancement *Near-infrared photo after applying digital filter***
					

Figure 31

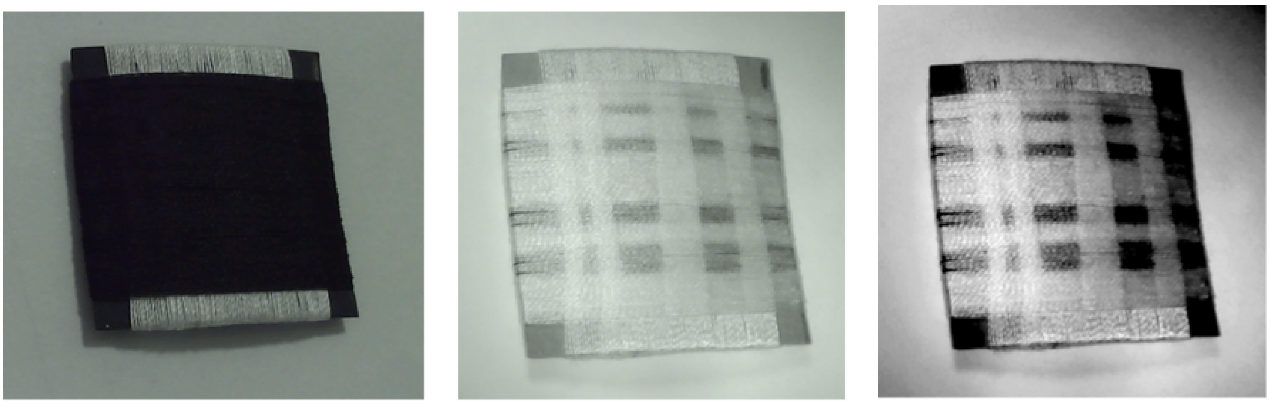


Figure 32. From Left to Right: a) Photo under AL, b) Photo under NIR, c) Photo after applying Filters

4.6.3 Measured Contrast After Filtering. Grayscale Contrast Evaluation

To quantitatively evaluate the enhanced visibility achieved through image filtering, grayscale brightness values were measured in the final post-processed NIR image using Adobe Photoshop (Figure 31).

The Eyedropper Tool (set to 5×5 average) was used to sample both dark and light regions within the middle layer (Figure 33, 34). **Grayscale values** were recorded as percentages (0% = white, 100% = black), and contrast was calculated using the **Michelson Contrast Formula:**

$$\text{Contrast} = \frac{I_{\text{dark}} - I_{\text{light}}}{I_{\text{dark}} + I_{\text{light}}}$$

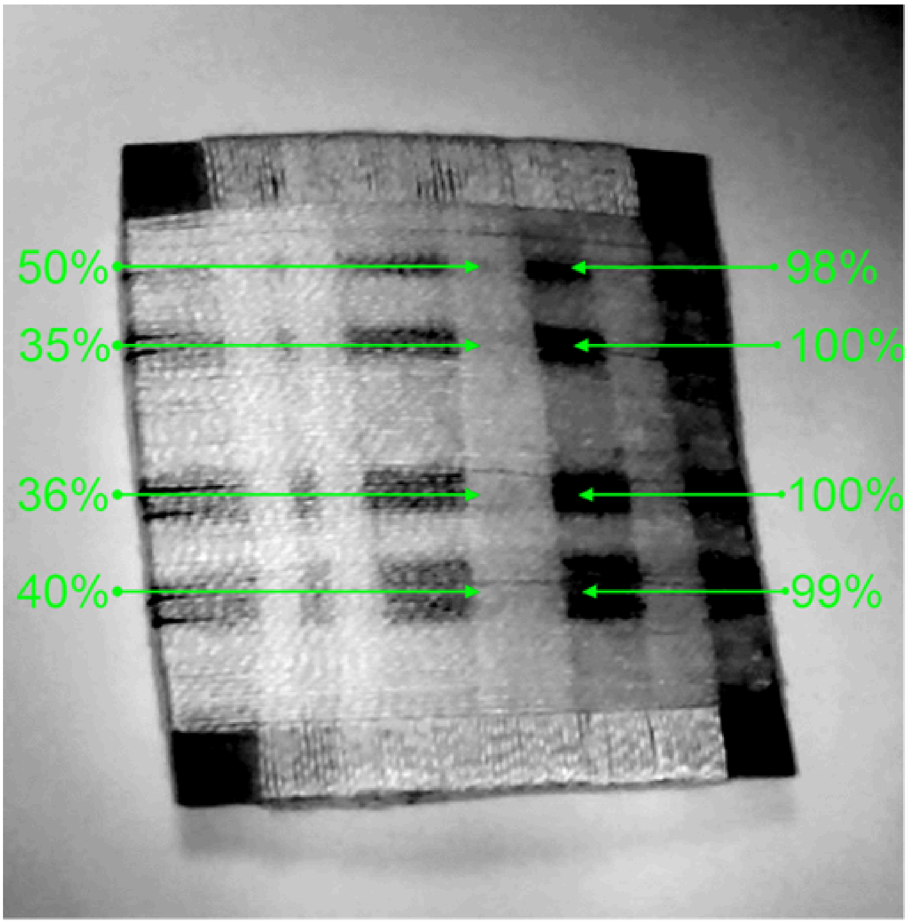


Figure 33

Area	Dark Area (%)	Light Area (%)	Michelson Contrast
1	99	40	0.424
2	100	36	0.471
3	100	35	0.481
4	98	50	0.342

Figure 34

These results reflect the effect of digital contrast enhancement. While the raw image provided basic visual differentiation, the filtered image significantly improved the distinction between brightness values. **Area 2 reached a contrast value of 0.481**, which exceeds the commonly accepted threshold (≥0.40) for machine-readable clarity. **Area 3 achieved a contrast of 0.324**, indicating a lower but still detectable level of visibility under NIR. These values demonstrate that image filtering enhances both visual and quantitative contrast, validating the potential of yarn-based data encoding. The findings confirm that the layered structure effectively creates high-contrast zones detectable under NIR imaging (Figure 34).

Result:

H_1 supported. The demonstrator samples produced clear internal contrast under NIR imaging. Several configurations measured above the 0.4 Michelson contrast threshold, indicating strong contrast levels suitable for machine recognition. The textile appeared fully black under artificial light, with no visible indication of embedded data. Under NIR, the contrast pattern became visible and spatially consistent, validating the effectiveness of material-based encoding

Conclusion

The outcome of Stage 4 confirmed that the selected layered structure—using a transparent top yarn, contrast-coded middle yarns, and an absorbing bottom layer—enabled the creation of invisible yet machine-readable data zones within woven textiles. The demonstrator appeared fully black under artificial light and revealed consistent contrast patterns under NIR imaging, validating the hypothesis. This success established a reliable material configuration for NIR readability, forming the foundation for further technical development.

Building on this validation, the next step involved contrast enhancement through digital post-processing to quantify visibility levels more precisely. This enhancement allowed for refined material evaluation and informed the transition to designing a full-scale demonstrator in AdaCAD.

Together, these steps enabled the translation of material behavior into a functional textile system, capable of embedding NIR-visible information suitable for digital product passport integration.

4.6.4 Weave Structure Design in AdaCAD

Following the confirmation of material performance, the final structure was designed using AdaCAD, a browser-based parametric design tool for creating multi-layer textile layouts. The top layer was defined using a tabby weave (1/1), chosen for its transparency under near-infrared (NIR) imaging. The middle layer was constructed using a twill weave (1/6), which provided increased visual contrast necessary for encoding data zones.

A QR code pattern was digitally embedded into the structure to define specific contrast areas. This pattern was designed to remain hidden under artificial light while becoming visible under NIR. The parametric workflow in AdaCAD enabled precise placement of yarns and rapid structural adjustments. The final design file served as a production-ready blueprint for constructing the demonstrator and illustrated the potential of digital tools in designing textiles with embedded, machine-readable information (Figure 35).

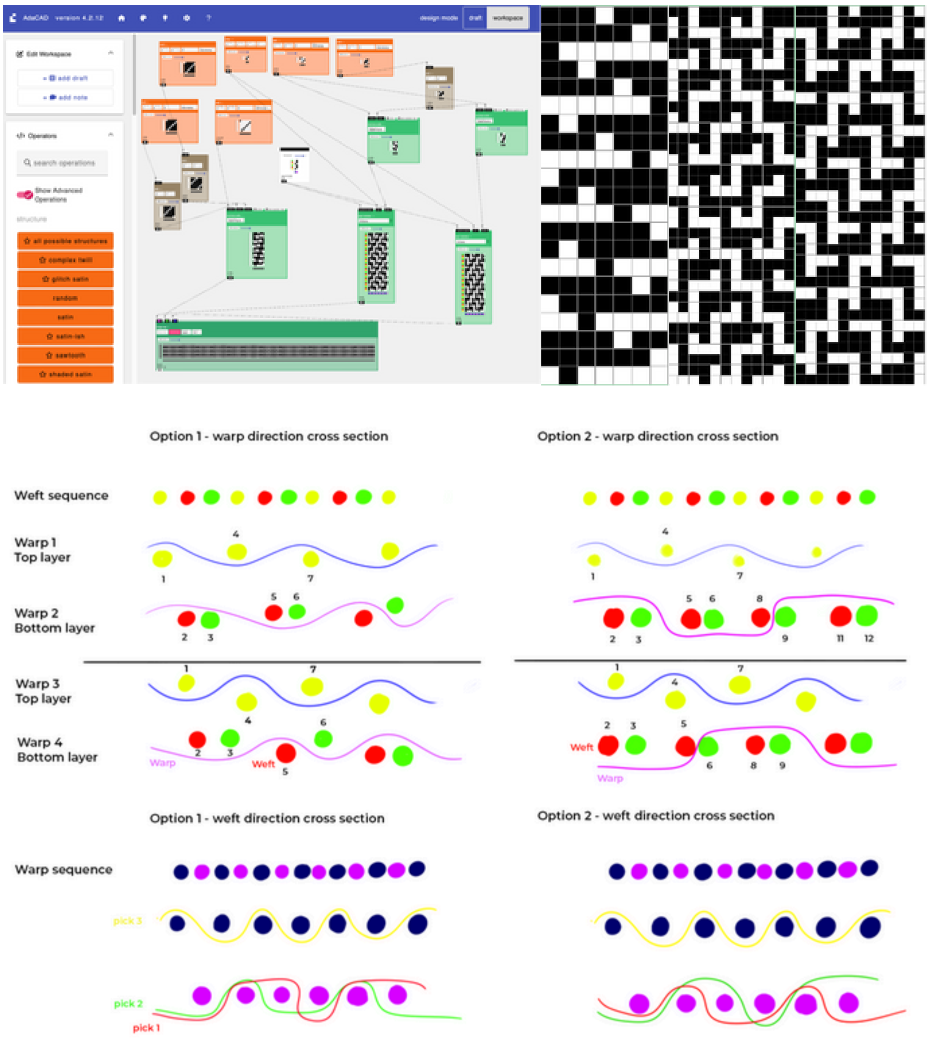
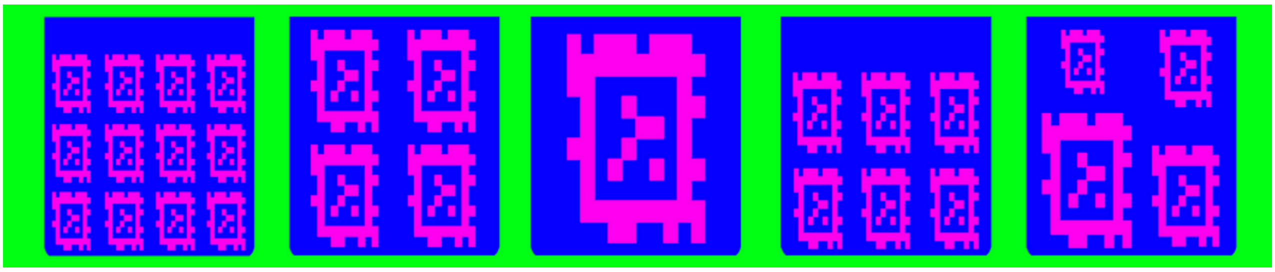


Figure 35

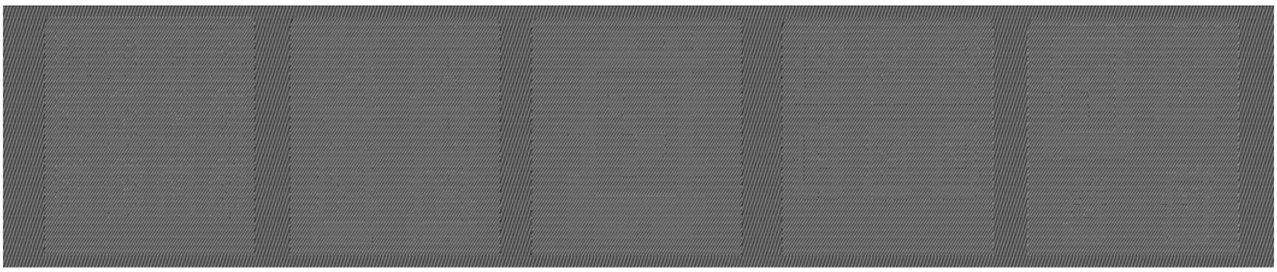
4.6.5 Final Demo Prototype

Using the AdaCAD design, the demo prototype was produced and tested again under both artificial and NIR lighting. The result confirmed the expected behavior: the structure remained visually black in artificial light and revealed contrast zones under NIR, validating the complete workflow—from material testing to digital design to physical output.

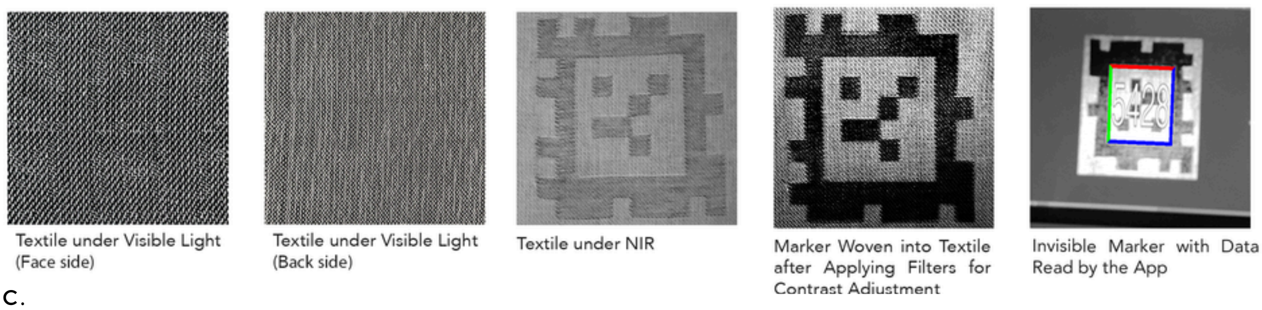
This demo prototype represents the first functional sample capable of embedding NIR-readable contrast using only yarn and structure, without surface treatments or electronics. It serves as a proof of concept for invisible data integration in textiles and supports future development toward digital product passport systems and machine-readable textile surfaces (Figure 36).



A.



B.



C.

Figure 36. Prototypes and imaging of the woven sample. (a) Photoshop file of the future woven prototype; (b) MoB file for weaving in TC2; (c) woven prototype, including face and back of the textile—photograph captured under visible-light LED and NIR, processed with filters to enhance contrast, and demonstrating the app recognizing the encoded number in the invisible marker.

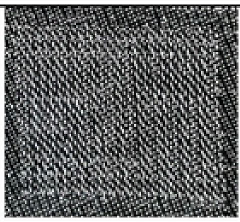
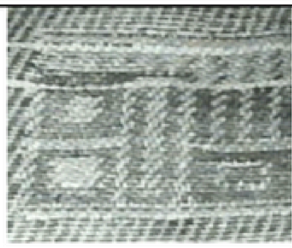
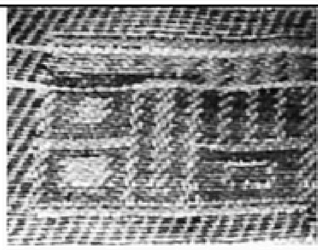
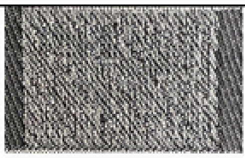
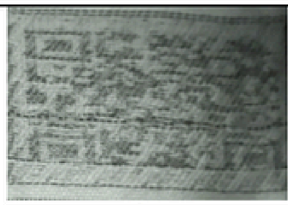
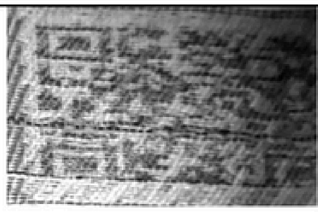
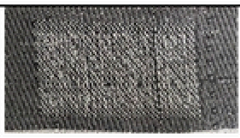
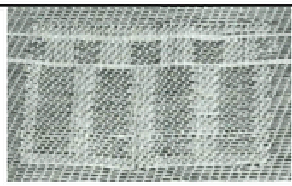
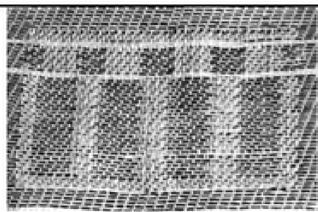
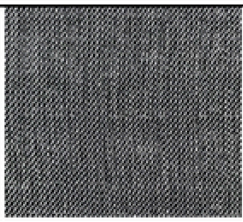
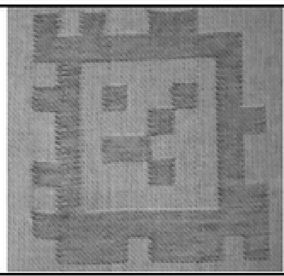
Sample	Visible Light Photo	NIR Photo	Filtered Image	Contrast Measurem ent
1				84 / 27= **0.51** 72 / 29 = **0.43** 65 / 33=**0.33** 94 / 66=**0.18**
2				85 / 28=**0.50** 94 / 22=**0.62** 87 / 54=**0.23** 86 / 43=**0.33**
3				85 / 28 =**0.50** 94 / 22=**0.62** 87 / 54=**0.23** 86 / 43=**0.33**
4				99 /49 = **0.34** 95 / 24 = **0.60** 97 / 38 = **0.44** 99 / 26 = **0.58**

Figure 37

Results of the Demo Prototypes

Grayscale-based Michelson contrast values were calculated from filtered near-infrared (NIR) images of four woven textile samples. Each sample contained embedded zones designed to produce contrast between dark and light areas for data encoding. The values were measured after applying brightness and saturation adjustments to improve zone legibility in post-processing (Figure 37).

Sample 1 included four contrast zones. Two zones—84/27 (0.51) and 72/29 (0.43)—exceeded the 0.40 threshold typically used to indicate sufficient contrast for machine readability. The other two—65/33 (0.33) and 94/66 (0.18)—remained below this threshold, indicating reduced visibility. These results confirm that internal contrast is highly dependent on the combination and arrangement of yarns within the textile layers.

Sample 2 showed two zones—94/22 (0.62) and 85/28 (0.50)—with sufficient contrast, while the other two—87/54 (0.23) and 86/43 (0.33)—did not meet the threshold. This outcome illustrates that certain yarn pairings result in stronger optical separation under NIR conditions.

Sample 3, constructed with the same yarn and layering configuration as Sample 2, produced identical contrast results. The consistency across both samples confirms that the contrast levels depend on the optical behavior of the yarns, rather than on the pattern layout or minor structural differences.

Sample 4 displayed the most balanced results. Three zones—95/24 (0.60), 99/26 (0.58), and 97/38 (0.44)—met or closely approached the 0.40 visibility threshold. Only one zone—99/49 (0.34)—remained below. This indicates stable and repeatable contrast performance within a single textile structure.

In summary, filtered NIR images revealed that woven zones with Michelson contrast values above 0.40 were consistently more visible, confirming the importance of yarn selection, layering strategy, and post-processing in enabling machine-readable contrast within compound woven textiles. * Additional results are presented in Appendix 1B

5. RESULTS

The developed four-stage approach, consisting of material classification, individual yarn testing, controlled layering, and full-scale demonstrator weaving, enabled a systematic investigation into how invisible, machine-readable markers can be embedded and retrieved within woven textiles. This methodical progression made it possible to answer the research questions by linking material properties to structural design and optical behavior under near-infrared (NIR) imaging.
The first major result showed that black yarns, while indistinguishable under artificial light, exhibited diverse behaviors under NIR exposure. Polyester yarns generally allowed light transmission, whereas wool and cotton yarns either absorbed or reflected NIR light.

These differences were not fully explained by fiber type alone, indicating that dye chemistry and finishing treatments, collectively referred to as yarn composition, play a significant role in optical performance. This insight established the material foundation necessary for constructing hidden markers.
Second, the research produced a visibility classification system comprising four categories: transparent, translucent, opaque white, and opaque black.
This system was critical for identifying yarn pairings capable of creating high-contrast zones within the textile structure, detectable by machine but invisible to the human eye.
These classifications provided a material logic for embedding data without requiring external tags or printed markers.

Third, the implementation of **multi-layer compound weaving** proved that it is possible to structurally encode information using only the physical arrangement of yarns.
Layering transparent polyester yarns above yarns with strong absorptive or reflective properties enabled the formation of markers that were legible under NIR imaging. The resulting woven structures maintained full visual neutrality and tactile consistency, confirming the feasibility of embedding data within the textile itself.
Fourth, the final demonstrator, developed in the fourth stage, successfully embedded three distinct data markers using jacquard-controlled compound weaving. These markers were retrieved using an 850 nm NIR camera, validating both their visibility and structural durability.

The demonstrator met criteria for traceability, machine-readability, and manufacturability, showing alignment with the requirements of Digital Product Passport (DPP) systems and industrial textile workflows.

These findings contribute to the field of Human-Computer Interaction by introducing a passive, non-electronic interface model.

The research demonstrates that machine-readable information can be integrated directly into textile structures through material and structural logic alone.

By transforming the textile into a data-bearing surface without visible cues or electronic components, the study expands the scope of interaction design to include structurally encoded, materially driven systems. The four-stage approach was essential to uncovering this potential and provides a replicable method for future exploration of material-based interaction in textile systems (Figure 38, 39).

Textile under Visible Light (Face side)

Textile under Visible Light (Back side)

Textile under NIR

Marker Woven into Textile after Applying Filters for Contrast Adjustment

Invisible Marker with Data Read by the App

Figure 38, Final Prototype

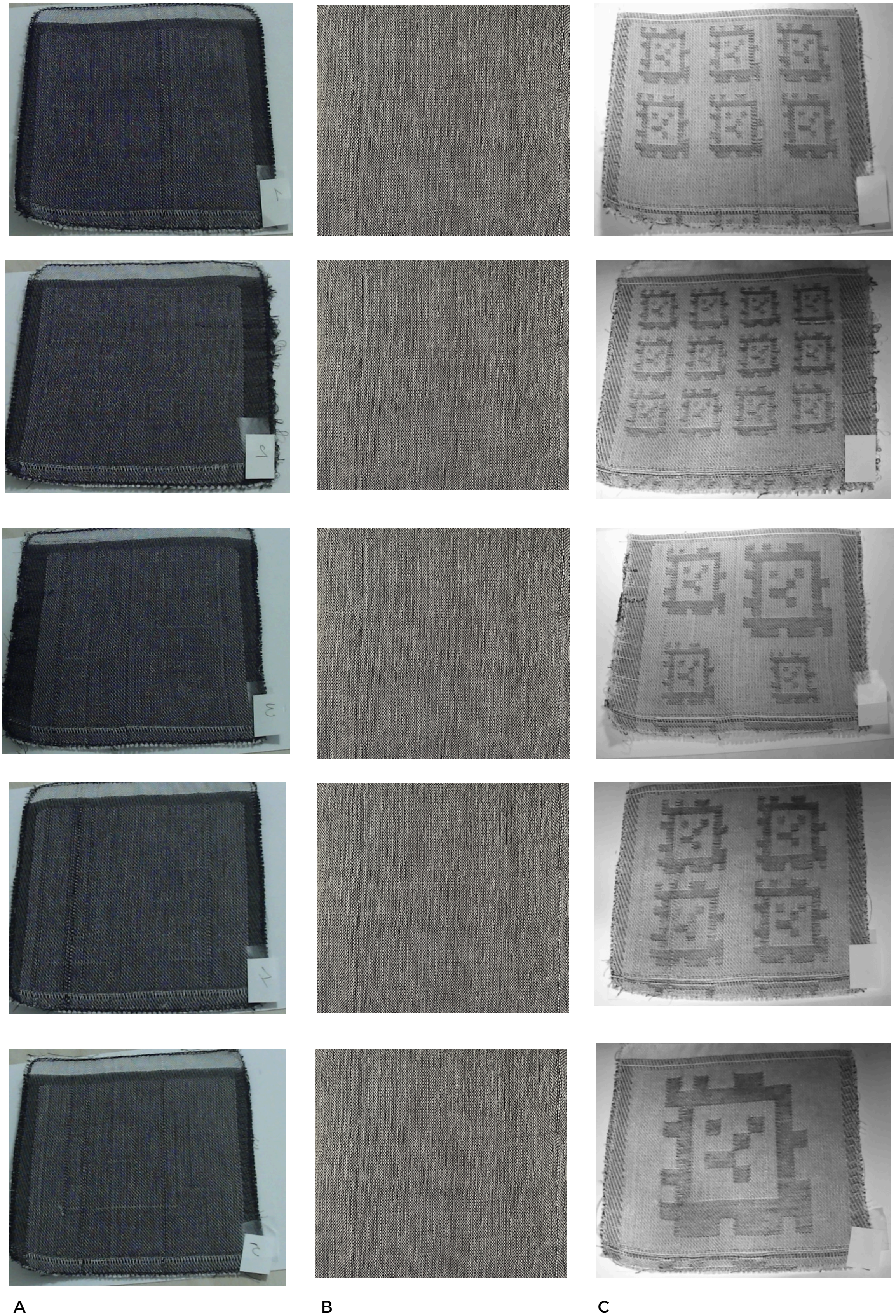


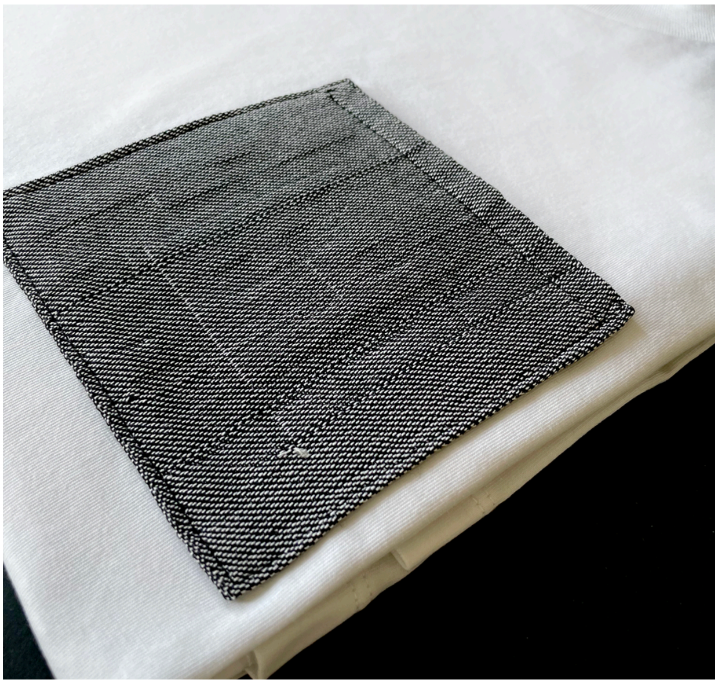
Figure 39. Final prototypes of woven pockets with different sizes of embedded markers (AprilTag): A – visible light, front side; B – visible light, back side; C – embedded AprilTag under NIR. Yarns: Polyester / R-PET Polyester/Cotton.

Application Context: Toward Integration with Digital Product Passport Systems

The successful development of a woven prototype capable of embedding invisible, machine-readable contrast using only yarn and structure presents a foundational step toward integration with digital product passport (DPP) systems. As textile legislation evolves, particularly under the European Union's Ecodesign for Sustainable Products Regulation, the ability to link physical products with digital records becomes increasingly important for traceability, authentication, repair, and circular recovery.

The demonstrator presented in this study offers a potential alternative to printed QR codes or RFID tags by embedding information invisibly and directly into the textile structure. By functioning as a passive physical identifier detectable through near-infrared (NIR) imaging, the woven marker may serve as a persistent access point to a product's digital record without impacting visual design or fabric usability.

Future research may focus on linking these markers to product-specific IDs, ensuring scanner compatibility, and developing standards for material-based identifiers in digital traceability systems. This approach could enable seamless sorting, reuse, or recycling while aligning with emerging compliance frameworks and digital material passports in the textile industry.



5.1 Limitations in Results

While the overall research confirmed the feasibility of embedding invisible contrast using near-infrared (NIR) imaging, several tests produced inconclusive or unusable results. These outcomes are important to acknowledge, as they define the boundaries of the method and help refine future experimentation (Figure 40).

White Yarn Contrast Tests

An early attempt was made to test white yarns made from cotton, wool, and polyester under NIR imaging. The goal was to assess whether white yarns could serve as high-reflectance contrast zones. However, these tests consistently failed to produce useful internal contrast. Under NIR light, the white yarns reflected excessively, flattening the image and reducing the distinguishability of layered structures.This effect made it impossible to define clear contrast boundaries between yarn layers.

Use of Translucent Yarns

Some yarns initially classified as "translucent" under NIR (mainly mid-density wool) were tested in contrast-layer configurations. These yarns allowed partial NIR transmission while scattering light. The result was a blurred or diffused image that lacked the sharp contrast required for data retrieval. These yarns were excluded from further stages, as their intermediate behavior created visual noise without contributing to contrast clarity.

Failed Contrast from Consistent Layering

A number of early layered samples, particularly those using the same yarn type across multiple layers such as all-cotton or all-polyester, were unable to produce any detectable contrast under NIR. Even when the top and bottom layers differed in thickness, no meaningful differentiation appeared. These outcomes underscored the importance of combining yarns with distinct NIR absorption or reflectance characteristics.

Inadequate Results with Colored or Untested Yarns

Although not formally included in the test matrix, some exploratory trials with non-black yarns were attempted during the early phases. These were not continued due to inconsistent behavior under NIR and limited control over dye composition. In each case, the spectral response was either too reflective (similar to the white yarns) or too variable across the surface, preventing reliable classification.

Conclusion of Failed Results

The failed attempts revealed that clear NIR contrast requires a transparent top layer over strongly absorptive or reflective yarns. Uniform reflectors or scatter-prone materials hinder visibility. These insights guided later material choices and point to the need for further research into dye chemistry and yarn processing.

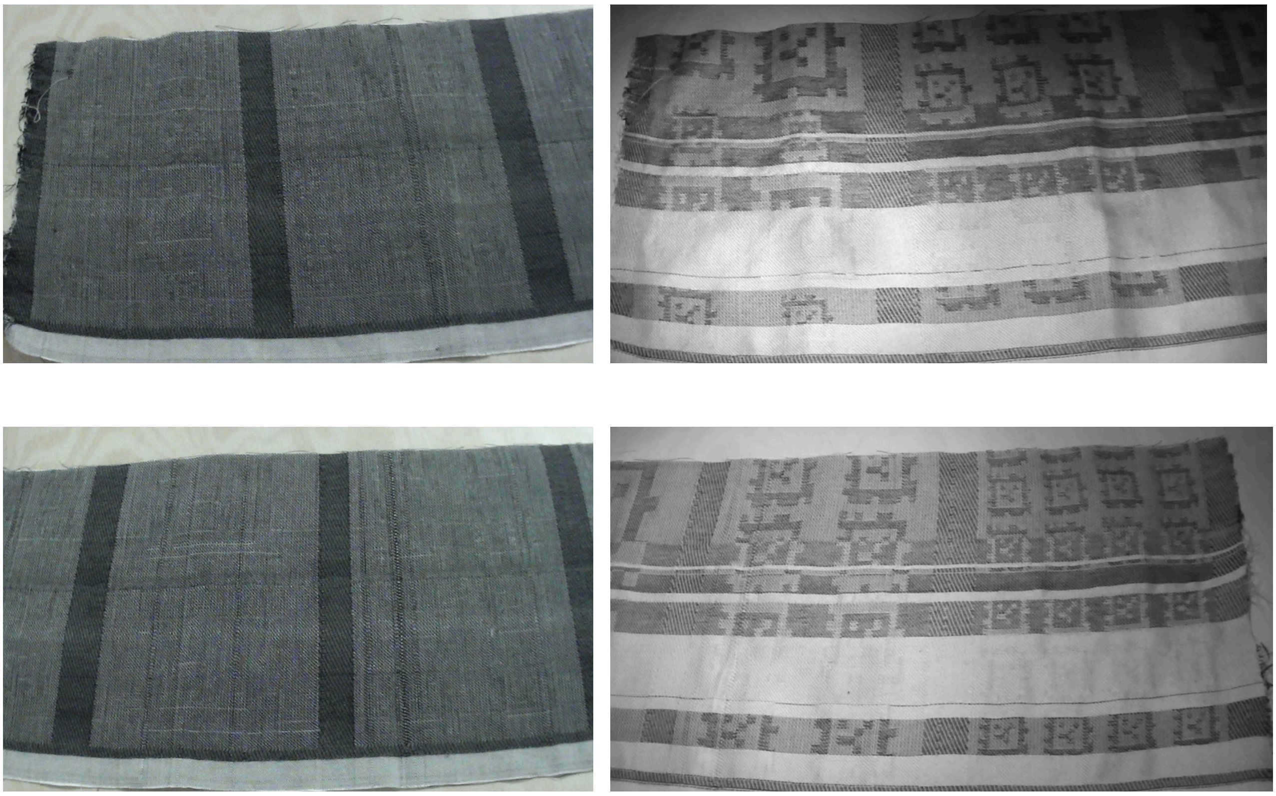


Figure 40

6. DISCUSSION

This study demonstrates that structurally embedded, machine-readable markers can be integrated into woven textiles through a combination of material selection and compound weave construction. These findings show that weaving, although fundamentally different from additive manufacturing, can achieve comparable results in embedding invisible data through its own structural logic and spatial control.
Extensive research on embedded, invisible markers has been concentrated in 3D printing.

This is largely due to the voxel-level control and internal structuring capabilities of additive manufacturing, which enable designers to embed data in forms that are visually undetectable but machine-readable using imaging systems such as near-infrared (NIR).

Techniques like InfraredTags and BrightMarker leverage these affordances by embedding internal geometries or using NIR-reactive filaments (Dogan et al., 2022; 2023). The precision, resolution, and volumetric freedom available in 3D printing have made it a logical platform for such work.

This research translates those principles into the domain of woven textiles, using the interlacing of yarns rather than layer-by-layer deposition to encode information within the fabric structure.

While weaving lacks the volumetric layering of 3D printing, it allows the controlled placement of optically differentiated yarns across multiple layers.
The classification system developed in this study, based on NIR visibility, provides a material framework for selecting yarn combinations capable of forming contrast zones that are invisible under visible light but detectable under NIR imaging.

The application of this method to 2D woven textiles offers practical advantages for flat fabrics such as garments, interior textiles, or technical materials. In such cases, embedded markers can provide traceability or authentication without requiring visible tags, coatings, or electronics. This is particularly relevant in contexts where printed or electronic tags may be removed, damaged, or aesthetically undesirable.

However, 2D implementations also face limitations. Marker resolution is constrained by the loom’s capabilities and the number of yarn types that can be simultaneously handled.

Additionally, 2D fabrics are subject to flexing, abrasion, and folding, which may influence the long-term stability and readability of the embedded patterns.

Extending the method to 3D woven structures presents further opportunities. These include fully fashioned garments, footwear uppers, or composite preforms, where spatial complexity enables the integration of markers within volumetric zones of the product. In such cases, embedded markers could be concealed in areas that are inaccessible or protected, offering increased durability and tamper resistance.

However, these benefits come with new challenges. The increased density and layering in 3D woven fabrics may reduce NIR penetration and introduce optical occlusions. Additionally, precise alignment and marker registration become more complex on curved or spatially variable surfaces, particularly in industrial-scale production environments.

Another important consideration is industrial applicability, especially in relation to the emerging Digital Product Passport (DPP) frameworks. The method developed in this research could offer a robust alternative to QR codes, RFID tags, or printed labels. Because the data is embedded into the fabric structure itself, the markers are passive, persistent, and not reliant on electronic components.

This supports longer product lifecycles and improves compatibility with automated sorting and recycling systems.

However, to enable widespread adoption, further development is needed in areas such as automated detection, environmental durability, and integration into existing manufacturing workflows.

In the context of Human-Computer Interaction (HCI), this research contributes to the development of passive, materially embedded interfaces. It challenges the assumption that interactivity must involve visible indicators, sensors, or electronics, and instead shows that structural and material logic can enable machine-readable interaction without user-visible cues. The use of NIR aligns with practices in automation and computer vision, further integrating material-based design into digital recognition systems.

In summary, while the field of embedded material markers has been dominated by 3D printing, this research demonstrates that weaving—through compound layering and material selection—can achieve comparable results in a fundamentally different manufacturing context.

Both 2D and 3D woven textiles present viable opportunities for integrating data markers, each with distinct benefits and constraints. The outcomes of this study suggest new directions for durable, non-electronic, and scalable approaches to data embedding in textile systems.

A key limitation was the lack of transparency regarding yarn composition and dyeing processes. Despite their identical appearance under artificial light, yarns behaved differently under near-infrared (NIR) imaging. These differences could not be traced to specific dye formulations or treatments, as such information is rarely provided by suppliers. Kaur et al. (2024) demonstrated that even minor variations in dye concentration and temperature can significantly alter NIR reflectance, reinforcing the difficulty of predicting yarn performance. This unpredictability makes it unclear how other dyed yarns—especially those using synthetic, reactive, or natural dyes—will respond under NIR.

This study was limited to only three yarn types: 100% cotton, 100% polyester, and 100% wool, all in black. While this allowed for controlled material testing, it restricts the generalizability of the findings. There is no current evidence on how yarns in other colors behave under NIR imaging. As pigment chemistry strongly influences light absorption and reflection, the NIR properties of colored yarns remain a significant gap in knowledge.

In particular, the presence of carbon black in many black synthetic yarns poses a known obstacle, as this pigment absorbs NIR light and blocks contrast formation (Sagitto, 2023; Hossain, 2023).

Although NIR-transparent black pigments are being developed (Ampacet, 2020), their use in commercially available yarns is limited and undocumented.

As a result, yarn classification in this study was based entirely on empirical testing, reducing replicability and limiting scalability across different supply chains.

Another constraint is the number of yarns required to produce effective embedded contrast. With current materials, it was not possible to generate NIR-readable zones using only one yarn. At least three to four distinct yarns were necessary in each layered structure. This increases the textile's thickness and complexity, reducing its suitability for applications requiring flexibility, thinness, or soft drape.

This complexity also impacts conventional design workflows. Designers generally select yarns based on visual, tactile, or functional criteria, without access to information about their optical properties under NIR imaging. The absence of predictive digital tools means that integrating machine-readable markers currently relies on trial-and-error, making the process time-consuming and limiting scalability. To embed these markers effectively and efficiently, the development of digital design aids—such as simulation software and material databases that model NIR behavior—is essential. Such tools would allow designers to incorporate optical functionality early in the design process, balancing aesthetic and structural requirements while reducing reliance on costly physical prototyping.

The use of a fixed white cotton warp on the TC2 loom further restricted testing. This introduced a reflective background that affected all woven samples and prevented testing with other warp materials. As the warp could not be changed, certain layer configurations and optimizations were not possible.

The pre-weaving phase required extensive manual classification of each yarn's NIR behavior. While necessary for the study's accuracy, this approach is not practical at scale without standardized material data or automated testing workflows. Integration into manufacturing would require tools such as hyperspectral analysis or NIR-specific labeling from suppliers.

All detection tests were conducted in static, controlled lighting conditions. The system's behavior under real-world conditions—such as fabric movement, varied angles, or different scanning distances—was not evaluated. These factors are critical for implementation in automated sorting lines, wearables, or tracking systems where reliability across varying conditions is essential.

6.1 Recommendations for Future Research

This research demonstrates the feasibility of embedding invisible, machine-readable information into woven textiles using the near-infrared (NIR) behavior of commercially available yarns. Based on the outcomes and limitations of the current work, the following directions are recommended for further investigation:

Expand the Range of Yarn Colors and Finishes

This study focused on black-dyed yarns to ensure visual uniformity and maximize contrast under NIR imaging. Future research should explore yarns dyed in other colors and with different finishes to assess how dye chemistry and surface treatments influence NIR absorption, reflection, and transmission. This will help evaluate whether the approach can be applied to a broader range of textile types and aesthetics.

Investigate Weave Structures and Their Influence on Contrast and Readability

While a few weave structures were applied in this study, and a compound structure was specifically designed to embed contrast, weave structures were not systematically studied as a variable. Future research should explore how different weave architectures—such as plain, twill, satin, and multilayer interlacings—affect NIR visibility and the readability of embedded information. Understanding the role of interlacement logic, yarn floats, and density could offer new ways to optimize structural encoding within woven textiles.

Support a Range of Fabric Hand Feels and Aesthetic Qualities

Rather than minimizing textile thickness, future research should explore how NIR-based contrast can be achieved across a wide variety of fabric weights, drape qualities, and surface textures. This includes lightweight, soft textiles as well as thicker, more structured materials. Adapting the method to different material properties will expand its applicability across sectors such as fashion, interiors, and technical design.

Evaluate Performance Under Real-World Conditions

All testing in this project was conducted under controlled, static conditions. To assess practical usability, future research should evaluate the performance of embedded markers during movement, folding, stretching, and under varying lighting and scanning environments. This will support validation in real-life scenarios, including industrial sorting, wearables, or traceability workflows.

Explore Pattern Resolution and Data Capacity

Further work is needed to determine how small or complex a woven pattern can be while still maintaining legibility under NIR imaging. Identifying the limits of resolution, spacing, and contrast will support the design of more compact or information-dense markers that can be integrated unobtrusively into textile surfaces.

Develop Structured and Machine-Readable Encoding Systems

This study focused on visual contrast rather than structured data representation. Future research should explore how machine-readable formats—such as binary codes, grid layouts, or fiducial patterns—can be embedded into textile structures in ways that are both technically readable and structurally compatible with industrial weaving. This would allow textiles to function as passive data carriers for identification, sorting, or interaction.

Assess Material Consistency Across Production Sources

Yarns with similar specifications showed different behaviors under NIR imaging, likely due to undocumented differences in dye composition or finishing. Future research should evaluate this variability across suppliers and production batches, and work toward establishing predictable material performance for NIR-responsive applications.

Include Durability and Lifecycle Testing

While durability was not a primary focus of this study, long-term behavior remains a critical factor. Future work should assess how embedded contrast responds to washing, abrasion, UV exposure, and thermal stress. This is particularly relevant for circular applications where textiles must retain embedded data across extended lifecycles.
These directions aim to strengthen the technical, structural, and material understanding required to scale woven NIR marker systems into robust, traceable, and industry-compatible solutions.

Connect Embedded Data with Product Ecosystems and User Value

As woven materials begin to interact with digital systems and service infrastructures, future research should investigate how embedded textile markers can support broader product ecosystems. This includes enabling functions such as traceability, authentication, maintenance tracking, or recycling guidance through integration with digital platforms. Exploring how these embedded data points contribute to the product lifecycle—from production and use to reuse and recovery—can help ensure that material innovation is aligned with real-world needs. Designing these systems with users, manufacturers, and service providers in mind will be essential to deliver meaningful, accessible, and future-ready applications.

7. CONCLUSION WOVEN MEMORY: EMBEDDING INVISIBLE MARKERS TO ENHANCE DIGITAL TRACEABILITY

Every textile carries a history. Some hold it in visible patterns, others in wear and use. But what if a textile could carry memory invisibly—woven into its structure, retrievable only by machines tuned to a different spectrum of light? This research set out to explore that question, asking not how to add data to textiles, but how to make data part of the textile itself.

This thesis investigated how invisible, machine-readable data can be embedded and retrieved from woven textiles using near-infrared (NIR) imaging. The focus was not on coatings, tags, or electronics, but on the behavior of yarns —specifically 100% cotton, polyester, and wool, all black in color—under NIR light. Through a systematic classification of their optical responses, it became possible to identify how some yarns transmit, some absorb, and some reflect infrared light. This enabled the design of layered structures that appear uniform under artificial light but reveal contrast under NIR imaging.

Across four stages of experimental work, yarns were tested, layered, and woven into controlled prototypes. A final demonstrator confirmed that contrast-based data can be embedded structurally into textiles without altering their surface appearance. These embedded zones remain invisible to the human eye but can be accessed by NIR-enabled machines—offering a passive, durable, and tagless approach to material identification.

While the method relies on multiple yarn types and remains limited in its flexibility, thickness, and color range, it demonstrates a foundational principle: textile memory can be designed, embedded, and retrieved through material logic. This concept has direct relevance for traceability frameworks like the EU's Digital Product Passport and broader circular economy initiatives.

The woven memory created in this research is not yet scalable or universal—but it shows that textiles can carry more than form and function. They can carry information, silently and invisibly, across the full span of their lifecycle.

8. PERSONAL REFLECTION

It started with a simple question: can a textile hide information and reveal it only under the right conditions? At first, it felt like an abstract idea—too technical, maybe even impossible. But as I began testing yarns, layering materials, and capturing contrast through technology, the idea took shape.

What I learned is that with the right technology and a supportive team, even unconventional concepts can become real. Manufacturing wasn't a barrier—it was a tool. Weaving became a way to code, and textiles turned into carriers of memory.
This project showed me that the line between the visible and invisible is not fixed. It can be designed, woven, and revealed—if you're willing to experiment.

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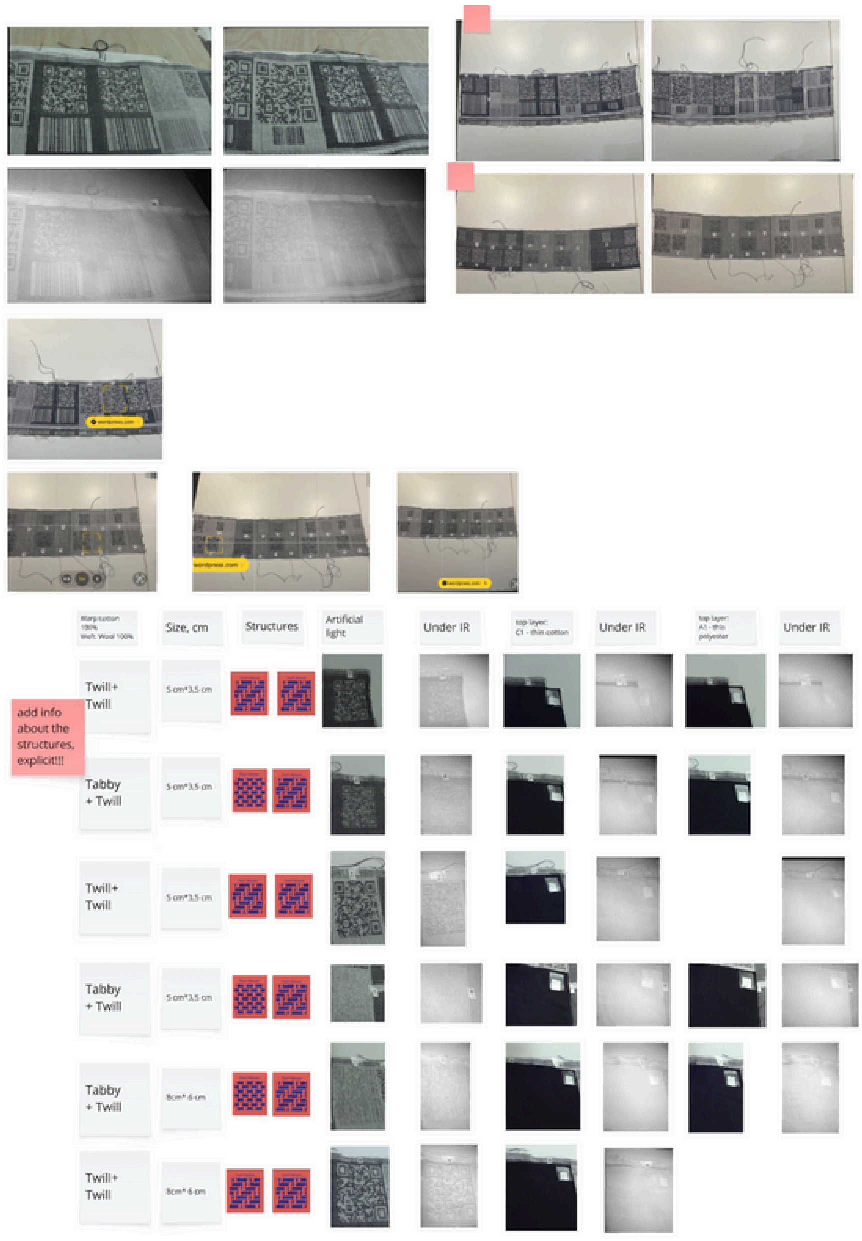
APPENDIX 1A

Test of Combination of White Textiles

APPENDIX 1B



Tests of Weaving Structures and Readability of QR Codes

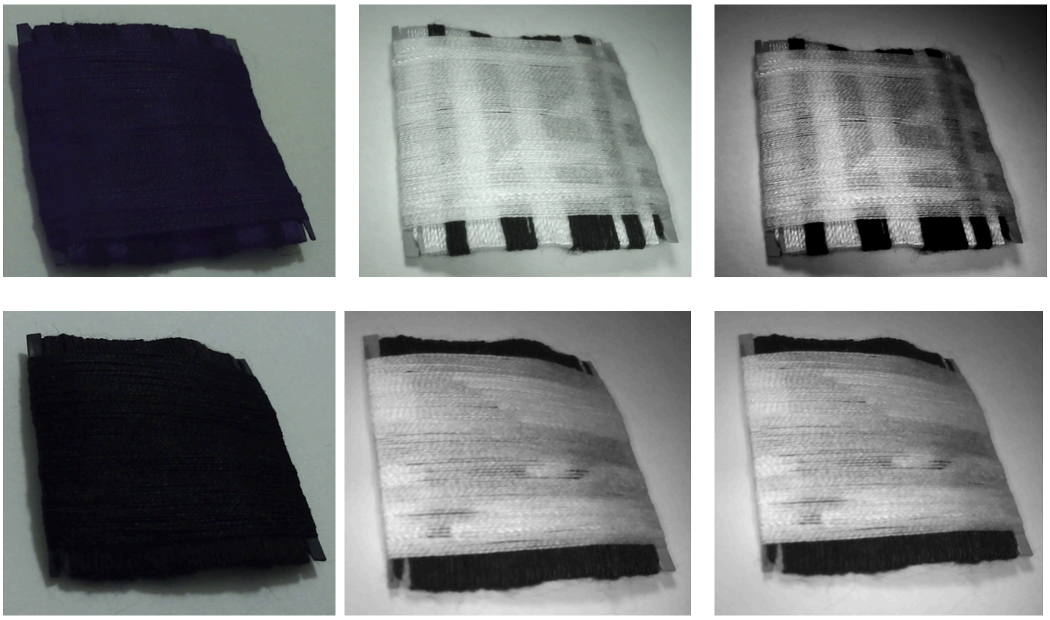


Photo under Artificial Light

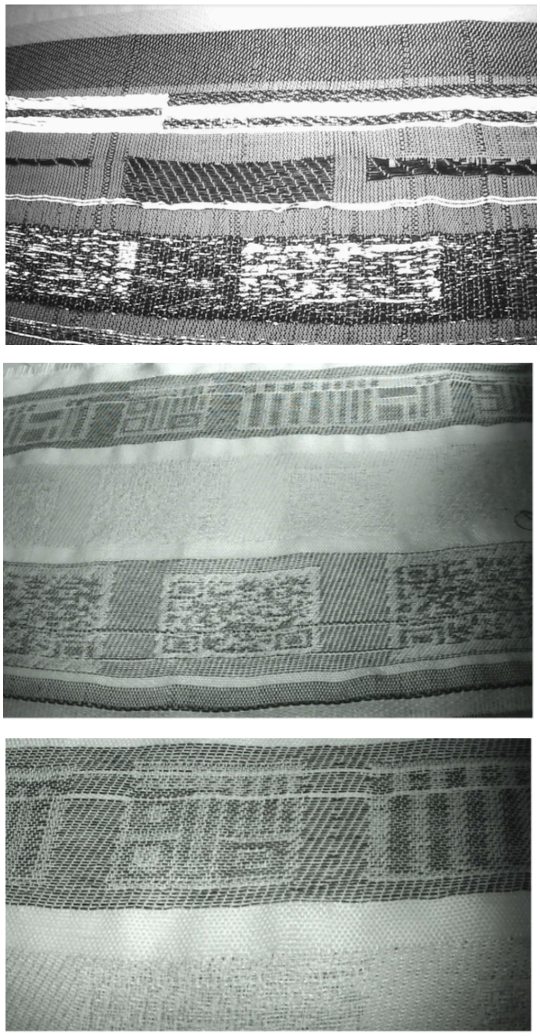


Photo under NIR

APPENDIX 1C

Literature Review approach

APPENDIX 1D

DESIGN FOR our future

TU Delft

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME
Complete all fields and indicate which master(s) you are in

Family name	Zelenina	IDE master(s)	IPD ☐ Dfl ☐ SPD ✔
Initials		2nd non-IDE master	
Given name	Yulia	Individual programme *(date of approval)*	
Student number	5624479	Medisign	☐
		HPM	☐

SUPERVISORY TEAM
Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair	Holly Mcquillan	dept./section	SDE, MF
mentor	Jacky Bourgeois	dept./section	SDE, KInD
2nd mentor	Mustafa Doga Dogan		
client:			
city:	Delft	country:	The Netherlands
optional comments	The chair mentor and the 2nd mentor have agreed to supervise the SPD student's thesis, believing the project is interesting and can benefit all participants' research and professional development.		

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in **by the Chair** of the supervisory team

Sign for approval (Chair)

Date: 2024.11.18 13:31:30 +01'00'

Name Holly McQuillan Date 18/11/2024 Signature

CHECK ON STUDY PROGRESS

To be filled in **by SSC E&SA** (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total ______ EC

Of which, taking conditional requirements into account, can be part of the exam programme ______ EC

	YES	all 1st year master courses passed
	NO	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

Name ______ Date ______ Signature ______

APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES		Supervisory Team approved
NO		Supervisory Team not approved

Comments:

Based on study progress, students is ...

	ALLOWED to start the graduation project
	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

Name ______ Date ______ Signature ______

Personal Project Brief – IDE Master Graduation Project

Name student Yulia Zelenina **Student number** 5624479

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Embedding Data into Textiles: Designing for Digital Product Passport Compliance and Manufacturing

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

Introduction

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

We are exploring the integration of data into textiles in alignment with the upcoming Digital Product Passport (DPP)legislation, set for 2027. The DPP will require product-related data to be embedded directly into materials, a direction we believe holds significant potential for innovation.
The project focuses on various methods of embedding and connecting data within textiles, including the creation of digital traces. We aim to investigate how these data-carrying textiles can foster collaboration among stakeholders across the supply chain, bridging gaps and enhancing transparency. By exploring concepts like data physicalization, we will examine how to engage stakeholders effectively in the process and ensure the data embedded serves a meaningful purpose.
We plan to develop prototypes that demonstrate how these integration methods align with DPP legislation, highlighting their practical applications for future manufacturing and compliance. This research approach not only advances the field but also showcases the potential of data-embedded textiles to reshape circular practices and regulatory adherence.

References:
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https://www.sciencedirect.com/science/article/pii/S0959652622051125?via%3Dihub

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introduction (continued): space for images

click to add picture

image / figure 1

image / figure 2

Personal Project Brief – IDE Master Graduation Project

Problem Definition

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

This project addresses the challenge of embedding product-related data into textiles to comply with the forthcoming Digital Product Passport (DPP) legislation, mandated for 2027. As detailed in Threads of Traceability, textiles must evolve from passive materials to active carriers of vital product information throughout their lifecycle (https://dl.acm.org/doi/10.1145/3643834.3661531). The DPP will require the integration of key data—such as material composition, origin, and circularity practices—making textiles essential for ensuring transparency and enhancing consumer engagement.
However, current manufacturing methods lack standardized approaches for embedding this data without compromising the aesthetic quality of the fabric. Traditional tags and labels, often removed by consumers, undermine traceability and limit the garment's ability to share information. Our project seeks to explore innovative techniques for embedding data directly into textiles, including woven identifiers, digital traces, and QR codes, to ensure compliance with DPP requirements while improving the user experience.
Furthermore, we aim to investigate innovations in the supply chain, particularly within companies like PVH and Trimco Group, to identify opportunities for advancing compliance with legislation while fostering innovation. This approach presents a unique opportunity to transform textiles into interactive materials that promote collaboration among manufacturers, consumers, and regulators.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design an approach for developing data-embedded textiles to improve product transparency and traceability for consumers and manufacturers in the context of the upcoming Digital Product Passport (DPP) legislation, culminating in a functional prototype that demonstrates this integration within the sustainable fashion industry.

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

The approach for this graduation project employs a research-through-design methodology, integrating qualitative research and iterative design processes to develop data-embedded textiles aligned with the Digital Product Passport (DPP) legislation. Initially, a comprehensive literature review will inform the understanding of existing data integration methods, such as QR codes, RFID tags, and woven identifiers.
Qualitative interviews with stakeholders—including consumers, manufacturers, and sustainability experts—will gather insights on their needs and expectations regarding data transparency in textiles. This will be complemented by data analysis to identify key themes and patterns from the interviews.
Based on these findings, the project will focus on creating a strategic framework for effectively embedding data into textiles, ensuring the final design solution meets stakeholder requirements while promoting circularity and compliance with DPP standards. This methodical approach will facilitate the development of innovative textile solutions that enhance product transparency and traceability in the fashion industry.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	10.10.24
Mid-term evaluation	03.02.25
Green light meeting	12.05.25
Graduation ceremony	02.07.25

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	✔
For how many project weeks	33
Number of project days per week	3

Comments:
The following holidays are included in the timeline: 27 october-3 November 2024; 21 Dec 2024-5 Jan 2025; 18-21, 27 April and 5 May 2025

Motivation and personal ambitions

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

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

I am eager to begin my master's graduation project, which explores the intersection of textiles and technology in the context of the upcoming Digital Product Passport (DPP) legislation. My motivation stems from a strong interest in circular fashion and the potential of data-embedded textiles to enhance transparency in the supply chain. This project aligns with my goal of contributing to circular design by addressing environmental challenges through data integration in textiles.
I aim to expand my skills in research methodologies, stakeholder engagement, and design thinking—developed during my MSc program—while deepening my understanding of data integration using tools like QR codes and RFID. I will also explore various weaving and knitting techniques and analyze relevant literature, including government documents, to understand policies such as the DPP.
My learning objectives include:
Knowledge: Understand circular practices in fashion and how data can support these initiatives.
Technical Skills: Experiment with design software and textile techniques to visualize data-embedded textiles.
Document Analysis: Analyze government documents and policies relevant to the project.
This project offers a unique opportunity to combine my academic background with my interest in circular innovation in fashion.

Project timeline Planning

	A	B	C	D	E	F
1	TASKS	Kick-off	Project work. Mid term	Project work	Project work	Wrap-up
2	Draft project brief and get it approved, Compose supervisory team and kick-off meeting	10/Oct	03/Feb	12/May		02/Jul
3	Conduct literature review.					
4	Analyze collected data and summarize findings					
5	Define research and design methods					
6	Develop a clear approach for prototyping and testing					
7	Build initial prototypes					
8	Test methods and gather feedback					
9	Submit midterm evaluation form and attend formal evaluation					
10	Adjust methods based on midterm feedback					
11	Collect more data if needed and refine prototypes					
12	Complete 80% of the final thesis draft					
13	Prepare for the green light meeting					
14	Review and secure final approval for the graduation date					
15	Finalize thesis and prepare for the public presentation					
16	Submit the thesis and deliverables before the graduation day					
17	Present project and attend degree audit and evaluation.					
18	* Due to the part-time nature of the thesis, the team will meet once a month to evaluate the progress of the thesis.					

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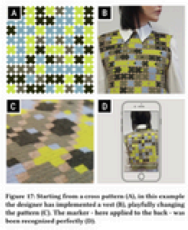

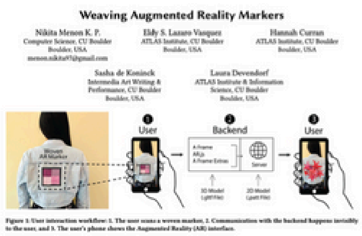

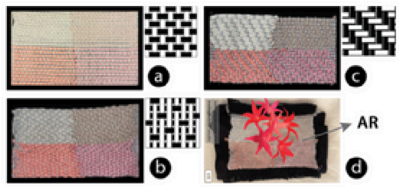

Figure 3: a. Plain weave, b. Satin weave, c. Twill weave, d. Woven AR marker recognition