Garment Device:
Challenges to Fabrication of Wearable Technology

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ABSTRACT
Smart garments, also known as wearable technology are designed with textiles engineered to perform specific functions. Progress in intelligent yarns and fibers present viable opportunities to design garment devices embedded with technology. This paper discusses the importance of a multidisciplinary team to advance research on smart textiles, and the use of digital fabrication as a viable method of production. Using Shima Seiki CAD systems and machinery, virtual knit designs are developed with modeling software, then realized into actual products by means of computer driven knitting machines. Akin to 3D printing, computer aided knitting is a form of digital fabrication for prototypes but can also be utilized to produce final products and scale manufacturing.

General Terms
Performance, Design, Reliability, Experimentation.

Keywords
Digital fabrication, digital knitting, garment device, iFibers, intelligent fibers, intelligent yarns, iYarns, knit simulation, mass customization, seamless knitting, smart garment, textile device, 3d knitting, wearable technology

1. INTRODUCTION
Smart garments also known as wearable technology are designed with textiles engineered to perform specific functions such as sensing and monitoring of vitals in patients and athletes. [3] The field of wearable technology is poised to explode in the next 10 years and has received considerable attention from various industries including medical, military, safety, high fashion and active sportswear. [6] Many wearable electronics currently on the market include well-known examples such as Nike Fit, Addidas MiCoach, Cutecircuit's Galaxy Dress and T-shirtOS, and the "hi-call" Bluetooth enabled phone-glove. It should be noted that these devices still use some form of conventional "hard" electronics, pointing to the challenges that still remain for fully integrated textile devices to become a reality.

Wearable technology presents new design challenges that cannot be solved without multidisciplinary efforts. [13] This paper discusses our approach to finding methods of production that

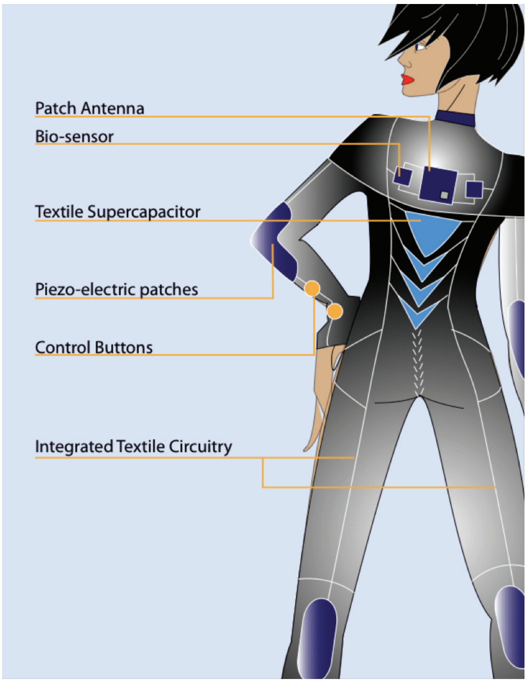

Figure 1. Concept of a garment device with integrated systems

can help advance the field of wearable technology, combining theoretical and experimental work in diverse disciplines for the successful design, production and true *wearability* of smart garments. We discuss our conceptual approach to adaptive production design methods where solutions for innovative power supply, integration of electronics/circuitry and communication system can be addressed from prototyping to full-scale production. (figure 1)

2. CONCEPTUAL APPROACH
In our initial work on smart textiles we explored concepts primarily based on the garment's aesthetic, similar to the work of fashion designer Hussein Chalayan. Through our research we quickly found that this type of work could not be mass-produced because of power supply limitations and other required hard bulky components, compromising design integrity. We subsequently sought to form a multidisciplinary team to develop fundamental components for smart textiles and a future generation of smart garments, which we refer to as textile and garment *devices*. Rather than viewing garments as containers of electronics, lets imagine garments as devices themselves, blending modes of communication and actuation directly into wearable textiles. Garment devices incorporating ergonomics

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and electronics into textile structures, have the potential to be soft and comfortable. These devices could literally transform the body into an interactive interface. [14,15]

2.1 Garment Device Fabrication

While the production of garment devices is informed by current manufacturing methods from both the garment and electronics industry, there is a need to develop new integrated approaches to textile device manufacturing in order to address issues intrinsic to the field. [9] As pointed in the examples above, smart garments are currently blending the traditional textile cut and sew approach, with electronics added to the garment by inserting hard removable components in various "pockets". Garment devices will need to meet the requirements of both industries and be much more rugged than any of our existing electronic devices. Not only will we demand that our garment devices perform as well as any of our current portable devices, we will also want them to be thin, comfortable, durable, washable and stretchable just like what we wear every day. [9]

For garment devices to become a reality, more research is needed in new materials, especially *intelligent* yarns and fibers (iYarns, iFibers) that can be combined with existing ones. [3, 12] There is also a need to rely on proven flexible and reconfigurable state-of-the-art production methods currently available in the garment industry. In order to address these issues, Drexel University has formed a multi-disciplinary collaboration that includes industrial and fashion designers, material and electrical engineers, computer scientists and medical doctors. Perhaps most importantly we have industry partners such as EY technologies providing design and fabrication of iYarns; and Shima Seiki, a global leader in 3D knitting simulation software and advanced computerized knitting systems. These systems not only enable rapid prototyping of garment structures incorporating iYarns for testing and evaluation, but can also be utilized to produce final products and scale manufacturing. These are key components to the success, prototype testing and production of future garment devices.

2.2 Knitting: An Adaptive Production Method

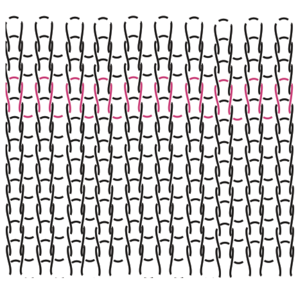

Figure 2. interconnected loops of a knitted fabric

Knitting is known as the intermeshing of yarns into loops resulting in fabric, it is an ancient form of textile production used extensively in the fashion industry. (figure 2) Today knits are widely used in active sportswear where the loop structure combined with elastic yarns can produce garments that offer freedom of movement, comfort and shape retention. Form fitting garments that stretch as the body moves can be blended with iYarns and engineered to perform specific functions, effectively creating garment devices. Knitting is a proven method of garment production, interconnected to fashion for hundreds of years. The first mechanical knitting machine dates back to 1589, a stocking frame invented by Englishmen William Lee. Knitting is an early form of 3D fabrication that can be done by hand with a single set of needles or by the most advanced knitting machine. Flat bed knitting machines have hundred of needles and dozens of yarn carriers yet, loops of yarns are still mechanically formed one by one and laid down one row at the time. (figure 3) Additionally, creative arrangements of the loop structure combined with the ability to bring many different types of yarn to the knit architecture, can lead to the creation of seamless three-dimensional shapes. A review of garment manufacturing methods over the past decades considers seamless knitting amongst one of the most promising form of innovative fabrication for garments. [12]. Knitting enables us to; explore versatile design concepts that allow rapid reconfiguration of form and rapid substitution of materials; investigate sustainable and mass customizable manufacturing methods for economic viability of production including minimizing labor and material waste; leverage the capabilities of existing mass production equipment that incorporate digital fabrication.

Figure 3. *(left)* Industrial flat bed knitting machine *(right)* Yarn carriers over a needle bed

2.3 Knitting And Digital Fabrication

It is our belief that computer aided knitting can be viewed as a form of digital fabrication similar to 3D printing. Digital fabrication suggests flexibility in production with an array of different kinds of materials, it is generally understood as virtual designs developed with modeling software that are produced by means of computer driven equipment. [4] Shima Seiki has designed their own proprietary modeling software to run their equipment. Their technological developments in knit simulation and virtual sampling have made possible the use of their knitting equipment as rapid prototyping machine with the ability to mass-produce as needed. [2] With this software, computer interfaced machine knitting has essentially entered the world of digital fabrication, transforming this mechanical fabrication method into an emerging technology relating to the design process as well as manufacturing realms.

The current modeling software however limits digital modeling of complex knitted forms, pointing to parametric modeling as the next logical step in software development, similar architecture and industrial design. Here it is interesting to point out that a parametric knit modeling software has been developed for animation characters. [1] Though not translatable to knitting machine language, programs of this kind could lead to new ways of understanding knitting in 3D form without having to master the esoteric technicalities of knit programming. [17] Like 3D printing, state of the art computer controlled knitting machines capable of 3D knitted construction hold considerable potential for innovative design solutions. In addition, knitting machines currently have more flexibility in production than a 3D printer given that a large array of materials, yarns and iYarns, are readily available for experimentation and production. Virtual 3D knitting can allow this ancient method of mechanical production to play an important role in the digital fabrication of garment devices and various complex 3D forms. Additionally, if finite element analysis (FEA), a computer model of materials that can be stressed and analyzed in a virtual environment, [18] could be incorporated in the knit modeling software, one would be able to test how a proposed design would perform prior to manufacturing.

Parametric software that could connect to the current Shima Seiki knit programming software would unlock the possibilities of this technology. There would still need to be some necessary translation to the machine language given the mechanical nature of the equipment but to close the gap would exponentially grow this already versatile technology. At present we can program and knit a variety of forms with some degree of program automation. Arbitrary shapes can be experimented with and components that fit together can be fabricated. We are experimenting with different types of materials from conductive yarns to carbon fiber.

3. DESIGN PATH TO GARMENT DEVICES

It is currently possible to use the Shima Seiki system to design and knit virtual garments of predetermined styles, specify their size and color and check them for accuracy and fit on avatars.

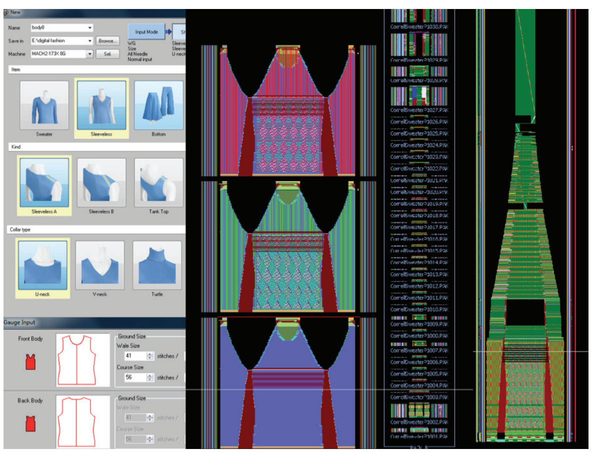

Figure 4. Automated software *(top left)* Garment library *(bottom left)* Imput of machine gauge and garment size *(middle)* Automatic garment development *(right)* Garment in machine language

Figure 4 demonstrates how this is achieved by: accessing the garment library: choosing a specific style and size: and automatically processing the file into knitting machine language. Garments can be simulated and virtually knitted with various types of yarns and specific colors, the virtual sample can be checked for accuracy before being knitted on the machine. Figure 5 shows the digital product we created next to the actual product fabricated by a machine in our laboratory. Additionally new aspects of the software allow us to bring in an avatar and draw design line on 3D forms to create patterns to be knitted. It is now possible to not only introduce structural knits directly onto a virtual model, but also to make changes to the knit structure in real time. With this equipment, we set out to design smart garments, leveraging current technology to develop new modes of fabrication for garment devices, while exploring the development of a more parametric system that incorporates FEA. The following sections describe two examples of our current research activities and our exploration of knitting textile devices in the digital fabrication realm.

Figure 5. Digital fabrication *(left)* Digital top *(middle)* top as it comes out of the machine *(right)* Actual garment

3.1 Prescription Manufacture

In this project we explore customized manufacturing of garment devices that blend modes of medical diagnostics and functional technologies into wearable textiles to improve patient care and safety. Wearable sensors can provide a means to monitor the wearer's health through physiological measurements in a natural setting or can be used to detect and/or alert the wearer or physician of potential emergency needing immediate medical attention. Fabric sensors are being widely studied in the field of wearable technology and are viewed as essential components of electronic textiles. [10] Prescription Manufacture set out to incorporate comfort and ergonomics into new types of medical instrumentation using the flexible and reconfigurable production method of computerized knitting systems. We are experimenting with digital fabrication that can be translated to and/or generated by the Shima Seiki software and knitting machines. In our work, although it is not yet possible to construct complete virtual models that can be directly knitted on the machine, a close approximation of the actual product can be visualized before being made by using different component of the knitting system.

An example of a product currently under development is a maternity smart fabric bellyband to monitor uterine activity and assess fetal wellbeing. This project leverages new development in iFibers, iYarns and knitting technology as well as passive radio frequency identification (RFID) for the creation of a

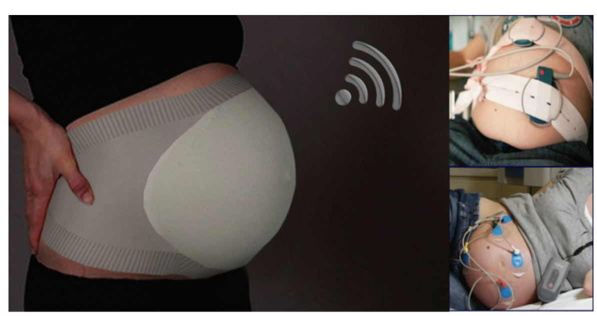

Figure 6. Smart Fabric Bellyband - Garment Device to replace current bulky equipment

wearable wireless telemetry device that reduces bulk, improves comfort, and enables greater mobility in pregnant women. (figure 6) For the bellyband, we experimented with digital fabrication of different shapes that would use iYarns in the knitting machines to make the passive RFID. We considered a

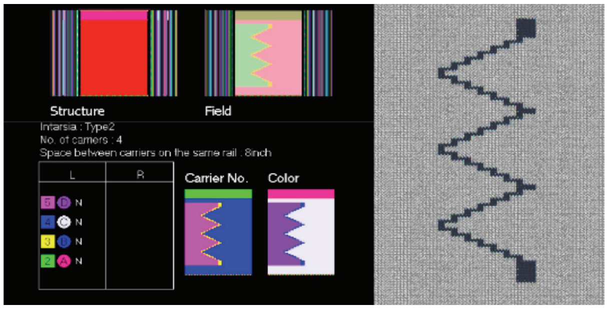

Figure 7. Examples of digital knit fabrication
(left) Automated antenna program *(right)* Virtual sample

multitude of conductive pathway designs for our antenna. [11] Although we were able to use the automatic software functions to knit virtual samples for evaluation of the design before sending it to the knitting machine, (figure 7) all had to be physically knitted and tested for feasibility given that FEA is not currently possible with the current knitting software. Using the patternmaking software, we created a pattern for the bellyband's overall design and exported it to the 3D software. We then assigned elasticity and stiffness to represent the knitted fabric, virtually stitched the pattern and checked it for fit on a pregnant avatar, including pressure and tension of the cloth on different parts of the body. The final pattern shape was exported to the knit programming software. In this final step, the bellyband pattern is combined with the RFID design to produce the actual bellyband. Though these steps are not fully automated, they provide helpful information to fine tune the knit program and give a close approximation of the final size and shape needed for the prototype. (Figure 8)

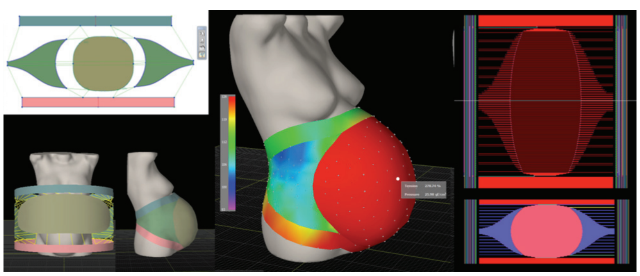

Figure 8. Bellyband fabrication process
(top left) Bellyband pattern *(bottom left)* Virtual stitching process *(middle)* Tension and pressure of the cloth *(right)* Pattern shape in machine language

These new types of garment devices will provide patients discrete monitoring allowing them to remain mobile, comfortable and active. Garment devices not only have the ability to monitor patients they have the potential to administer custom remote treatments by a physician, effectively becoming devices with diagnostic networks and treatment systems. However, given that the majority of body sensing technique were developed to be used in controlled environments that are not suitable for everyday life, both physically and socially, [5] for these devices to be effective and ubiquitous in every day life, new models of sensing and actuation must be established. Wearable mobile health monitoring is gaining momentum but it is still lacking solutions in the manufacturing processes, robust communication systems and adequate power sources.

3.2 Textile Supercapacitor

A fundamental challenge for garment devices is electrical energy storage. Supercapacitors are energy storage devices made with activated carbon material that can provide high current pulses. [16] If combined with low power energy harvesting devices as power supply, they could eliminate the need for batteries in application such as wireless sensor networks in garments. Ultimately our goal is to combine these many devices into a single garment device. In our previous work we screen printed woven cotton and polyester electrodes with activated carbon as first proof of concept for a textile supercapacitor. [7] We then successfully incorporated spun carbon fiber yarn into a knit architecture to fully integrate the supercapacitor directly into the textile. [8] To fully address the integration of the supercapacitor into a garment, the next generation of spun carbon fiber yarn is being designed to better meet *wearability* requirements of garment devices. Figure 9 shows an example of a virtual prototype intended to demonstrate how energy storage devices can be paired with energy harvesting materials, to power and charge small portable electronics, wearable sensors or antennas.

Figure 9. Virtual prototype of a garment device

Examples of our research show how digital fabrication and virtual sampling allow design ideas to be flushed out, carefully considered and understood by all members of a multidisciplinary team. Additionally, automation provides economy of material use in sampling, particularly for expensive, highly specialized yarns. Knit fabrication for garment devices is an especially valuable tool given the expense and rarity of smart materials. Samples can be produced one at the time for testing and evaluation with minimal cost for additional set up. Once a prototype is approved, it can be scaled up for production on the same equipment by simply making the piece as many times as desired.

4. CHALLENGES

Virtual simulation of fabric remains complex, highly variable and difficult. Fiber type and blends together with yarn twist provide for infinite variation of materials that can be knitted. Figure 10 shows two gloves knitted on the same machine from the exact same file, the different types of yarn yielded vastly different glove size. For digital fabrication to become a reality in knitting, modeling software and FEA that can reflect different

Figure 10. two gloves knitted on the same machine from the

types of yarns to predict accurate size of the end product is needed. However, the promise of combining the rich history of knitting with powerful simulation software could positions this ancient production method as a key player in 21 Century manufacturing, allowing flexibility and ease of fabrication.

5. CONCLUSION

In our research we aim to develop wearable technology through the exploration of versatile design concepts, and investigate manufacturing processes that are sustainable and mass customizable. Garment devices have the potential to become expressive technology or customizable diagnostic and treatment networks. Our laboratory is dedicated to help advance the field of wearable technology, laying the foundation for modular and flexible production intended for a variety of high performance textiles applications. The integration of digital knit fabrication holds remarkable potential for innovative and customizable design solutions in an array of applications. It offers a future of many opportunities including sustainable methods of production and rapid prototyping. Multidisciplinary research, with strong support from industry partnerships, enables us to fabricate future fabrics and materials that empower designers to create products that can be “smart”, functional and beautiful. A designer’s vision aided by digital fabrication can help fuel and inspire new technological advances and solve production challenges, offering unique applications poised at the cutting edge of research and contemporary design.

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