ABSTRACT

SATAM, DNYANADA SHANKAR. Design and Material Considerations for High Performance Army Combat Uniforms. (Under the direction of Drs. Hoon Joo Lee & Nancy Cassill.)

As the saying goes, *"Necessity is the mother of invention"*, the military requires new modifications in its uniforms to surmount the climatic conditions and to reduce threat of various warfare agents during their mission. The requirement of the hour is for the Army Combat Uniform (ACU) to be better-protective, more breathable uniform fabrics which also have superior mechanical properties. The purpose of this research is to study the design of ACU specifically with the new technologies and materials that could be used for their manufacture.

The design of the ACU is governed by its protective functions, quality, and cost. Along with protection, the key performance features identified include high tensile strength, light weight, fire-resistance, moisture management, and temperature control. The current uniforms are composed of nylon-cotton blended (50/50 NYCO) woven fabrics while the use of nonwoven fabrics has been limited in the manufacture of ACUs. This research presents the parameters required to use nonwoven fabrics and Computer Aided Design (CAD) for the production of the ACU. This work considers the necessity of domestic mass production of defense materials.

Developing a new class of ACU produced with CAD technologies and nonwoven materials, which need advanced manufacturing facilities instead of human resources, could be a stepping stone for the design of new-age ACU. Composite nonwoven fabrics provide all

of these properties along with enhanced durability and wash resistance. In addition, many nonwovens can be ultrasonically bonded to create seams that are impervious to penetration of chemical-biological warfare agents. This research also proposes the idea of incorporating smart textiles into the ACU. A method of producing oleophobic fabrics which can make the uniform protective against chemical-biological warfare agents has also been experimented during the course of this research.

The final output of this research is a House of Quality Matrix (HQM) which explains the intricacies of designing an ACU. This matrix was developed using the concept screening matrix and concept scoring matrix which rank the requirements for an ACU according to level of importance and rate the features and functionality of the current ACU. The HQM matrix could be used for future product development of ACU in order to ensure a systematic approach for the design process.

Design and Material Considerations for High Performance Army Combat Uniforms

by
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DEDICATION

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To my wonderful family and friends

for their loving support and understanding

BIOGRAPHY

Dnyanada Satam was born on February 27, 1986 in Mumbai, India. Her parents are Shankar and Deepa Satam and she has a younger brother Pranav. Dnyanada grew up in Mumbai, India where she graduated with a Bachelor of Technology in Fibers and Textile Processing from Institute of Chemical Technology (ICT), Mumbai, India, one of the leading schools for Chemical Technology globally, in 2007. To get a wholistic industry exposure, she undertook an internship at a technical testing laboratory - Texanlab, India.

She moved to Raleigh, North Carolina in Fall 2007 to pursue her Master's in Textile Technology and Management at North Carolina State University. She was inducted in Phi-Kappa-Phi Fraternity for maintaining an overall GPA of 4.0 during her Master's degree. As a student delegate for the program 'Doing Business in the International Marketplace'-Mexico she learnt about the culture and effective trade practices in an international marketplace and participated in Expo ANTAD international trade show in Guadalajara, Mexico. In Summer 2008 she was an applied research intern at *INVISTA S.à.r.l.* She worked for the consumer brand LYCRA® fiber on technical projects, data analysis and market research for new product development.

Apart from academic and professional networking, she is also interested in reading, traveling, Indian classical dances and music. She is currently completing the requirements for her graduate degree and looks forward to a career in the apparel industry where she can contribute her knowledge and get hands on experience in the field of Apparel Management.

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Introduction

"Clothing is our most intimate environment. What makes it a unique environment is that it is carried everywhere with an individual, creating its own room and its own climate within the larger climate of our surroundings" (Watkins, 1995, xv). Military individuals rely on clothing for protection as well as life support. Military clothing must perform a broader range of functions than most other types of clothing. Since the Second World War improvements in fabric technology have led to dramatic changes in clothing worn by soldiers. Military clothing is no longer viewed as just a means of identification and protection against the elements but is now considered as an integral part of the soldier's fighting kit. There is a growing awareness of the importance of clothing in enhancing the performance of soldiers and protecting their lives during combat (Muran, 2005). Such awareness has prompted militaries around the world to step up their research and development efforts to create the ideal combat uniform.

The ever changing defense domain, due to the wider environment such as finance, society and politics and complex combination of threats and changes, poses significant challenges to the developers and researchers of combat uniforms. The design for combat uniforms is complex because the threats to soldiers constantly change as a consequence of change in the nature and location of warfare and development of new weapons (Sparks, 2008). In addition to considering the functional characteristics to tackle the threats, the designer must also be aware of the basic mission related requirements and their influence on the design and the comfort and fit requirements. Thus, the process of New Product Design is of utmost importance for the development of army combat uniforms.

The U.S. military is second largest in the world, after the People's Liberation Army of China. As of April 2007, about 1.4 million people were on active duty in the U.S. military with a nearly 50/50 split between males and females (2005 est.) (U.S. Department of Defense). To cater to these huge needs, mass production which requires a large labor force is necessary. However, there has been a constant decrease in the number of workers employed in the U.S. apparel industry since the last quarter of the twentieth century due to globalization in the textile industry. This has led to global sourcing and offshore manufacturing (Plunkett Research Ltd., 2007). Meanwhile, labor costs have steadily increased worldwide (U.S Bureau of Labor Statistics, 2008). Due to the continuous growth in labor costs, it is expected that manufacturing units will prefer more mechanized processes, which require less labor. Labor costs can be saved during sewing operations using automated assembly techniques as a consequence domestic production of military clothing will be available.

The current utility fabrics used for military uniform production are woven fabrics consisting 50% nylon and 50% cotton. Some of the recent developments in military clothing include progress in minimizing weight and maximizing wear comfort. Nonwovens, being highly engineered, can be used as fabrics for manufacturing military uniforms. Thus, the dual objective of reducing the work force and gaining large production can be accomplished by applying new fabric materials, such as nonwoven fabrics and automated assembly techniques in military clothing production. The modern war-fighting scenarios and environments that the soldiers face include domestic and foreign terrorism, peace keeping, nation building, low and high density conflicts, special operations, military operations in urban terrain and worldwide climatic conditions (Tassinari and Leitch, 2004). Smart textiles can provide protection to safeguard the troops in these modern battlefield environments. In this research the potential design considerations for Army Combat Uniforms have been studied in terms of application of new materials and production technologies for manufacture of these uniforms.

Purpose of this Study

The purpose of this study is to examine the New Product Design (NPD) process for the military uniforms. This work will specifically examine and identify the opportunities and design phases for Army Combat Uniforms (ACU). This examination will focus on four product requirements: mobility, communication, personal protection, and logistic support. The study will focus on exploring the various material considerations and production technologies that can be used to enhance these features of the ACU. In this research, materials were designed based on science and technology rather than statistics. This study is divided in three phases. The Phase I involves analysis of the new product development process for the military uniforms. The Phase II focuses on an in-depth study of the opportunity identification and the design phases using the Watkins's design process as the conceptual framework for identifying the materials and technologies for high performance ACU. Finally, a House of Quality matrix is developed in the Phase III that will provide as a model for future selection process for technologies to be incorporated in ACUs. The NPD process from Urban and Hauser (1993, p. 38) and the Watkins's design (1995, p. 337) process serve as conceptual framework to study the NPD process for military uniforms and materials and technologies for manufacture of the ACU respectively.

The objectives of this study for the three phases are as follows:

Phase I

1. Study the New Product Design Process (adapted from Urban and Hauser, 1993) for military uniforms.

Phase II

2. Collect information on the current Army Combat Uniform (ACU), including their current features and issues.
3. Study the current threats to the soldiers, by studying the battlefield environment.
4. Discuss the materials and technologies identified, as an opportunity for changes in the ACU and thus study the opportunity identification phase for the ACU.
5. Propose a method for preparing superhydrophobic and superoleophobic surface and prepare a prototype sample showing superhydrophobic and superoleophobic characteristics.
6. Suggest a model for mass customization of ACUs
7. Study of novel sewing techniques for manufacture of ACUs
8. Compare the potential designs vs. the current ACU using a concept evaluation matrix.

Phase III

9. Use the above results to develop a House of Quality Matrix as a future guide for selection of technologies to be incorporated into future ACUs.

The overall research question for this study is: “How can incorporation of nonwovens, smart textiles, and mass customization in the manufacturing of the ACU enhance the functionality of the combat uniforms?” Specific research questions developed from the overall research question are:

1. Should nonwoven fabric be used instead of woven fabric for the manufacture of the ACU?
2. What features could be incorporated into an ACU to make it more functional?

Significance of this Study

There is limited documented research on the use of nonwoven fabrics for the manufacture of the ACU and incorporation of smart textiles into the ACU. There exists no documented research on the application of mass customization and the use of intelligent design models for manufacturing and buying ACUs respectively. This study provides documentation for application of nonwovens and smart textiles, to provide a high performance combat uniform. Along with protection, the key performance features provided by the newly designed uniform include camouflage, high strength, light weight, moisture management, and temperature control. The intelligent design model developed in this study will allow soldiers to buy uniforms online in a more systematic manner. This will also lead to application of mass customization to the manufacturing of the combat uniforms.

Limitation of this Study

1. The high performance combat uniform designed during this study has not been tested for all of the criteria suggested in this research.
2. The intelligent design model for mass customization proposed during this research is hypothetical and has not yet been piloted.

Chapter 2

Review of Literature

New Product Design

New Product Design (NPD) is a term that describes the complete process of bringing a new product or service to market. It can be divided into two stages. The first stage can be termed as the "truth-seeking" early stage, which evaluates the novel products' prospects, and eliminates the risky ones. The second stage can be termed as the "success-seeking late stage", which focuses on maximizing the value of products which are being developed (Bonabeau, Bodick, & Armstrong, 2008). New product design is essential for the organic growth of a company. The main reasons for needing of NPD are: increased competitive pressures deregulation and globalization, exploding product variety, shorter product life cycles shrinking time to market, demand for products that are high performance, and price pressure (IMB & SAP, 2005).

There are several categories of new products. The different characterizations of new products includes changes to augmented products, core product revision, line extensions, new product lines, repositioning, and innovation. These characteristics are displayed in the diagram below.

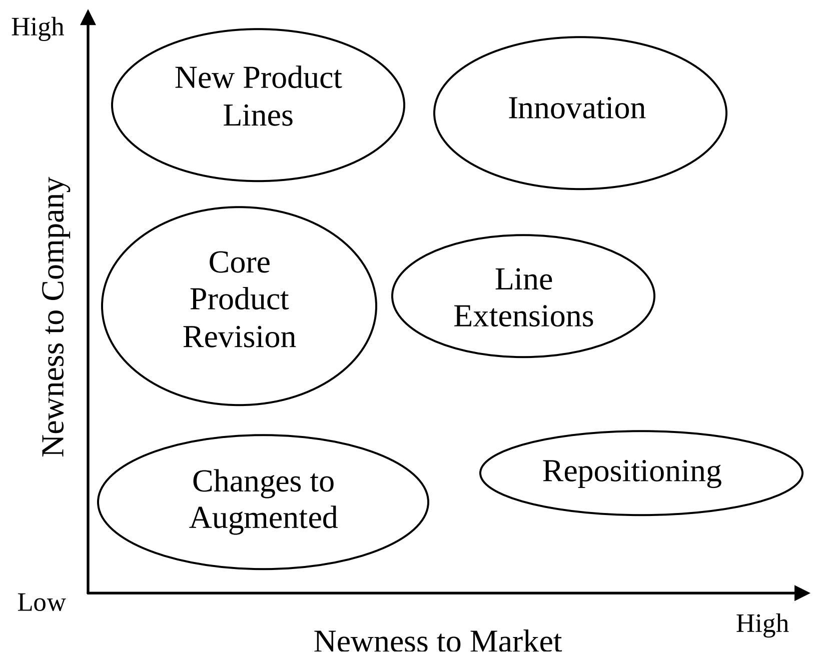


Figure 1. Characterization of New Products

NPD process is becoming increasingly risky, expensive and reliant on disparate knowledge bases that are spread across multiple firms. Urban and Hauser in their book “Design and Marketing of New Products” (1993), describe the NPD process as a five step decision process which includes the steps referred to as: opportunity identification, design, testing, introduction, and life-cycle management.

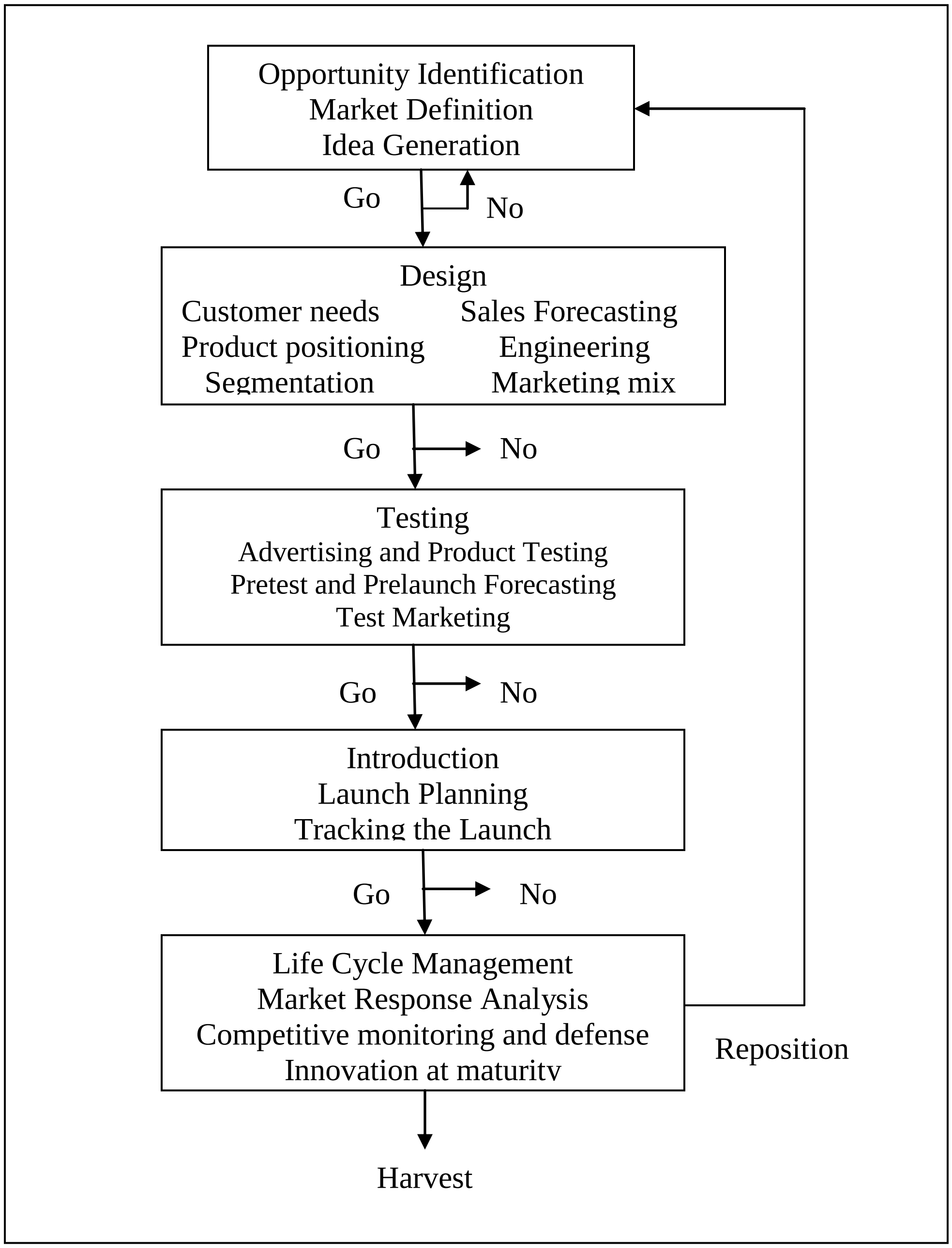


Figure 2. New-Product-and-Service Design Process

Source: Urban and Hauser, Design and Marketing of New Products (1993), pg. no. 38, Prentice-Hall, Inc., New Jersey.

The decision process is a set of sequential activities that minimize risk and maximize creativity. The first step in the decision process is *opportunity identification* which defines the best market to enter and generates ideas that could be the basis of entry. Once the opportunity is identified the next phase is the *design* stage that includes converting the ideas into a physical and psychological entity through engineering, advertising and marketing. The third stage in the decision process is *testing* which serves as a market analysis for both the product and its advertising. If the testing is successful the product is launched due to which it goes to the *introduction* stage of the decision process. The product may be introduced on the full-scale basis or market-by-market basis. The final stage in the decision process is the *life cycle management* that maintains the profitability. At the end of the mature phase the product is either repositioned or redesigned. Use of the decision process enables the new product teams to meet the consumer needs.

Opportunity Identification and Concepts

The first step for implementing the NPD process is to identify the areas of opportunity (markets) and generate ideas to tap potential of these markets. Markets that have high sales potential can be entered early, are competitively attractive, generate economies of scale, require small investments for large awards and are a low risk are likely to be the successful ones. These markets are defined based on demographics, attitude, pricing decisions and consumer needs (Urban and Hauser, 1993). The two most common techniques for market selection are cluster analysis (a groups of customers are formed with same set of characteristics in the same group but different among groups) and substitution among products (set of products that are substitutes for one another are found). The market profile analysis is used to screen the potential markets from a large number of markets. After market definition the organization develops ideas for products to take advantage of identified opportunities. A large number of ideas are generated through direct searches, technological innovation, exploratory consumer studies, facilitating lead user solutions, integration of technology and marketing, national development programs, alliances, acquisitions, and licensing. A screening process is used to select a few good ideas from those generated. This complete step can be coined into a single term called the "Discovery Stage" (Cooper, 2002)

Design

After opportunity identification and market selection, the next step in the NPD process is to design the product physically and psychologically exploit the market opportunity creating benefits for its customers. The Core Benefit Proposition is a short and to the point statement that states the unique benefits that the product provides the customers and also the benefits required to meet and surpass the competition. The design process comprises of three sub-processes: opportunity identification, refinement, and evaluation (Urban and Hauser, 1993).

The stage gate process is a prevalent review process in the NPD process. It is both a conceptual and an operational model for moving new products from idea to launch. After generating and screening, new product ideas and their screening the first stage in the stage gate process is scoping, which is comprised of preliminary market, the technical and business, and financial assessment. At the end of this scoping stage, a recommendation for the project is developed along with a proposed plan of action for stage 2. This is described as the Building Business Case stage or the homework stage. The three main components of the business case are product and project definition, project justification and project plan-the path forward. It is the last stage before the third stage of product development, wherein the actual detailed design and development of a new product or production process takes place. After the development stage the proposed new product is verified and validated with tests and trials in the marketplace, lab, and plant. The final stage of the stage gate process is the launch stage, in which commercialization of the product takes place via market launch and full production start-up (Cooper, 2002).

The Voice of the Customer (VOC) is the stated/unstated needs of the customer. It is a process used to gather feedback from the customer to develop a successful product. Understanding VOC can occur at any of the five stages of the NPD process. It is generally done through product value analysis, focus groups, and sample surveys. VOC can not only solve problems by capturing consumer needs but also lead to other product opportunities.

Testing

The testing stage validates the viability of the product considering the product itself, its production process, customer acceptance and economics. This stage includes the following set of activities (Cooper, 2001):

- In-house product tests: These include laboratory tests to check the product quality and performance under lab conditions.

- User or field trials of the product: Tests the product functions under actual use conditions and estimates the potential customers' reactions to the product.
- Trial, limited, or pilot production: Tests the production processes and are used to determine the precise production costs.
- Pretest market, test market, or trial sell: Studies the consumer reaction and the effectiveness of the launch plan.
- Revised business and financial analysis: Checks the economic viability of the product based on revenue and cost data.

Introduction (Product Launch)

Once the product has been tested the NPD process enters the product launch stage. This involves complete commercialization of the product through both marketing launch and production launch. Even if the product is designed well and tested, there is a risk factor present for achievement of profit goals during the launch of the product because of unexpected changes in consumer, competitive, technological, and economic environments. The Product Launch Process must address all of the steps necessary to start volume production, plan and execute marketing activities, develop needed documentation, train sales and support personnel (internal and external), fill channels, and prepare to install and support the product. An improved product launch process results in faster time-to-market and time-to-profit (Cooper, 2002; DRM Associates, 2002).

Product Life Cycle Management

Product life cycle is a tool to trace the stages of a product's acceptance from its introduction to demise. The product life cycle theory studies the introduction, growth, maturity, and decline stages of the process.

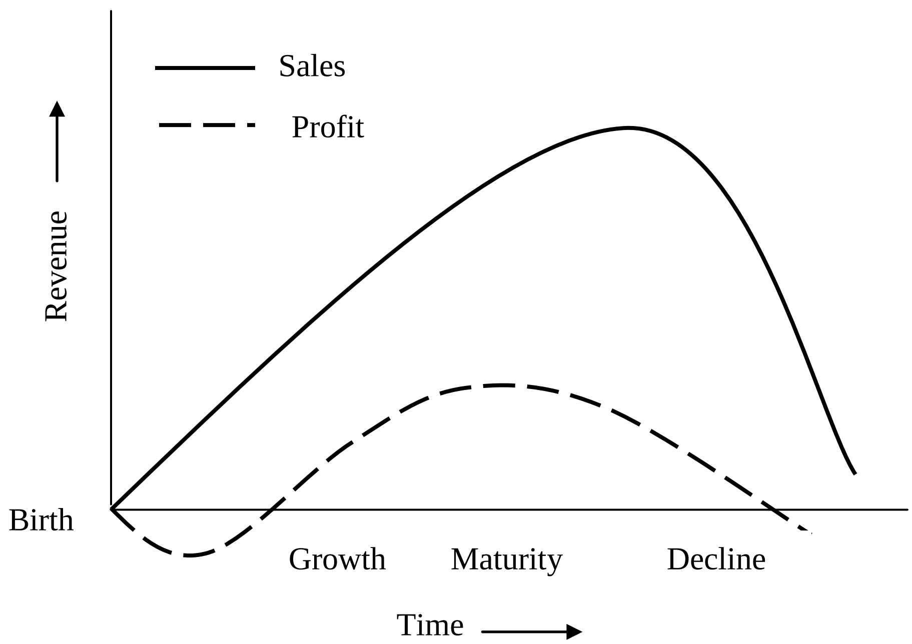


Figure 3. Ideal Form of a Product Life Cycle

Source: Urban and Hauser, Design and Marketing of New Products (1993), pg. no. 559, Prentice-Hall, Inc., New Jersey.

The introduction stage is characterized by high costs, low sales volume, and no/little competition. In this stage the demand for the product has to be created and the customers have to be prompted to try the product. During the growth stage costs are reduced due to economies of scale and the sales volume increase significantly, which leads to profitability. Competition for the market begins to increase as new players enter the market. In the mature stage, the product is well established in the market, and the sales volume is at its peak. Due to an increase in competition each player seeks to differentiate from its competitors using brand differentiation and feature diversification. Sometimes, despite the best management, the product demand will decline. In the case of intense competition, only the firms with unique core competencies will survive (Cooper, 2002; DRM Associates, 2002).

Functional Apparel

In the Second Edition of her book, Clothing: The Portable Environment, Susan Watkins (1995) outlines the design process for functional apparel. Functional clothing is a portable environment that protects the body, increases health and safety, improves a worker's job efficiency and/or increases body function. Functional clothing has specific requirements for fabric, lining, and accessories and is created for a select group of users with particular needs that arise due to interaction with the environment. Any garment can be placed along the Aesthetic-Functional Continuum (Figure 4), as developed by Plumlee and Pittman (2002). This is because all apparel items must meet minimal functional and aesthetic requirements, such as allowing some freedom of movement, and color and texture. In this figure we can see that surgical gowns are placed near the functional end of the continuum, as they have requirements dominated by performance needs.

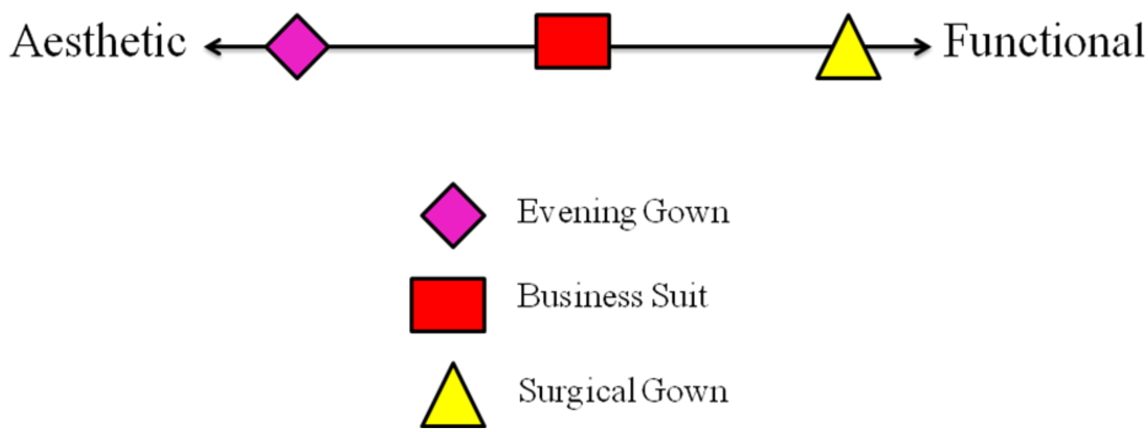


Figure 4. Aesthetic-Functional Continuum

Source: May-Plumlee, Traci and Pittman, Amanda. (2002). Surgical Gown Requirements Capture: A Design Analysis Case Study. *Journal of Textile and Apparel Technology and Management*, *2*, 1-10.

With the increasing technological developments that lead to new hazards, creating functional protective clothing has become increasingly challenging. According to Watkins (1995), military clothing is a form of functional apparel which has a very complex design process. This is because the clothing meets a variety of needs and serves a variety of purposes, thus, each situation generates a wide variety of conflicting criteria.

Watkins's Design Process

The design process for functional apparel outlined by Watkins (1995) is shown in Figure 5. This process may vary with the designer or may change for each designer due to the nature of the problem being solved. Each step builds on those that precede it; the designer is continually uncovering more information and gaining new insights into the problem.

Analyz → Define → Ideate → Select → Implement → Evaluat

Figure 5. Design development process for functional apparel

Source: Watkins, S. M. (1995). *Clothing: The Portable* Environment (2nd ed.). Ames, IA: Iowa State University Press.

Analyze

The analysis stage of the design process is responsible for design inspiration. It involves basic exploratory research that familiarizes the designer with the needs of the product users and the problems associated with the product. Direct observation is one of the most basic data collecting methods. It involves going to the site of work or recreation, where protective apparel is needed, and watching both the people and environment to obtain relevant information. Other data collecting methods include: participant observation, indirect observation, direct communication, and laboratory simulation. In addition to these methods, literature review helps in learning the areas related to the design problem and the language of the field. This allows the designer a greater opportunity to talk with the specialists and read the literature of the field, in order to generate a more complete analysis.

According to Watkins, the analysis stage needs to include an investigation of the design setting (the environment), individuals associated with the project, and materials that are available for use in the design setting. Designers face a difficulty with the analysis stage that can never be complete. The most difficult decision for a designer is when to stop the analysis process and move on.

Definition

The definition of design problem provides the designer with a statement of goals that the designer needs to meet to solve the problem. After sorting through the information collected in the analysis phase, the most essential elements of the problem are determined and defined. If the definition is ill-conceived the designer may ultimately work to solve the wrong problem. Definition forms the basis of subsequent design ideas and the final design product.

Ideation

Ideation is the creative, idea generating stage of the design process. According to Watkins, the ability to generate creative ideas evolves in part from experience and in part from the way individuals process and use information. One of the most used techniques for generating ideas is brain-storming, which is a group technique. It generates a quantity of ideas without any concern for quality, encourages expanding on an idea that originated with another group member, and forbids criticism of ideas. Some of the other methods suggested by Watkins for idea generation are Synetics, developed by William J. Gordon, Use of manipulative verbs to view problems in unique ways suggested by Osborn, Mind Mapping developed by Buzan. Like analysis, it is hard for the designer to consider the process of idea generation complete. There is never only one correct answer; a better design can always be developed.

Select

Many designers believe that the most creative design behavior takes place during the idea selection phase, rather than the ideation stage. The designs generated during the ideation stage are broken down into small concepts, or attributes, so that creative recombination can take place. During the selection stage it is important to prioritize criteria, which are the basis for the design selection.

Evaluate and Implement

Evaluation involves taking a critical look at the decisions made during the design process through numerical ratings. These ratings are based on tests conducted with many subjects or the informal, subjective opinion of the designer. Evaluation techniques include observation, interview, questionnaires, laboratory testing, and field testing. Implementation is the point where the product evolves from the process, and the chosen ideas are put to work.

Development in Military Clothing

Military uniforms should be distinctly different from the ethnic dress of various nations. The clothing of the German Landsknecht of the 16th century is an example of distinctive military fashion. The ornamental peak of the military uniform was reached in the early19th century in Western Europe. It consisted of brightly colored coats and trousers of matching or aesthetically contrasting colors. It was reasoned that this practice provided a feeling of unity among troops. This influence extended to the general public, which was the source of new recruits (Wichmann, 2006). With the improvements in the firepower, range, and accuracy of weapons, the First World War finally ended the expensive practice of furnishing colorful uniforms. This occurred because the colors made the troops easily visible targets, which lead to increase casualties. Uniforms of varying shades of khaki and grey were used in World War II, but the cut and outline appearance of the different armies were distinctive, which helped in identifying the armies from different nations.

Camouflage clothing was developed to reduce the visibility of soldiers for their protection. Modern uniforms are more suited for combat in modern conditions, and the uniform design is governed by factors like utilitarian necessities of the war and economic frugality (Military uniform, 2008). Many modern military forces utilize a system of combat uniforms that make it difficult to detect the soldier, both during daytime and at night, even with the assistance light amplification devices, such as night-vision goggles. These “digital” print uniforms provide a “splotched” appearance that leads to visual concealment in variety of surroundings.

History of the U.S. Army Uniforms

The army uniforms for the United States Army in the 18th century were similar to British Army uniforms of the same era. Each soldier would receive a wool regimental coat, with linen smallclothes in spring, and a wool regimental coat with linen smallclothes in fall, as a uniform. Changes in army uniforms reflected the civilian styles of that time. At the time of the War of 1812 significant changes were made in the uniform styles that lasted until the mid-19th Century. A uniform coat that was blue with red collar and cuffs was introduced in 1810. In February 1812 a single breasted “coatee” with a red collar and cuffs and 10-button front closure was introduced. Under the regulations of 1851 the coatee was eliminated and the frock coat was introduced as the service uniform for all soldiers. The regulations in 1858 and 1860 established the uniform for the American Civil War. The uniform consisted of black felt army hat with appropriate branch insignia, a frock coat with branch piping for foot troops, uniform jackets with colored lace for mounted troops, and sky-blue trousers. In 1874 the military issued a uniform that consisted of a single breasted sack coat with five brass buttons in front and one on each cuff, made of dark blue wool with branch colored piping on each cuff. In May 1884 the Army introduced a brown cotton canvas fatigue uniform, followed by a khaki cotton field service uniform (Cole, 2007). On October 7, 1940 a lightweight windbreaker jacket made of olive drab cotton poplin with a flannel lining replaced the wool service coat in the field. In 1943 the Woman’s Army Corps joined as a permanent part of the Army establishment. The service and field uniforms worn by woman paralleled the men’s uniform. On September 2, 1954 the Army Green Uniform, in shade 44, was announced. The new coat was single breasted, with four bright brass general service buttons in front, a roll collar, and notched lapels. The uniform was worn with a light tan shirt and a black four-fold service necktie. In 1964, instead of wool serge, a polyester and wool tropical blend was used. In 1975, a durable press utility uniform made of olive green shade 507, polyester and cotton blend was introduced. On October 1, 1981 the Battle Dress Uniform (BDU) that consisted of a coat made of 50% nylon and 50% cotton blend in woodland pattern camouflage, with matching trousers, and a field cap was introduced. In 1988, a hot weather version of the BDU was introduced. Also, for operations in the Middle East a Desert Camouflage Uniform (DCU) was introduced (Cole, 2007).

On June 14, 2004 the Army Combat Uniform (ACU), consisting of a coat, trouser, black beret or matching patrol cap, moisture wicking T-shirt, moisture wicking socks, and brown combat boots was officially established as the combat and garrison uniform for the Army. The color scheme composed of gray, tan and sage green digital pattern. The ACU has a single-breasted coat, with integrated blouse bellows for increased upper body mobility, and a plastic zipper closure that can be opened from either the top or the bottom. A front placket covers the zipper, and is secured by hook-and-loop (Velcro ™) fasteners. The coat has a Mandarin collar that can be worn up or down. On each sleeve, near the shoulder, there is a slanted pocket with a hook-and-loop covered flap closure, which has an integrated infrared identification square on the outside. Below each sleeve pocket there is an elbow pouch for an internal elbow pad insert (Cole, 2007).

In 2007 the Army the introduced Improved Outer Tactical Vest (IOTV) which has bullet stopping capabilities. In addition to increased protection, the IOTV redistributes weight of the shoulders to the lower torso of the wearer. It is equipped with a mesh inner cover, to improve airflow, and a cushioning pad in the lower back areas, to mitigate back injuries due to impact or blunt force trauma (Cole, 2007).

Requirements for Combat Uniforms for Current Battlefield Scenario

Understanding the types of hazards and threats that a soldier has to face in the ever changing defense domain is an important, and the most basic step for developing uniforms and protection system. Military uniforms need to protect the user from different threats and hazards, and also provide comfort properties. The design process of a military uniform is a complex system that requires a systematic approach. This approach starts with identifying the user's needs (including hazard and threat identification). Table 1 lists few examples of common threats and their effects (Gomes, 2008).

Table 1. Examples of hazard/threats and their effects

Threat or Hazard	Effect
High environmental temperature	Heat stress (e.g. heat stroke, heat exhaustion)
Cold environmental temperature	Cold stress (e.g. frostbite, hypothermia)
Identify location of soldier	Detection
Chemical	Damage through skin, eyes and inhalation
Biological	Damage through skin and inhalation
Flame	Melting of material to skin or burns
Fragmentation	Ballistic impact, blunt force trauma
Ballistic	Ballistic impact, blunt force trauma

Source: Gomes, C. A., (2008), "Designing military uniforms with high-tech materials", *Military Textiles, Edited by Eugene Wilusz.* Boca Raton: CRC Press; Cambridge, England: Woodhead Publication.

In this section, the features that are necessary to be incorporated into the ACU for modern war-fighting scenarios are discussed.

Physiological Monitoring

For operational success in extreme environments it is critical to know a soldier's physiological status on the battlefield to predict that soldier's performance. Both health and performance of a soldier can be impaired in adverse environmental conditions. Commanders and combat medics require real-time physiological status and readiness information of soldiers to support operational decisions. Getting such information leads to quick identification and location for treating the casualties on the battlefield. Currently the army uses battle simulation software to predict the operational outcomes based on input variables such as mission, terrain, and climate. However, for accurate outcomes, predictions require to be on individual or unit-level basis. The solution for this problem is the development of physiological status monitoring (PSM) systems that can provide remote situational awareness and life-sign detection based on heart-rate, respiration rate, and other performance status indicators (Military operational medicine research program, 2009).

Thermal Management

A military uniform is designed to function within a wide range of the operational environments, e.g. from desert to arctic conditions. Heat transfer can take place between a person and their environment by convection or radiation either of which results in a negative or positive heat balance. A positive heat balance occurs if the environment is warmer than the person, and a negative heat balance occurs if the person is warmer than the environment (Naval Aerospace Medical Institute, 1991). Thermal management can either be active requiring a power source, or passive, requiring no power source.

Passive Thermal Management

In a hot environment evaporative cooling can be used for thermal management. Any fabric that can be worn next to the body and that allows sweat from the body to be wicked to the outer surface of the fabric can facilitate evaporative cooling. The US military used polypropylene fabrics as the next-to-skin layer for many years, but currently the US military uses Polartec® Power Dry®, which has a bi-component construction. This bi-component construction moves at least 30% more moisture away from the skin than single component fabrics. In a cold environment insulation that can trap warm air around the body is an important feature for a protective clothing system. The current military protective clothing for cold environments is a multi-layer system like the US Army's new generation III Extended Cold Weather Clothing System (ECWCS). This is a seven-layer, 12-component system that keeps the soldiers comfortable, dry, and warm in extreme conditions. The system protects troops from temperature ranging from -51^{o}C (-60^{o}F) to 4^{o}C (40^{o}F) (Kennedy, 2007).

Active Thermal Management

For active thermal management in hot environments, the US army Natick Soldier Research Development and Engineering Center (Natick Soldier RD & E Center) has developed the Air Warrior Microclimate Cooling Garment (MCG), which is a lightweight, comfortable, breathable, tube-type (tubing is between two layers of 100% cotton fabric) undergarment worn against the skin. A microclimate cooling unit (MCU) circulates a coolant fluid that can remove up to 180 watts of body heat from the torso (Natick, 2006). The US military has not yet adopted active thermal management in cold environments, but this could be done through electric resistive heating by applying voltage to series of conductive yarns and as current is passed through them, heat is produced.

Signature Management

Signature management masks all the elements that make the soldier stand out in front of the enemy. The sub-categories of signature management include visual, infrared, olfactory and auditory.

Visual

Camouflage patterns provide the least amount of contrast between the soldiers and their background when viewed by the enemy thus blending the soldiers into the background. Historically, the US military branches wore the same type of camouflage uniforms until the digital camouflage pattern MARPAT was released by the Marines. This digital pattern resembles computer pixels, but from a distance it blends into the background faster than any other current camouflage design (Stone, 2001).

Infrared

The contrast of the human body against the environment is very obvious, a hot body in a cold climate can be ‘seen’ as well as a cold body in a hot environment, with the use of Infrared (IR) imaging technology (U.S. Military’s Special Operation introduces New High-tech Combat Uniforms for Extreme Winter Conditions, 2003). This technology is used in special thermal imaging cameras that can detect hidden soldiers by measuring the temperature of the object. Texplorer® has developed a garment called Ghost® that incorporates metalized fibers which reduce IR emissions and thus lower the temperature gradient. Night vision devices use the near-IR (NIR) spectrum that is reflected by the objects. NIR is managed by selecting dyestuff that mimics the spectral reflectance of the different environments of the soldier (Dugas, Zupkofska, & Kramer, 2004).

Olfactory

Human odor originates from bacteria living on skin that expel waste in the form of odorous gas. The olfactory target indicator identifies the area where the soldier is using the sense of smell. Metallic compounds based upon metals such as silver and copper that exhibit antimicrobial properties can be used with the fabrics to reduce the odor of the soldier as well as to improve his/her health. X-Static®, a silver-coated textile fiber that provides permanent anti-odor and antimicrobial properties is currently being used in US military socks and T-shirts. It not only provides odor elimination, but also helps in temperature regulation, instantaneous static reduction, and is also used for wound care (Jowers, 2006).

Auditory

The auditory signature of a soldier has to be reduced, as a soldier can be found by using sense of hearing. The hook and loop Velcro® fasteners produce an unnatural sound, so it is preferable to use a button. Also, laminated fabrics produce a crisp ‘swishing’ sound, so fabrics with finish could be used instead.

Chemical and Biological Defense (CBD) Management

Protection against chemical liquids, vapors, and bio-aerosols is the basic function of a chemical and biological defense system, and a breach in this system may lead to serious injury or loss of life. It is generally observed that increased protection against chemical and biological warfare leads to lower comfort and breathability. Historically, butyl rubber and activated carbon have been used as CBD materials. Though butyl rubber is a chemical-resistant impermeable elastomer, it is not breathable and could cause soldiers to overheat. Activated carbon has an extremely large surface area and high adsorptive properties for high boiling point gases and vapors (e.g. nerve agents). It has very low removal efficiency for low boiling point gases (e.g. blood gases such as cyanogens chloride) and choking agents (e.g. phosgene and chlorine), but this can be improved by impregnating it with heavy metals and triethylenediamine. The main shortcoming of using activated carbon is that it is required in large amounts, which leads to increases in weight and it has a limited functional life.

One of the techniques for CBD defense is to make the garment oil and water repellent. Jiang, Meng, & Qing (2005) studied the application of perfluorooctylated triazine pyridine quaternary ammonium salt (FPAQ) on cotton fabrics using the pad-dry-cure technique for imparting oil and water repellency. Though water and oil repellency was reported, the contact angle measurements show that the resulting surface did not show superhydrophobicity or oleophobicity. The oil repellency was better for wetting liquids with higher surface tension. Lee, Michielsen, & Little (2007) developed a superhydrophobic surface after chemical modification of nylon-6, 6 woven fabrics by treatment with 1H, 1Hperfluorooctylamine. The water contact angles measured were as high as 178°. Plasma polymerization is used for chemical modification of material surfaces that leads to better functional properties. Radio frequency plasma discharges containing simple fluorinated gases and vapors have been proven to impart water-repellency (hydrophobicity) to textiles, but the oil-repellency (oleophobicity) imparted by these treatments is to a very smaller degree. Willis (2008) used pulsed electrical charges containing perfluoroalkylated monomers as textile finishes for imparting oil-and-water-repellency. Augustyn, Brunye, Mahoney, & Kramer (2008) have studied the various factors and analyzed the trade-offs and interdepencies of different parameters involved in CBD equipment design that are related to human physical and cognitive performance while using the CBD equipment.

Flame Resistance

Fire protection is an important issue for soldiers in Iraq and Afghanistan due to the phenomenon of ‘flashover’. Flashover is a brief but intense burst of heat and flame at the moment of an explosion and can affect anyone who is trapped inside a vehicle or aircraft that is hit by a roadside bomb or rocket–propelled grenade (Burgess, 2007). The heat from flashover can melt polyester and other man-made fibers having petroleum components and fuse to the skin, thus causing significant burns. Currently the Army uses flame-resistant clothing made from Nomex® fiber, which is a polyaramid. The key for designing a protective uniform is to test the uniform as well as the individual components. Test ASTM F 1930: Standard Test Method for Evaluation of Flame-Resistant Clothing for Protection against Flash Fire Simulations Using an Instrumented Manikin is used for checking the flame resistance of an ACU.

Environmental Defense

An ideal combat uniform needs to windproof, waterproof and breathable to protect the soldiers from wind, rain and snow. Many technologies like finishing, laminated film and fiber encapsulation are used to impart resistance to water and wind.

Body Armor

Body armor needs to protect the soldier from impacts and blunt force resulting from bullets, fragmentation, knives and armor piercing threats. It also needs to be comfortable and flexible enough to enable soldiers to be mobile. Soft body armor has a shell covering the ballistic fiber. For example: the US Army Air Warrior flexible body armor vest shell is made using meta-aramid (e.g. Kevlar®). The US Army Air Warrior flexible body armor vest Inceptor Body Armor (IBA) which is a layered ballistic para-aramid system with Cordura® as the shell covering, and Kevlar® and/or Twaron® as the ballistic filler. Hard body armor is required to protect the soldier from armor piercing threats. Lightweight hard armor plates consist of a ceramic face supported by a fiber-reinforced composite, which fractures the projectile core upon impact and absorbs a significant portion of the kinetic energy.

Specifications, Standards and Handbooks for Testing ACUs

The ACU is tested for according to following specifications and standards. In this section the standard tests have been listed.

Federal Standards

i. FED-STD-4 -Glossary of Fabric Imperfections

Non-government Publications

AATCC Standards

i. AATCC Test Method 8 –Colorfastness to Crocking: AATCC Crockmeter Method
ii. AATCC Test Method 15 –Colorfastness to Perspiration
iii. AATCC Test Method 16 –Colorfastness to Light
iv. AATCC Test Method 20 –Fiber Analysis: Qualitative
v. AATCC Test Method 20A –Fiber Analysis: Quantitative
vi. AATCC Test Method 61 –Colorfastness to Laundering, Home and Commercial, Accelerated
vii. AATCC Test Method 81 –pH of the Water-Extract from Bleached Textile
viii. AATCC Test Method 135 –Dimensional Changes of Fabrics after Home Laundering
ix. AATCC Test Method 143 –Fabric Appearance/Smoothness
x. AATCC Evaluation Procedure 1 –Gray Scale for Color Change

xi. AATCC Evaluation Procedure 2 –Gray Scale for Staining

xii. AATCC Evaluation Procedure 8 –AATCC 9- Step Chromatic Transference Scale

xiii. AATCC Evaluation Procedure 9 –Visual Assessment of Color Difference of Textiles

xiv. AATCC Smoothness and Appearance Replicas

ASTM International

i. ASTM D-737 –Standard Test Methods for Air Permeability of Textile Fabrics

ii. ASTM D-1424 –Standard Test Methods for Tearing Strength of Fabrics by Falling-Pendulum Type (Elmendorf) Apparatus

iii. ASTM D-1683 –Standard Test Methods for Failure in Sewn Seams of Woven Apparel Fabrics

iv. ASTM D-3775 –Standard Test Methods for Warp End Count and Filling Pick Count of Woven Fabric

v. ASTM D-3776 –Standard Test Methods for Mass per Unit Area (Weight) of Fabric

vi. ASTM D-5034 –Standard Test Methods for Breaking Strength and Elongation of Textile Fabrics (Grab Test)

vii. ASTM D-6413 –Standard Test Methods for Flame Resistance of Textiles (Vertical Test)

National Fire Protection Association

i. NEPA 1971 – Standard Protective Ensemble for Structural Fire Fighting

Physical Requirements for the ACU

This section lists the physical requirements for the fabric use for manufacturing of ACU (this information was retrieved from documents received from Natick).

Table 2. Physical requirements for the ACU

Characteristic	Requirement
Weight, oz./sq.yd. **Minimum** **Maximum**	 5.5 8.5
Yarns per inch, (minimum) **Warp** **Filling**	 70 60
Breaking strength, pounds (minimum) **Warp** **Filling**	 100 80
Tearing Strength, pounds (minimum) **Warp** **Filling**	 4.0 4.0
Air permeability, cu.ft./min./sq.ft. (minimum)	10.0
Flame Resistance: **Initial –** **After Flame, seconds (maximum)** **After Glow, seconds (maximum)** **Char Length, inches (maximum)** **After laundering –** **After Flame, seconds (maximum)** **After Glow, seconds (maximum)** **Char Length, inches (maximum)**	 2.0 25.0 4.5 2.0 25.0 4.5
Thermal stability (maximum) **Initial** **After laundering (25 cycles)**	 10 10
Fabric Appearance/Smoothness rating (minimum) **Initial** **After laundering (20 cycles)**	 5 4
Seam Efficiency, percent (minimum)	80

Nonwoven Production in the U.S.

Nonwovens today are witnessing a tremendous boom in market as the most highly engineered fabrics. Manufactured at high speeds and low costs, nonwovens yield performance better than their woven and knit counterparts in many applications (Vaughn, 2000). The global production of nonwovens in 2006 reached 5.63 million tons, which is equivalent to $20 billion (USD) and equals approximately 140 million square meters. Tonnage has increased at an average annual growth rate of 7.6% per year from 2001-2006. The export volume of the U.S. nonwovens is twice the import. However, there has been a quick growth in the U.S. nonwoven imports compared to exports, due to foreign operations established by the U.S. nonwoven producers (European Commission, 2005).

The U.S. nonwoven industry is growing at a significant estimated rate of 3.9%. The U.S., being the largest market for nonwovens, harbors more than 550 firms with more than 160,000 employees (Gagnloff, 2004). According to the report "U.S. Nonwovens market to 2011" by Freedonia, (2007) the U.S. demand for nonwoven roll good will grow 4.5% annually through 2011. Association of the Nonwoven Fabrics Industry (INDA) and European Disposables and Nonwovens Association (EDANA) (nonwoven trade associations) have forecasted that the volume of nonwoven production will increase at a rate of 7.3% globally for the period of 2004-2009 (Lee and Cassill, 2006). According to the INDA report "Worldwide Outlook for the Nonwovens Industry: 2004-2009", the North American nonwoven industry will advance 5.3% per year for the period between 2004 and 2009 and the nonwoven production in North America is expected to increase up to 33%. U.S. nonwoven producers seem to be a potential to support the domestic production of U.S. military uniforms.

Major Nonwovens Market Segments

According to the IBISWorld Industry Report (2008), “Non-woven Fabric Mills in the U.S.”, the health and medical products manufacturing industry is expected to be the largest market for non-woven fabrics. This growing market segment that includes medical supplies, medical gowns, hygiene masks, wipes, packaging, blankets, and hygiene products is expected to make up more than a quarter of industry sales during the year. Figure 6 shows the market segment and share for the U.S. non-woven fabric industry.

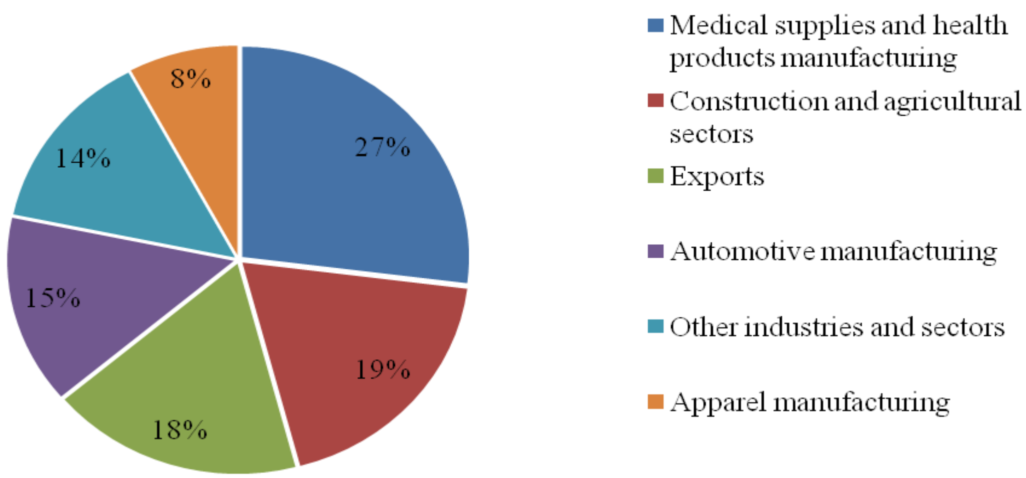


Figure 6. Market segments and share for Non-woven Fabric Mills industry in the US during 2008

Source: IBISWorld Industry Report (2008). *Non-woven Fabric Mills in the U.S-31323.* June 12, 2008.

The construction industry utilizes another major portion of non-woven fabric products. This market segment was expected to account for around 18.9% of industry sales in 2008. The automotive manufacturers that utilize non-woven fabrics in roof linings, engine insulations, trunk liners, air filters, etc. accounted for 14.5% of industry demand in 2008. Apparel manufacturing accounted for about 7.8% of industry revenue in 2008 and it mainly includes protective clothing manufacturing segment, particularly against fire and chemicals. Exports accounted for approximately 17.9% of industry revenue, which increased from 13.9% in 2002. The main reason for this increase is the demand for high-quality non-woven products from downstream manufacturers in China, Canada, and Mexico (IBISWorld, 2008).

Nonwoven Fabric Technology

Nonwoven fabric is a fabric which does not involve conventional weaving or knitting. Instead, a web of loose fibers is made and bonded by a variety of technologies to make a strong fabric. According to the INDA, nonwovens are a sheet, web, or bat of natural and/or man-made fibers or filaments, excluding paper, that have not been converted into yarns, but are bonded to each. Nonwoven fabrics are highly engineered fabrics which may be limited life, single-use fabrics or very durable fabrics, depending on the type of end-application. They can provide multiple specific functions, such as absorbency, liquid repellency, resilience, stretch, softness, strength, flame retardancy, washability, cushioning, filtering, bacterial barrier, and sterility. These properties are often combined to create fabrics suited for specific jobs while achieving a good balance between product use-life and cost.

Nonwovens can mimic the appearance, texture and strength of a woven fabric. In combination with other materials they provide a spectrum of products with diverse properties, and are used alone or as components of apparel, home furnishings, health care, engineering, industrial and consumer goods. For applications in military uniforms, a fabric should meet certain requirements, such as superior strength, comfort, flame retardancy, and bacterial barrier. Nonwovens, being highly engineered, can combine all these properties in one fabric. If nonwoven manufacturing techniques are selected correctly, the resultant fabric can easily match the required standards. The main nonwoven production steps web formation and web bonding and the different techniques to carry out these steps are described below.

Web Formation

Dry laying- The important web laying technologies under this category are air laying, and carding.

Air laying- Air laying refers to the nonwoven web forming technique which overcomes the high fiber orientation by capturing the short fibers from an air stream and collecting them on a moving belt/screen (Nelson, 1992).

Carding- The principle of carding is the mechanical action in which the fibers are held by one surface while the other surface combs the fibers, causing individual fiber separation. Therefore, carding essentially streamlines individual fibers by combing action and produces thin webs, which are further cross-lapped to achieve the desired fabric weight (Kamath, Dahiya, & Hegde, 2004(a)).

Wet laying- Wet laying is similar to air laying, only fibers are suspended in water and collected on a moving belt. This step needs excess water to be removed from the web prior to bonding.

Spunbonding- Spunbond fabrics are produced by depositing extruded, spun filaments onto a collecting belt in a uniform random manner, followed by bonding the fibers. Compared to meltblowing, spunbonding produces coarser fibers (Kamath, Dahiya, & Hegde, 2004(b)).

Web Bonding

Chemical bonding- Chemical bonding techniques use adhesives to provide structural integrity to nonwoven webs. The commonly used adhesives are chemical binders, which are generally water-borne latex, as they are economical, easily applied, and effective. Vinyl materials like polyvinyl acetate, polyvinylchloride, styrene/butadiene resin, butadiene, or their combinations are used for preparation of latex binders. Fabric properties like stiffness/softness, water affinity, elasticity, durability, and ageing are governed by the chemical composition of the binder. Binder composition also determines solvent resistance, cross-linking nature, and adhesive characteristics (Johnson, 1992).

Mechanical bonding- The mechanical bonding technologies for nonwoven webs are needle punching, stitch bonding, melt-blowing, and hydroentangling.

Needle punching- Needle punching technique involves fabric formation by means of fiber entanglement by the repeated penetration of barbed needles through a performed dry fiberweb (Foster, 1992).

Stitch bonding- Stitch bonding is a bonding technique which consolidates fiber webs by putting stitches in the web. This helps in interlocking of the structure and provides the necessary integrity to the nonwoven web (Kamath, Dahiya, & Hegde, 2004(a)).

Melt-blowing- Melt blowing is a process that produces fibrous webs directly from polymers or resins using high-velocity air to attenuate the filaments. It is used almost exclusively to produce microfibers rather than fibers which are of the size of normal textile fibers. Melt-blown microfibers generally have diameters in the range of 2 to 4 µm, although they may be as small as 0.1 µm and as large as 10 to 15 µm (Kamath, Dahiya, & Hegde, 2004(c)).

Hydroentangling- Hydroentangling, hydraulic needling, or spunlacing refers to the nonwoven bonding technique which employs high pressure water jets to entangle fibers and provide the necessary fabric integrity.

As shown in Figure 7, it can be emphasized that among all the nonwoven bonding techniques, hydroentangling can be best put to use for producing military uniforms. While other bonding techniques such as chemical bonding, needle punching, or thermal bonding result in a papery feel, hydroentangling retains a soft fabric-like structure.

The important properties that a hydroentangled nonwoven possesses are softness, drape, conformability, and relatively high strength. Among all nonwoven bonding techniques, hydroentangling produces the most conventional fabric-like feel, yet retains the high strength (Kamath, Dahiya, & Hegde, 2004(d)). By modulating parameters such as input energy, water jet pressure, and fiber blends, high strength hydroentangled nonwovens can be produced at line speeds much higher than woven/knit fabrics.

The important requirements to be met by a fabric for military uniforms include strength, comfort, flame retardancy, bacterial-barrier etc. A hydroentangled nonwoven is strong, comfortable, and conformable and may be used as a potential option for military uniforms.

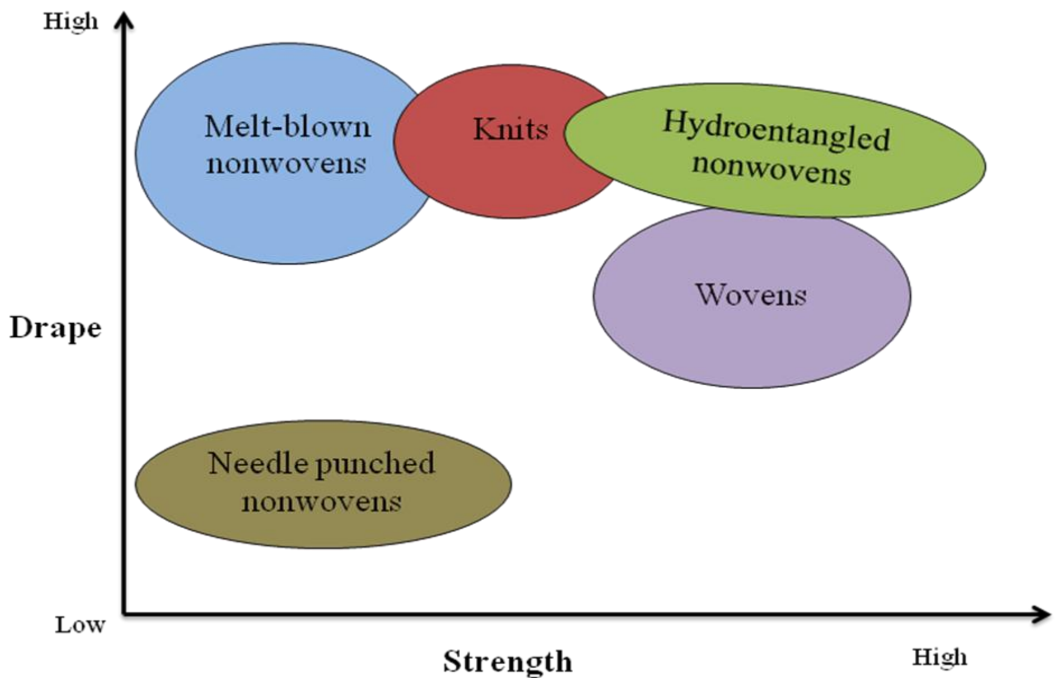


Figure 7. Property map of drape and strength-qualitative

Source: Kamath,M.G., Dahiya,A., and Hegde, R.R. (2004(d)). Spunlace (Hydroentanglement). Retrieved on May 29, 2008 from Web site: http://web.utk.edu/~mse/pages/Textiles/Spunlace.htm

Thermal bonding- Thermal bonding can be defined as a bonding technique for nonwoven webs wherein a thermoplastic element, in the form of a film (continuous or fibrillated), fiber or powder (but not aqueous dispersion of film forming, emulsion polymerized polymers), is integrated into the web (Rogers, 1992). The bonding is initiated by thermal energy and no fluids need to be evaporated (except when using wet-laid webs). Thermal bonding may be done by calender bonding, through air bonding, ultrasonic bonding, or infrared bonding

Calender bonding- This process involves the use of a calendar with a hot metal plate. Depending on the engraving on the heating rolls, the bonding may be area or point bonds. Bonding occurs through simultaneous application of heat and pressure. The heat causes the fiber to become thermoplastic and the pressure enhances mechanical bonding by forcing the binder polymer to flow in and around the carrier fibers (INDA, 2008).

Through air bonding- This technique involves the application of hot air to the nonwoven web. Hot air flows just above the nonwoven through holes which is sucked through the open conveyor apron that supports the nonwoven as it passes through the oven.

Ultrasonic bonding- In this process, rapidly alternating compressive forces are applied to localized areas of fibers in the web. These compressive forces generate stress that is converted to thermal energy, which leads to softening of the fibers as they are pressed against each other. The softened fibers are then cooled and solidified at the bond points. Natural fibers cannot be bonded; they need to be blended with some amount of synthetic fibers.

Infrared bonding- In infrared bonding the webs are exposed to a radiant energy source in the infrared range. The radiations are absorbed by the webs, and thermoplastic binder melts without affecting the carrier fibers. Bonding occurs upon removal of the energy source when the binder solidifies.

Overview of Smart Textiles

Materials that can actively monitor and optimize themselves and their performance on a continuous basis with their adaptive capabilities and integrated designs are called "smart materials". Over the last few years smart materials have made their way into the textile world. Smart textiles can be referred to as high-tech textiles, which sense and respond to environmental stimuli in a controlled or predicted manner (Tao, 2001). These stimuli can be mechanical, thermal, chemical, magnetic, biological, or of any other form. Zhang and Tao (2001) classified smart textiles in three groups, passive, active and very smart textiles. Passive smart materials are sensors that can anticipate environmental conditions. Active smart materials have both sensors and actuators, due to which these materials sense the stimuli from the environment and also react to them. The very smart materials are in the developmental stage, which would go a step further and will be able to adapt their behavior according to the stimuli from the environment.

Wearable electronics, nanotechnology, phase change materials, and shape memory materials are some of the key methods by which the smart textiles are currently being developed. Smart textiles find their applications in numerous fields; from highly complex life support systems and life saving military uniforms, to stain resistance, and fun and entertainment. According to the US technology market research and strategy consulting firm Venture Development Corporation (VDC), the global market for smart textiles reached $304 million in 2005, and is expected to grow to $642.1 million by 2008 at a Compound Annual Growth Rate (CAGR) of 28.3% (Venture Development Corporation (VDC), 2006). The U.S market for smart textiles was estimated to be $78.6 million in 2007, and is expected to reach $391.7 million in 2012 at a CAGR of 37.9% (BCC Research, 2007). The U.S. is the key player in development of smart technologies, mainly because of large defense research and development budgets.

Smart textiles can be made from smart fibers by incorporating sensors into the base fabric, or by applying smart coatings to the fabric. Developments in polymer technology have made it possible to provide smart fibers having attributes such as conductivity, phase change, Quantum Tunneling Composites (QTCs), shape memory, energy absorption, and anti-microbial polymers.

Electrical conductivity can be built into textiles by using polyaniline or polypyrrole polymers. Electroactive polymers are also able to react to electrical stimuli (Technical Textiles Market, 2005). To incorporate electronic functions to textiles, the electronic components can be integrated into the finished garments, or conductive fibers or yarns can be woven or knitted into the clothing. The garments or fabrics that have electronics and interconnections stitched or woven into them are called as electronic textiles (Meoli and May-Plumlee, 2002).

Materials that are able return to a pre-programmed shape with the right stimuli are called as shape memory materials (Otsuka and Wayman, 1999). Shape Memory Polymers (SMP) and Shape Memory Alloys (SMA) are two of the most common forms of shape memory materials. In the case of SMA, the structure of the materials changes to the martensite phase, where they can be easily deformed and, upon heating, the structure changes to the austenite phase, which is the parent phase as the material “remembers” its original phase. The SPMs show shape memory properties because of the polymer structure and morphology, and the effect of the thermal transition temperature, which triggers glass transition or melting point (Lendline, 2003). Phase Change Materials (PCM) are hydrocarbon polymers with different chain lengths, in the form of gels, powders, and liquids, that enable fibers and fabrics to act as latent heat-storage materials. This depends on the change of physical state of the PCMs. The PCMs melt and absorb heat when the temperature increases and reaches melting point. Due to this, the flow of thermal energy through the fabric is inhibited and the temperature is maintained (Ying, Kwok, Li, Zhu, & Yeung, 2004).

Polymers termed as quantum tunneling composites contain particles which are non-conducting in the relaxed state, but become conductive when stressed by compression, twisting, or stretching. Such materials can be used in conjunction with other components. Polymer materials that can quickly change their color, hue, depth of shade, or optical transparency on application of external stimuli are termed as chameleonic fibers. These can either be electro-active or magneto-active polymers that can change their absorption and/or reflection of electromagnetic radiation in infrared, visible and ultraviolet frequency ranges (Mishra, Butola, & Singh, 2006). Anti-microbial polymers are able to reduce or neutralize the activity of chemical warfare agents and bacterial contaminants and thus provide biological protection. The anti bacterial agents can be added to the polymer before extrusion and spinning or by chemically grafting the anti-bacterial agent on the base polymer (Ackart, Camp, Wheelwright, & Byck, 2004).

Smart textiles represent technology that has applications across a wide range of sectors including transportation, construction, healthcare, food and packaging and defense. In this paper we will be discussing the application of smart textiles in the military and specifically to army uniforms.

Smart Textiles in Military

Military is one of the predominant markets for smart fabrics and is accounted for close to 10 percent of annual consumption of the smart textiles market (Stylios, 2004). Since the early 1990s, there has been an in-house smart materials and structures research program undertaken by the U.S. Defense Advanced Research Projects Agency (DARPA) (Wax, Fisher, & Sands, 2003). Incorporating smart textiles in military applications has been successful in the areas like body armor, artificial muscles, protective clothing, physiological monitoring clothing and other wearable electronic for communication. The U.S. government allocates hundreds of millions of dollars for homeland security research for new building materials in clothing. These innovations are filling needs that could provide security in the age of increasing terrorist attacks. The U.S. government invested at least $3 million in the 2004 Defense Spending Bill for research on electronic textiles to monitor soldiers' physiological conditions. In 2005, a $5.5 million contract was approved on the research and development of combat casualty care fabrics (Lam Po Tang, & Stylios, 2006). During the last decade, there has been an increasing research undertaken to integrate smart textiles with protective gear used by military.

Mass Customization

During the twentieth century, mass production was well established in both the textile and apparel industries (Anderson, 2004). This led to standardization of apparel production for the markets with stable demand but less product variety. Mass production has helped textile firms achieve the economies of scale for large product runs. Today, the demand requires smaller batch sizes since consumers want more variety in their selection of apparel. The industry needs a breakthrough in apparel manufacturing to accommodate this change (Bae, & Plumlee, 2004; Tu, Vonderembse, & Ragu-nathan, 2004)

Technological innovations in both manufacturing and personal communications in the textile industry change the way manufacturers and retailers relate to consumer demand (Anderson, Brannon, Ulrich, Marshall, & Staples, 1997). Due to the shortening of product life cycles, 'one size fits all' principle is no longer applicable in the apparel industry. Meanwhile, there has been a constant increase in the world population along with the growth in the world Gross Domestic Product (GDP) (Central Intelligence Agency, 2008). As the purchasing power increases, the consumer demands are more diversified. To deal with the challenges such as short product life cycles and the variety of trends caused by diverse consumer demands, the manufacturers must develop order fulfillment processes that have quick response to the unexpected changes in trends (Fulkerson, 1997). Pine provided several fundamental methods to achieve mass customization with undertaking low-cost production: create customizable products and services; customize services around standardized products and services; provide quick response through the value, and so on (Pine, 1993). A consumer-driven model and a consumer co-design of apparel for mass customization have been created and researched (Anderson-Connell, Ulrich, & Brannon, 2002; Ulrich, Anderson-Connell, & Wu, 2003).

Surveys show that consumer dissatisfaction related to misfit is increasing: 62% in men and 50% in women (DesMarteau, 2000; LaBat and Delong, 1990). According to Plunkett Research, Ltd. (2007), 30% of the clothes purchased online are returned due to lack of fit. The major fit problems are thought to be caused by the sizing systems and pattern grading (Ashdown and Dunne, 2006). Therefore, development of improved technologies in Computer Aided Design (CAD) can provide the solutions to apparel industries (Bye, LaBat, & DeLong, 2006). Technologies such as three dimensional (3D) body scanning and Computer Aided Manufacturing (CAM) can also reduce fit problems and make mass customization viable (Chi and Kennon, 2006).

Employment in the Apparel Industry

There has been a constant decrease in the number of workers employed in the U.S. apparel industry from 2001 due to globalization in the textile industry, which has led to global sourcing and offshore manufacturing. The number of manufacturing jobs in the U.S. apparel industry decreased from 425,000 in 2001 to 250,000 in 2006. Meanwhile, labor costs have steadily increased worldwide. Table 3 presents the growth of hourly compensation costs for apparel manufacturing. Due to the continuous growth in labor costs, it is expected that manufacturing units will prefer more mechanized processes which require less labor.

Table 3. Compensation costs for the apparel manufacturing (Unit: USD/hr)

Country	Year					
	2000	2001	2002	2003	2004	2005
United States (US)	13.21	13.63	13.85	14.57	14.88	15.41
Canada	10.37	9.7	10.13	11.77	14.4	N/A*
Mexico	1.43	1.63	1.75	1.74	1.74	1.89
Japan	13.82	11.84	11.55	12.56	13.5	13.48
France	11.54	11.61	12.71	15.7	17.78	18.37
Germany	15.89	15.81	17.17	20.8	22.91	23.08
Italy	11.88	11.66	12.6	15.61	17.6	N/A*
United Kingdom (UK)	12.69	12.78	13.69	16.07	18.98	N/A*

***N/A (Not Available)**

Source: U.S. Bureau of Labor Statistics, Retrieved on 20 November, 2008,

ftp://ftp.bls.gov/pub/special.requests/ForeignLabor/industrynaics.txt

Development of Technologies in Mass Customization

Mass customization has been developed to reflect customer individualization toward merchandise with the speed of mass production. There are two important characteristics of mass customization: individualization and speed. To fulfill these conditions, technological developments are necessary. The advancement in technology can improve manufacturing efficiency and production capacity, cutting down labor costs and shortening production times. The essential technologies are body scanning, garment modeling, digital pattern design, garment simulation and information technology. Since there have been significant technological advances in this field, we provide a brief introduction about them.

Body Scanning and Garment Modeling

Body scanning technology supports automation in the garment industry and Computer Aided Design (CAD) systems are used for mass customization to integrate the measurement information and apply it to the patterns accordingly (Istook, 2002). A conceptual model which automatically transfers body scanning data to commercial CAD/CAM software in order to decrease the complexity of data exchanges emerging from body scans was created by Carrere, Istook, Little, Hong, & Plumlee (2001). Computerized 3D body enables customers to modify the body model to match their own body shape on the internet during online shopping and helps apparel manufacturers easily communicate with their customers in the ordering process (Cho, Okado, Hyejun, Takatera, Inui, & Shimizu, 2005).

Digital Pattern Design

Mass customization provides the customers a choice to see their garment design. My Virtual Model (MVM), a Montreal-based company has shown that people personalizing and designing their own clothes and able to view their designs on a virtual model that represents them have a higher conversion rate and order more than average visitor (Guay, 2003). A digital pattern design is generated by two methods: the flat pattern process which is a two dimensional and the three dimensional draping method in which the flat fabric is directly draped on a 3D virtual body image. The 3D method provides well fitting patterns. In the 3D draping method, the 2D patterns are generated using Artificial Intelligence (AI) technology which reduces the labor requirements (Yang, Zhang, & Shan, 2007). Research has also been carried out to customize individual patterns by gradual mapping from 3D models to 2D patterns without considering the physical or mechanical properties of the fabric such as drape (Yunchu and Weiyuan, 2007).

Garment Modeling and Simulation

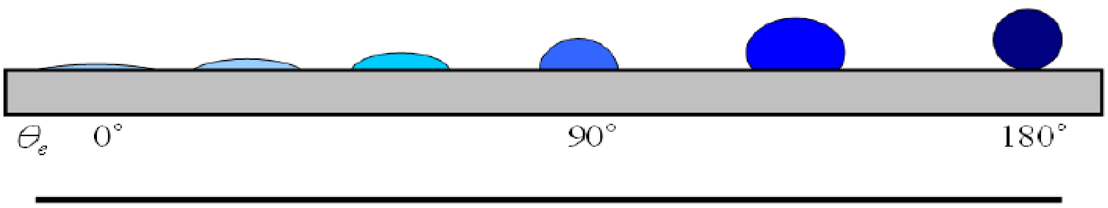
In mass customization, it is important for the customers to see their garment design immediately. The aim of garment modeling (or construction) and simulation is to visualize the apparel design with accuracy in a short amount of time. Garment simulation involves various technologies such as mechanical simulation, collision detection and rendering. The collisions between simulated garments and human bodies have been the major bottlenecks in cloth simulation, Zhang and Yuen (2002) focused on solving this problem and presented a coherence-based method for collision detection. Using these technologies, the three dimensional nonwoven fabric geometry in terms of fabric weight, fiber orientation and mixture of fiber density, fabric thickness and void spacing of the fabric can also be predicted (Ko and Pastore, 1992).

Computer Aided Process Planning (CAPP)

CAPP is the bridge between CAD and CAM; it transforms the design information into the manufacturing information and can be integrated with CAM. Over the past thirty years, many efforts have been made in area of CAPP and CAM. The development of Unit Production System (UPS), tension free spreading machine, automated cutting machine and digital sewing machine have improved the efficiency of CAM greatly. Also, new technologies have been used in CAPP. For example, Spragg, Fozzard, & Tyler (1998) used the intelligent agent to control the balance of the workflow. Chen, Racine, & Swift (1998) and Chan, Hui, & Yeung (1998) used a genetic algorithm to keep the balance of workflow. Wong, Chan, & Ip (2000) used a genetic algorithm to arrange the sequence between the spreading machine and the cutting machine. Czarnecki (1999) used the dual robot work cell to control the UPS. Based on these efforts, the speed of mass production has been improved greatly. In the past, research was concentrated on how to improve the efficiency of CAD system for the designer specialist. Today, it is important to consider how to help the common customer such as the soldiers who order uniforms online to design as a specialist.

Contact Angle and Wettability

Any surface having a water contact angle greater than 150^{o} and a roll-off angle less than 5^{o} is called as superhydrophobic surface (Wu and Shi, 2006). By a combination of surface chemistry and surface roughness a high contact angle can be obtained. A water droplet easily rolls off a superhydrophobic surface, thus washing off the dirt in the process and cleaning the surface. This wetting behavior is called as the Lotus effect or self-cleaning (Tavana, Amirafazli, & Neumann, 2006). For evaluation of surface tension and wettability the contact angles are measured (Kovats, 1989). The continuum of relationship between wettability and contact angle can be seen in Figure 8. It is difficult to measure the surface tension of the solid directly; so many researchers have evaluated surface tension on basis of contact angle.



Complete wetting In Equilibrium No wetting at all

Figure 8. Contact angle and wettability

Source: Lee, H.J. and Michielsen, S. (2006). Lotus-effect: Superhydrophobicity. Journal of Textile Institute, 97, 455-462.

Young's equation gives the relation between the surface tension and contact angle as follows (Pal, Weiss, Keller and Müller-Plathe, 2005):

$$\frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}} = \cos\theta_e$$

Where γ is the surface tension; and *SL*, *SL* and *LV* are the solid-vapor, the solid-liquid, and the liquid-vapor interfaces, respectively. Figure 9 below shows the positions of the interfaces.

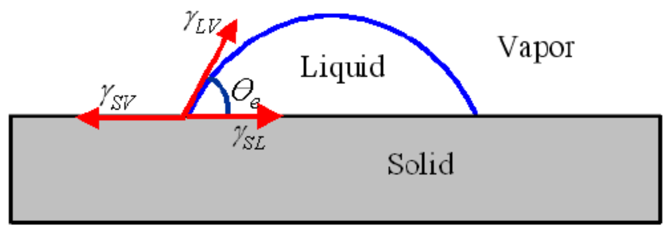


Figure 9. A drop on the flat surface showing the positions of surface tension at different interfaces

Source: Lee, H.J. and Michielsen, S. (2006). Lotus-effect: Superhydrophobicity. Journal of Textile Institute, 97, 455-462.

The Young's equation represents the contact angle as a well-defined property that depends on the surface tension coefficients of solid, liquid and gas. The surface structure affects the wettability of the surface (Alberti and DeSimone, 2004). No solid material is perfectly flat and Young's equation is valid for only partial wetting of solid having a smooth surface since liquid droplets are in contact with the upper part of the rough surface and the lower part is filled with air (Li and Amirfazli, 2005). When the surface is roughened, the liquid surface free energy decreases which results in two possible contact angles, the Wenzel apparent contact angle or the Cassie-Baxter apparent contact angle (Yoshimitsu, Nakajima, Watanabe, & Hashimoto, 2002). Figure 10 below shows the apparent contact angle on a rough surface.

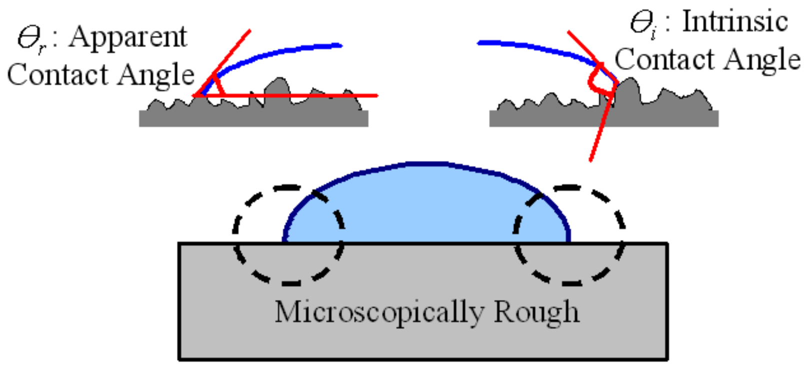


Figure 10. Apparent contact angle on a rough surface

Source: Lee, H.J. and Michielsen, S. (2006). Lotus-effect: Superhydrophobicity. Journal of Textile Institute, 97, 455-462.

According to Wenzel, the liquid fills the grooves on the rough surface and thus, the liquid contact angle at a rough surface can be stated as:

$$\cos\theta_r^{W} = r\cos\theta_e$$

Here, *r* is the ratio of the total wet area of a rough surface to the apparent surface area in contact with the water droplet ($r > 1$). The liquid is comes in contact with the rough surface if the Young contact angle is smaller than a critical contact angle θ_c.

Figure 11 shows the liquid drop behavior according to Wenzel and Cassie Baxter models.

Figure 11. A liquid drop behavior on a rough surface according to (a) Wenzel Model and (b) Cassie-Baxter Model.

Source: Lee, H.J. and Michielsen, S. (2006). Lotus-effect: Superhydrophobicity. Journal of Textile Institute, 97, 455-462.

The Cassie-Baxter model also includes porous surfaces and is thus an extended form of Wenzel model. According to this model, the liquid does not fill in the grooves of the rough solid and thus it sits on a composite surface made of solid and air. Cassie-Baxter model suggest that (Cassie and Baxter, 1944):

$$\cos\theta_r^{CB} = f_1 \cos\theta_e - f_2$$

Where f_1 is the surface area of the liquid in contact with the solid divided by the projected area, and f_2 is the surface area of the liquid in contact with air trapped in the pores of the rough surface divided by the projected area. The value of f_1 becomes identical to the value of r in the Wenzel model. When there is no trapped air.

Contact Angle Hysteresis

The contact angle observed when the contact line just begins to move due to increase of the volume of the liquid drop on the surface is called as advancing contact angle (θ_A). Conversely, the contact angle measured when the contact line just begins to recede due to decrease in the volume of liquid drop placed on a surface is called as receding contact angle (θ_R) (Patankar, 2003). According to Barhlott and Neihuis, when a self-cleaning rough surface is slightly tilted, the advancing contact angle of a water droplet easily reaches the receding contact angle due to which the drop rolls off easily washing the dirt and cleaning the surface as shown in the Figure 12 (Wang, Peng, Lu, Lui, & Wang, 2004).

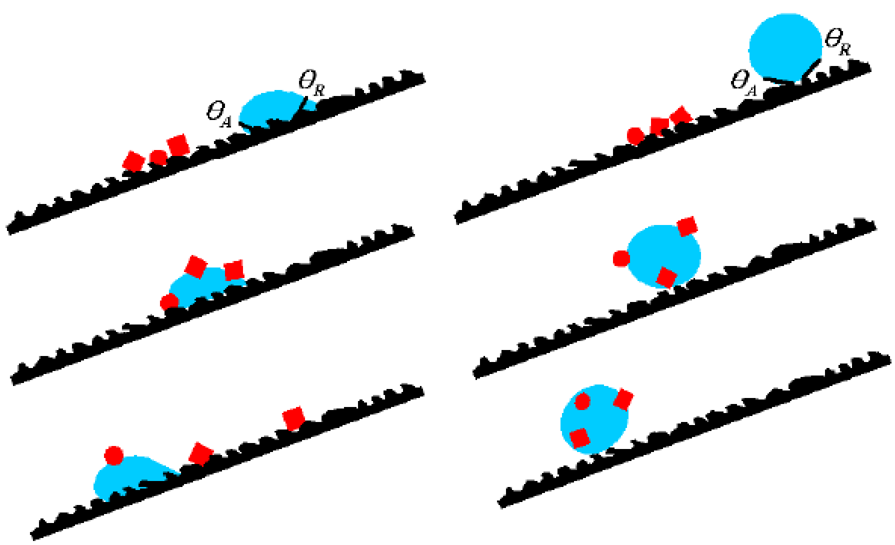


Figure 12. Self-cleaning effect due to superhydrophobicity

Source: Lee, H.J. and Michielsen, S. (2006). Lotus-effect: Superhydrophobicity. Journal of Textile Institute, 97, 455-462.

Chapter 3

Research Methodology and Experimental

Purpose of this Study

The purpose of this study is to examine the New Product Design (NPD) process for the Army Combat Uniform (ACU). This work specifically examines and identifies the opportunity and design phases. This examination will focus on four product requirements: mobility, communication, personal protection, and logistic support. The study will focus on exploring the various materials and production technologies that can be used to enhance these features of the ACU. In this research, materials were designed based on science and technology rather than statistics. This study is divided in three phases. The Phase I involves analysis of the new product design process for the military uniforms. The Phase II focuses on an in-depth study of the opportunity identification and the design phases using the Watkins's design process as the conceptual framework for identifying the materials and technologies for developing the high performance ACU. Finally, a House of Quality matrix is developed in the Phase III that will provide as a model for future selection process for technologies to be incorporated in the ACUs. The NPD process from Urban and Hauser (1993, p. 38) and the Watkins's design (1995, p. 337) process serve as conceptual framework to study the NPD process for military uniforms and materials and technologies for manufacture of the ACU respectively.

The objectives of this study for the three phases are as follows:

Phase I

1. Study the New Product Design Process (adapted from Urban and Hauser, 1993) for military uniforms.

Phase II

2. Collect information on the current Army Combat Uniform (ACU), including their current features and issues.
3. Study the current threats to the soldiers, by studying the battlefield environment.
4. Discuss the materials and technologies identified, as an opportunity for changes in the ACU and thus study the opportunity identification phase for the ACU.
5. Propose a method for preparing superhydrophobic and superoleophobic surface and prepare a prototype sample showing superhydrophobic and superoleophobic characteristics.
6. Suggest a model for mass customization of the ACUs
7. Study of novel sewing techniques for manufacture of the ACUs
8. Compare the potential designs vs. the current ACU using a concept evaluation matrix.

Phase III

9. Use the above results to develop a House of Quality Matrix as a future guide for selection of technologies to be incorporated into the future ACUs.

Research Design

This study represents a dominant quantitative approach with a less-dominant qualitative data collection procedure. Literature was reviewed on functional apparel, the NPD process (Urban and Hauser, 1993) and the Watkins Design Process. Also, the literature review summarizes novel materials and production technologies that can be incorporated in the ACU. The research methodology identifies three phases for this study. This study involves the collection of both primary and secondary data. The overall objective of the current research is to suggest a potential design for the high performance ACU. Since the army uniforms fall in the category of functional apparel, the new product design process is more complex than the fashion apparel. Figure 13 serves as the conceptual framework for the approach to the overall research.

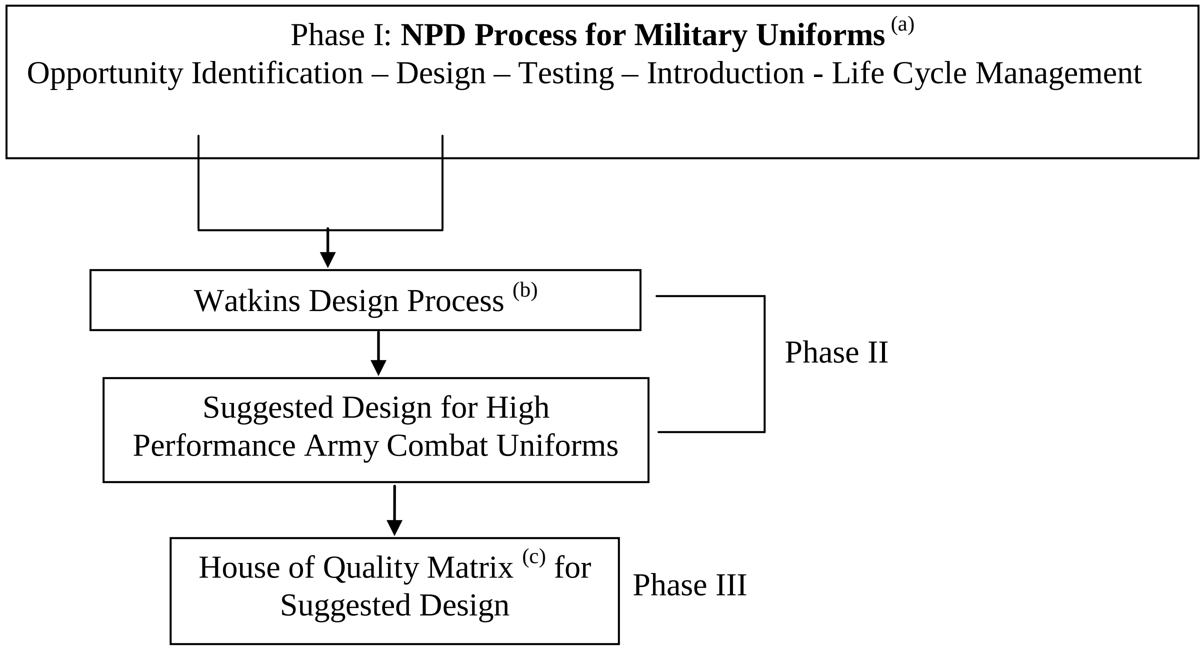


Figure 13. Conceptual framework of overall research

(a) Urban, G.L., Hauser, J.R., Design and Marketing of New Products (1993), Prentice-Hall, Inc., New Jersey.

(b) Adapted from "The Design Process" Watkins, Susan M. (1995). *Clothing: The Portable Environment* (2nd ed.). Ames, IA: Iowa State University Press.

(c) Urban, G.L., Hauser, J.R., Design and Marketing of New Products (1993), Prentice-Hall, Inc., New Jersey.

Phase I

The phase I of this research involved the study of the New Product Design process with respect to the military uniforms. It involved gathering information to understand each of the five stages of the NPD process: opportunity identification, design, testing, introduction and life cycle management. The analysis of this phase involved basic exploratory research for secondary information and undertaking interviews for gathering primary information. The primary data was collected by interviews with manufacturers of military uniforms and personnel working at the N.C. Military Business Center. This data formed the basis of next two phases of the current study. The analysis carried out in this stage also led to narrow the focus on identifying the opportunities specific for ACU in Phase II and an overview of the opportunity identification and design stages of the NPD process which helped the in-depth analysis of these two stages in the next phase.

Phase II

The phase II of this research intended towards identifying novel materials as well as production technologies that can be applied for manufacture of ACU. Watkins's design process is adapted for the study in this phase. It involved analyzing the opportunities for new design considerations for ACU with the collection of both primary and secondary data. Each stage of the design process served as a tool for accomplishing specific research objectives. Figure 14 gives a layout of conceptual framework implemented in phase II.

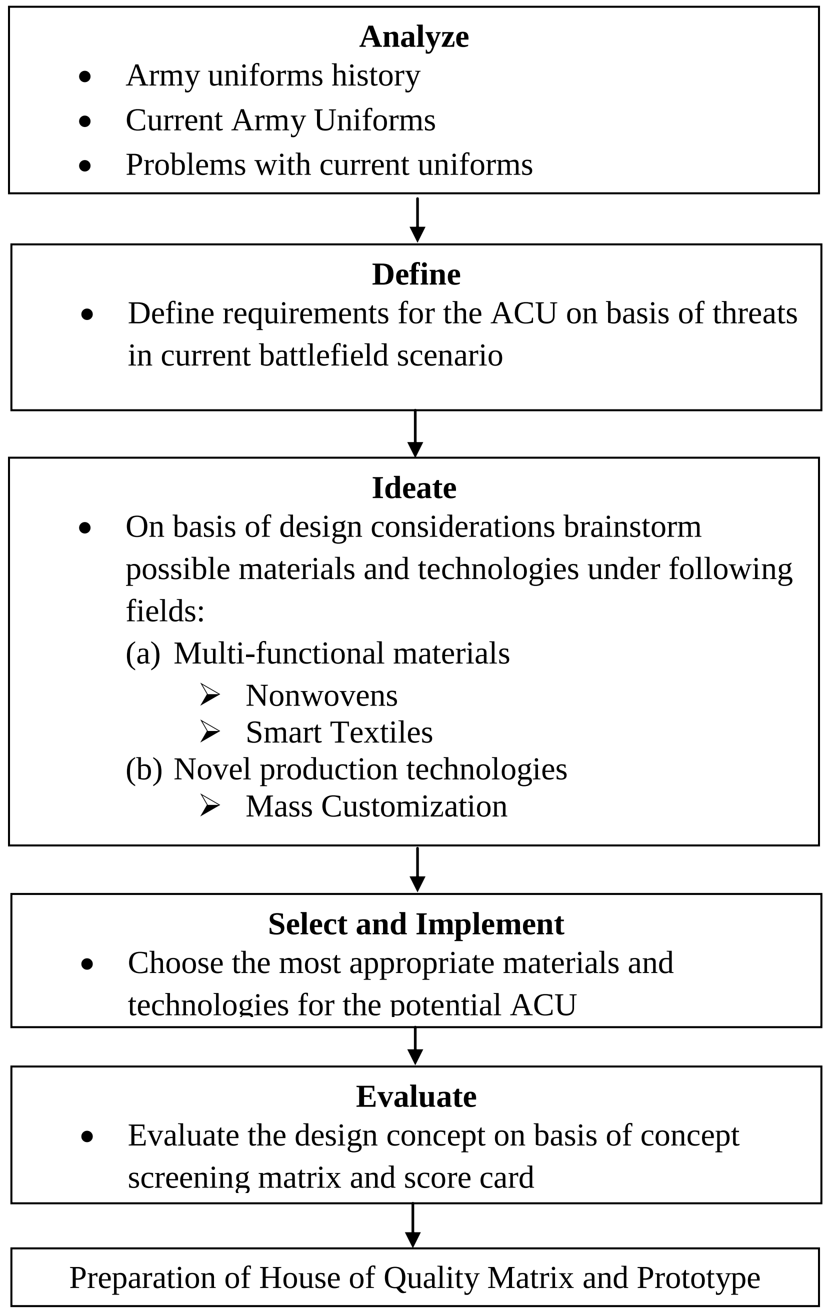


Figure 14. Design Process for Opportunity Identification and Design Phase

Source: "The Design Process" Watkins, Susan M. (1995). *Clothing: The Portable Environment* (2nd ed.). Ames, IA: Iowa State University Press.

Analyze

Research Objective: Collect information on the current Army Combat Uniforms (ACU), their current features and issues.

The analysis stage of this study involved basic exploratory research to become familiar with the current features of the ACU, the needs and requirements of the soldiers. A literature review and interviews for primary source of information were conducted.

The tools used for the analysis phase are:

- Natick Soldier RD&E Center, DARPA, Defense Threat Reduction Agency (DTRA) websites, publications and documents
- Internet search
- Journal publications
- Personal communication with Federal Government employees and researchers working in the field of military textiles

Through this research a clear perspective of the current features and shortcomings of ACU was obtained.

Define

Research Objective: Study the current threats to the soldiers by studying the battlefield environment and define the features required in the potential design for the ACU.

During this phase the current threats and battlefield environment were studied and on basis of the information collected during the analysis, the features required in the high performance ACU were defined. Definition of the features required assured that the needs of the soldiers were addressed.

Ideate

Research Objective: On the basis of design considerations brainstorm possible materials and technologies to identify latest innovations.

New ideas and design concepts to meet the requirements of the soldiers were generated in this phase. The ideas generated were along two dimensions. The first dimension was multi-functional materials and the second, novel production technologies.

The tools used for this phase were:

- Internet Research
- Journal publications
- Books in related areas
- Interviews with researchers working on military textiles

This phase helped to determine the possibilities that could be used to solve the problems related to requirements in ACU.

Select and Implement

Research Objective: Choose the most appropriate materials and technologies and suggest a potential design for high performance ACU.

In the selection phase the most appropriate materials and production technologies were identified. The next step was implementation of these to present a potential design of the high performance ACU.

Evaluate

Research Objective: Evaluate the design concept on basis of concept screening matrix and score card.

The suggested design concept was evaluated by comparing it with the current ACU using the concept screening matrix and concept scoring matrix.

Concept screening matrix- Concept screening is based on a method developed by late Stuart Pugh in the 1980s and is often called as Pugh concept selection. To prepare the matrix, the concepts identified are entered on the top of the matrix and the selection criteria are listed along the left-hand side of the screening matrix. These criteria are chosen based on the customer needs (i.e. specific features needed in the product). The criteria are usually expressed at a fairly high level of abstraction and typically include from 5 to 20 dimensions. The selection criteria should be chosen to differentiate among the concept. A relative source of "better than" (+), "same as" (0), or "worse than" (-) is placed in each cell of the matrix to represent how each concept rates in comparison to the reference concept or product relative to the particular criterion. After rating all the concepts, the number of "better than", "same as", and "worse than" scores are summed and these sums for each category are entered in the lower rows of the matrix. The net score is calculated by subtracting the number of "worse than" ratings from the "better than" ratings. Once the summation is completed the concepts are rank-ordered.

Concept scoring matrix- Concept scoring is used for better differentiation between competing concepts. As in the case of screening matrix, a scoring matrix is prepared with the concepts identified entered on the top of the matrix and the selection criteria are listed along the left-hand side of the screening matrix. After the criteria are entered, weights for the same are added to the matrix. Several different schemes can be used to weight the criteria, such as assigning importance value from 1 to 10, or allocating 100 percentage points among them. Once the ratings are entered for each concept, weighted scores are calculated by multiplying the raw scores by the criteria weights. The total score concept is the sum of the weighted scores. Finally, each concept is given a rank corresponding to its total score.

For the concept scoring matrix developed in this study, under the “weight” column each criterion/ feature required in the ACU is given a value on the basis of its importance such that the total weight for all the criteria sums upto 100. The current ACU and the new design have been rated on a scale of 1-10 based on the potential of each to meet a particular criterion. The higher the score, the better the uniform meets the criterion. For production cost a lower rating implies the cost of production is higher and vice-e-versa. For manufacturability, a higher rating implies ease of manufacture. The “weighted score” is calculated by multiplying the rating by the criteria weight and dividing it by 10. The total score for each concept is the sum of the weighted scores.

Both the concept screening and scoring matrices that were designed as a part of this research were developed on basis of survey and personal interviews.

The survey population consisted of:

- Personnel working for the Natick Soldier RD&E Center – 4 respondents
- Manufacturers of military uniforms – 2 respondents

Two different forms of surveys were used for this study. The responses were evaluated, analyzed and the final matrices were developed.

Phase III

Research Objective: Use the above research study to develop a House of Quality Matrix which could be used as a future guide for selection of technologies to be incorporated in ACUs.

The Phase III of this study developed a House of Quality Matrix (HQM) for the high performance combat uniform design suggested after the completion of phase II. The HQM was developed on basis of information collected during interviews with researchers working on the ACUs. The interviews were either be telephonic or via e-mails. After the HQM was developed it was given to the respondents for review and their suggestions were incorporated in the final model of the HQM. The model developed in this study will help in selection of technologies for ACU in a more systematic manner.

Experimental

Materials

Nylon-6 nonwoven fabric provided by the Nonwovens Cooperative Research Center (NCRC) (100 g/m^2; 3 denier) was used for preparation of prototype sample and to carry out experiments to impart superhydrophobicity and superoleophobicity to fabric surface. The line speed used for hydroentangling was 10 m/min with 1 pass and drying temperature of 120^{o}C. The manifold pressures used are given in Table 4.

Table 4. Manifold Pressures

Manifold	Pressure (bars)
1	30
2	90
3	120
4	150
5	150

Poly(acrylic acid) (PAA, M_w: 450 kD, Aldrich), sodium hypophosphite (NaH_2PO_2), 1H,1H,2H,2H-perfluorodecyltrimethoxysilane, 1H,1H-perfluorooctylamine, nanosilver solution (10 – 20 nm, NP Tech), 4-(4,6-dimethoxy-1,3,5-triazin-2yl)-4-methylmorpholinium chloride (DMTMM, Fluka), methanol (CH_3OH, Aldrich).

Grafting of PAA on Nylon-6 Surface

To increase the number of reactive sites of nylon the fabric was treated with PAA using the following procedure:

2 g/L PAA in water solution was treated onto NYCO and nonwoven fabrics and grafted using a coupling agent, DMTMM. The treated fabric was rinsed with distilled water and dried in air for 24 h. Figure 15 shows the grafting procedure of PAA on nylon-6.

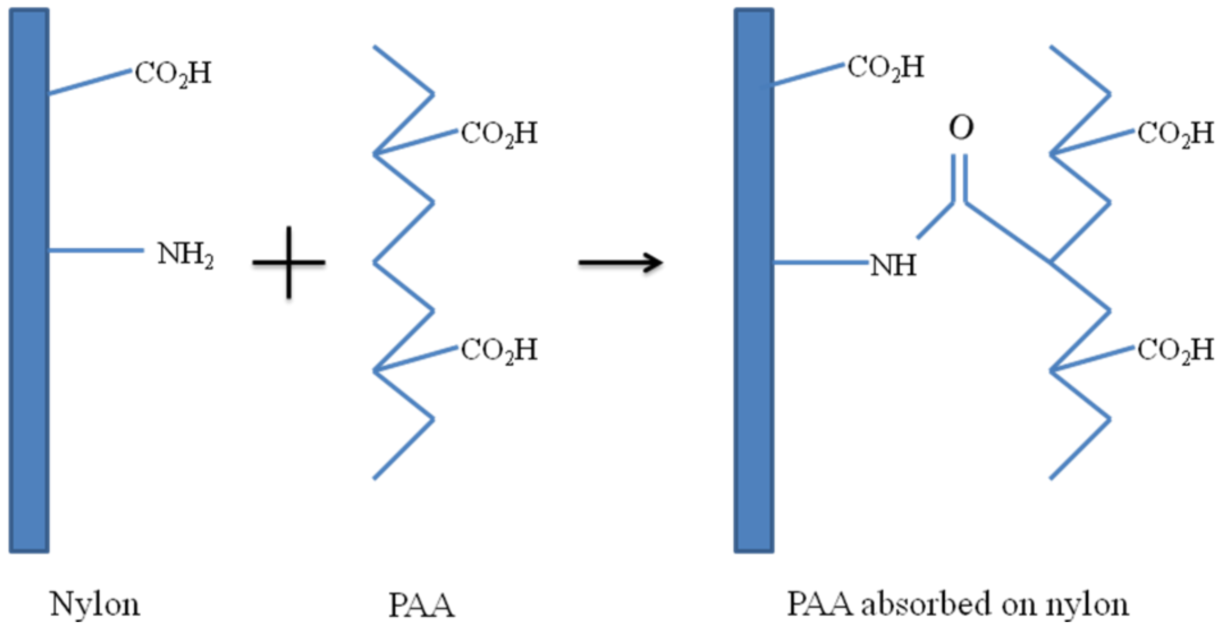


Figure 15. Graft of PAA on nylon-6

Grafting of Fluoroamine on PAA-grafted nylon-6 Surface

0.05 g 1H,1H-perfluorooctylamine was dissolved in 5 mL methanol. 0.15 g PAA-grafted nylon nonwoven fabric was immersed in this solution for 20 minutes. 0.03 g of DMTMM was dissolved on 5 mL methanol. This solution was added to the PAA-grafted nylon immersed in the 1H,1H-perfluorooctylamine solution and the reaction was continued for 24 h. Then the 1H,1H-perfluorooctylamine-grafted PAA-grafted nylon nonwoven fabric was rinsed in distilled water and methanol and air dried. Figure 16 shows the grafting procedure for 1H,1H-perfluorooctylamine on PAA- grafted nylon-6.

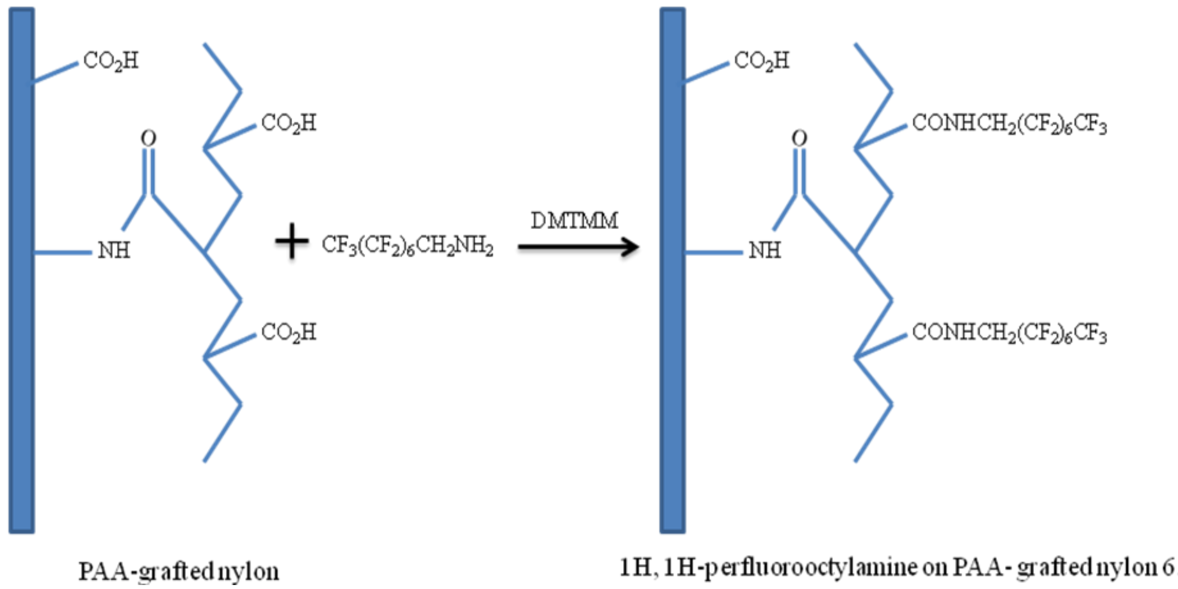


Figure 16. Graft of 1H,1H-perfluorooctylamine on PAA- grafted nylon-6.

Grafting of Fluorosliane on PAA-grafted nylon-6 Surface

1H,1H,2H,2H-Perfluorodecyltrimethoxysilane aqueous solution was mixed with methanol to treat on PAA-grafted nylon-6 surface. The PAA-grafted nylon-6 nonwoven fabric was chemically grafted with 1H,1H,2H,2H-Perfluorodecyltrimethoxysilane. The sample was dried followed by rinsing with distilled water. Figure 17 shows the grafting procedure for 1H,1H,2H,2H-Perfluorodecyltrimethoxysilane on PAA- grafted nylon-6.

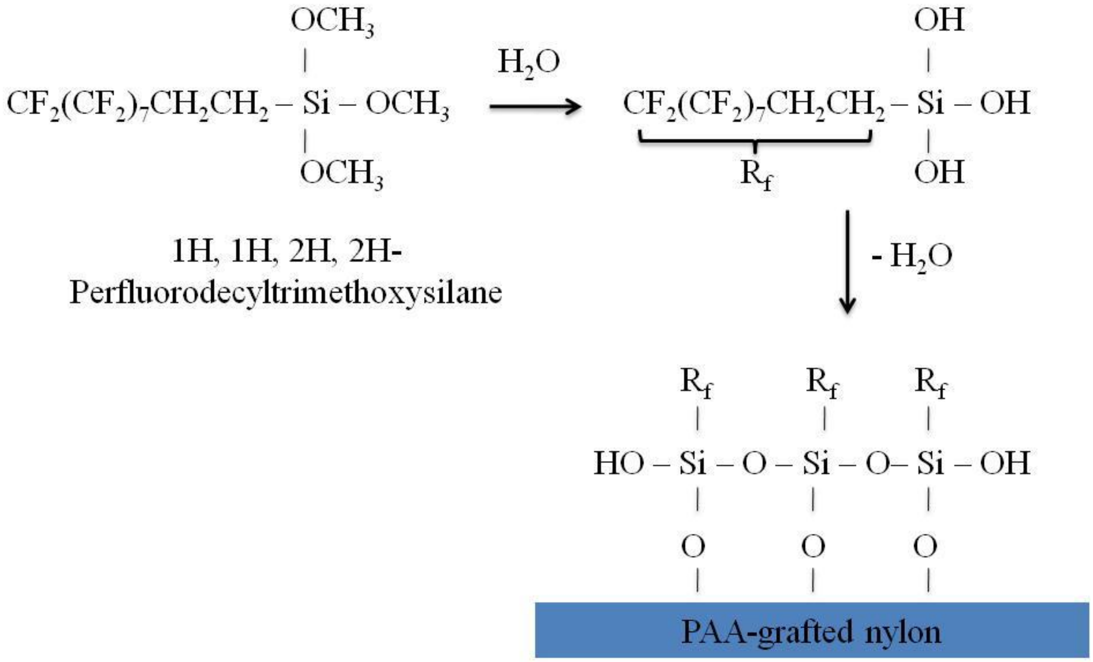


Figure 17. 1H,1H,2H,2H-Perfluorodecyltrimethoxysilane on PAA-grafted nylon-6.

Test Methods for Fiber and Fabric Testing

Tensile Strength for Nonwoven Fabric

The tensile strength of the webs was characterized by test method ASTM D5034 in machine and cross directions. The crosshead speed was kept constant at 12 mm/min during the course of the experiments

Trapezoids Tear Strength for Nonwoven Fabric

The trapezoid tear strength of the webs was characterized by test method ASTM D1117 in both machine and cross directions. The crosshead speed was kept constant at 12 mm/min during the course of the experiments.

Fiber Modulus and Tenacity Testing

The individual fibers were tested for tenacity and modulus values using an MTS Q-Tester (Test method: ASTM D3822) at a constant crosshead speed of 15 mm/min. While tenacity is the amount of force needed to break the fiber, modulus is a measure of fiber stiffness. These two properties are important fiber properties which affect the ultimate web properties. Flexural rigidity of a fiber, defined as the couple required to bend the fiber to unit curvature is one of the factors considered to have significant effects on hydroentangling efficiency. Fibers with low flexural rigidity can bend around small radii easily and require less energy to entangle compared to those with high flexural rigidity. Flexural rigidity shows a direct relationship with fiber modulus values.

AATCC Test Method 61Test No. 2A Colorfastness to Laundering, Home and Commercial: Accelerated (AATCC, 2007)

To test the superhydrophobicity of the current ACU and the prototype sample, specimens of both the garments were subjected to accelerated laundering that is equivalent to 25 wash cycles. AATCC Test Method 61 Test No. 2A was used for this purpose.

For this test the laundering machine was adjusted to maintain the bath temperature at 49^{o}C (± ^{o}2). The required volume of wash liquor was prepared with 0.15% of AATCC standard reference detergent of the total volume. The solution was preheated to the prescribed temperature. The test was run in 90x200 mm (3.5x8.0 in.) lever lock stainless steel canisters containing 150 mL of the total liquor volume and 50 steel balls with specimen size of 50x150 mm (2.0x6.0 in.) for 45 min. The contact angle for water and organic solvent (dodecane) was measured after every accelerated wash cycle to measure the hydrophobicity of the garment.

Contact Angle Measurements

The contact angle for the current ACU fabric and prepared surfaces was measured using a lab-designed goniometer. The volume of distilled water and organic solvent droplets was 2 µL. Mean values were calculated from at least three individual measurements each on a new spot. The contact angle images were obtained using an optical contact angle instrument and a high resolution zoom camera (Century Optics .65X or VPLL-ZM101, Sony Corp.).

Preparation of Prototype Sample

A prototype sample of the ACU jacket was prepared as a part of this research. This prototype was made using nylon-6 nonwoven fabric. This prototype sample was treated with nanosilver solution and 1H,1H,2H,2H-Perfluorodecyltrimethoxysilane to impart anti-microbial, superhydrophobic and superoleophobic properties to the final garment. The patterns of ACU jacket were created using Gerber Acumark® software and cut with an automated sewing machine. The prototype garment was sewn using ultrasonic sewing machine.

The following are the procedures for solution preparation and fabric treatment.

For Anti-microbial Treatment

Nanosilver solution was prepared using 150 mL of 200 ppm colloidal nanosilver solution and 150 mL methanol. This solution was stirred for 20 min. The nylon nonwoven fabric was then padded with this solution with 100% wet pick up. The padded fabric was dried at 70^{o}C for 3 minutes and then cured at 120^{o}C for 2 minutes. (This method for treating nonwovens with nanosilver for anti-bacterial property was used by Lee and Jeong (2005) and the results for the same were positive.)

For Superhydrophobic and Self Cleaning Effect

150 g of 1H,1H2H,2H-Perfluorodecyltrimethoxysilane solution was prepared. The nylon nonwoven fabric treated with nanosilver solution was then treated with this solution. The fabric was washed with distilled water and then air dried.

Definition of Terms

Mobility: Movement is the key factor to make clothing a person's portable environment. The ability of a person to move quickly and precisely with the garment is called as mobility. Mobility of clothing is often reduced as protection is increased. This is because thick layers of fabric may be needed for extreme protection that may interfere with the movement and the range and speed of joint motion. Therefore, it is important for the designer to determine the movements of the particular group for which clothing is created such that the garments created provide ease of movement to the wearer (Watkins, 1995).

Communication: Combat communication and networking between the soldiers during the war and for joint warfare (Tassinari and Leitch, 2004). New technologies available have enhanced the communication channels which also help in tracking a soldier during the war. It also aims at better exchange and flow of information between the troops during military operations.

Personal protection: Understanding types of hazards or threats is critical first step in developing systems for protection and enhancing safety of the soldier. Uniforms need to protect the soldier from many hazards as well as provide comfort. Also, uniforms should protect the soldier against known and unknown hazards.

Logistic support: It is responsible for planning, developing, acquiring and sustaining well-defined, affordable support strategies that meet the war fighter’s requirements for Army materiel throughout its life cycle (Integrated logistics support, 2008).

Chapter 4

Results

In the current research the New Product Design (NPD) process for military uniforms was developed using the New Product Design process (adapted from Urban and Hauser, 1995) as the basic framework. After studying the complete process for military uniforms, this research focused on the opportunity identification and design phases of the new product design process focusing on technological innovations for which the Watkins design model was used. In the current study, nonwovens are proposed materials for the manufacture of future Army Combat Uniform (ACU). Also, mass customization and ultrasonic sewing are suggested production technologies that can be incorporated in manufacture of future ACU. This chapter also gives the experimental results for the current ACU and proposed method to create a superhydrophobic and superoleophobic surface. A prototype sample which was ultrasonically sewn was fabricated using nonwoven fabric that was treated for superhydrophobicity and superoleophobicity. The current ACU and the new design for the ACU have been compared using concept screening and concept scoring matrices. A House of Quality Matrix that explains the intricacies and interdependencies of various elements involved in the design process of ACU has also been developed.

The following research objectives are addressed in this chapter:

1. Study the New Product Design Process (adapted from Urban and Hauser) for military uniforms
2. Discuss the materials and technologies identified as an opportunity for changes in the ACU and thus study the opportunity identification phase for ACU
3. Propose a method for preparing superhydrophobic and superoleophobic surface and prepare a prototype sample showing superhydrophobic and superoleophobic characteristics.
4. Suggest a model for mass customization of ACUs
5. Study of novel sewing techniques for manufacture of ACUs
6. Compare the potential design and current ACU using a concept evaluation matrix
7. Use the above results to develop a House of Quality Matrix as a future guide for selection of technologies to be incorporated in ACUs

New Product Design Process for Military Uniforms

Research Objective: Study the New Product Design Process (adapted from Urban and Hauser) for military uniforms.

The five stage decision process described by Urban and Hauser in their book "Design and Marketing of New Products" (1993) which is explained in Chapter 2: Literature Review can be applied to the product design process of the military uniforms. In this section a parallel has been drawn between the two and the new product design process for military uniforms has been put forward.

Opportunity Identification and Concepts

With the current technological advances and research and development, efforts are being made to create an ideal combat uniform. New design ideas can be generated by interviewing the military personnel and also by comparison with military uniforms of other countries of the world. In case of NPD process for military uniforms, the following are the initiating factors for innovation.

Growing Market Potential

According to the Stockholm International Peace Research Institute (SIPRI), 2008, the world military expenditure in 2006 for all purchases is estimated at $1204 billion in current prices. This represents an increase of 3.5 per cent in real terms since 2005 and of 37 per cent over the 10-year period since 1997. Thus there is an increasing market potential for the military textiles.

Technology

Militaries around the world have set up research and development efforts to create the ideal combat uniform because of the increasing awareness of the crucial role of clothing in enhancing the performance of soldiers and protecting their lives during combat. Research and development has been carried out towards the making of smart fabrics for combat suits of military personnel. Smart textiles are those that can sense the external environmental conditions or stimuli from mechanical, chemical, electric, magnetic or other sources. Nanotechnology will help to create textile structures with improved molecular organization.

Such molecular engineering helps to create unique properties in the fabric without affecting the handle, breathability or durability of the fabric. Nanotechnology could be used in making self-healing, self-cleaning materials and size and shape adjusting apparel. Biotechnology is another growing technology for developing functional activities in the fabrics. Developing bio-active fabrics that would assist the wound healing is an important breakthrough in this field. On the other hand, information technology can enable fabrics to become conductors of electric current and power in contrast to the hard circuitry thus enabling the use of such fabrics for communication (Hira and Sarkar, 2004)

Globalization

Emerging economies have more wealth to spend on equipping their military. With the increasing global military exchanges the requirements for the military uniforms have increased. Taking this into consideration China hiked its military budget this year by $44.9 billion to provide sleeker uniforms for its 2.3 million-member military (Bodeen, 2007).

Regulation

In case of new government regulations or deregulation, there may be a need to develop a new military uniform that meets the set requirements. The government's decisions play an important role in case of development of new military uniforms. The military in its efforts to provide the best possible comfort and protection for service members updates the uniforms in order to take advantage of new designs and fabrics that best meet the usage requirements. The specifications for the new uniform are drawn up by the government and then forwarded to the manufacturers.

Demographic or lifestyle changes

The forces of the United States military are located in nearly 130 countries around the world performing a variety of duties from combat operations, to peacekeeping, to training with foreign militaries (Global Security.org, 2008). The military uniform requirements change through different countries according to the climatic conditions in that country. Thus NPD is required for designing uniforms that provide comfort to the soldiers.

Consumer requests

Though the Department of Defense (DoD) makes the purchasing decisions in case of military uniforms, the uniforms are developed according to the soldiers' demand to provide them comfort when deployed on the field. As the soldiers are deployed in different parts of the world their requirements change according to the weather and geographical conditions. The uniform design updates are also targeted at enhancing the serviceman's appearance to a more modern look to boost his image and morale.

The main sources of idea generation would be through *exploratory consumer studies*, in this case interviewing the military personnel about the changes they would like in their uniforms which would provide them better comfort. As explained in the innovation stage *new technological developments* could also be an initiating factor for a new product development. For example:

- Some of the recent developments in military clothing include progress in minimizing weight and maximizing wear comfort. The US Army Natick Soldier RD&E Center is currently researching upon developing and incorporating enhanced nonwoven composite fabrics for military uniforms (Szczesuil and Narayanan, 2008). This proposed composite nonwoven military uniform fabric possesses high strength, softness, improved abrasion resistance, air permeability and printability for the camouflage pattern. The lighter weight and higher breathability adds to the comfort properties of the fabric.

- An article reports on the provisions of the 2004 Defense Spending Bill, approved by the U.S. Congress, in connection with the Polartec garments from the Malden Mills company to the U.S. Armed Forces. Included in this funding were three million dollars to continue research and development of *electronic textiles* that are the foundation of the U.S. Army's Combat Casualty Care program. The grant was to be used to continue efforts to design *electronic textiles* for the U.S. *military* to monitor and transmit soldiers' pulse, blood pressure, body temperature and location back to *military* medics responsible for their well being in the field (U.S. army backs electrotextiles, 2004).
- The "self-cleaning" process makes fabrics repel water, resist stains and even kill off the bacteria that grow in sweat and make clothes smell. The American military developed a new coating in a $14 million research program over five years. It was initially intended to turn soldiers' ordinary battle dress uniforms into kit that could offer protection in biological warfare. Tests found that the process could kill anthrax and other bacteria used as weapons. Soldiers have also tested treated underwear, wearing garments for several weeks in combat simulations. Dr. Jeffery Owens, the scientist at the US Air Force Research Laboratory said: "During Desert Storm most casualties were from bacterial infections rather than from accidents or friendly fire.

> We have treated T-shirts and underwear for soldiers who tested them for several weeks and found that they remained hygienic as the clothing was actively killing the bacteria. They also helped clear up some skin complaints in those testing them" (Gray, 2006).

New product ideas can also be generated by *comparing the military uniforms from the other countries* of the world which could be better than the U.S. military uniforms. The material, color, design, fit, the value-added properties of the fabric all could be different. For example:

- Battle Dress was a specific style of military uniform adopted by the British Army in late 1930s, and several other nations introduced variants of Battle Dress during the Second World War (Battle Dress, 2008).
- The Chinese military have undergone the largest-ever reform in their military uniforms, with 644 new items of clothing involved in the change (CRI English.com, 2007). By scrutinizing the technologies used by other nations to develop their military uniforms, the U.S Natick RD&E Center can adopt a new technology which is not currently in use for developing US military uniforms.

Ideas can also be generated by forming partnerships or alliances. For Example: A partnership agreement between Lenzing Fibers and TenCate Southern Mills to produce a new fabric for use in the manufacture of flame retardant battle suits for the U.S. Army (Product developments and innovations, 2007).

Design

The U.S army is deployed in different countries throughout the world, due to which the soldiers face different climatic and environmental conditions. This leads to need of new uniform design suitable for specific regions. A continuous and direct input from the soldiers regarding their needs is important during the NPD process for military uniforms.

Core Benefits Proposition

The military uniforms should be easy to maintain, comfortable, have good fit, durable, satisfy various climatic and utility needs and, most importantly must make the wearer proud of it.

The stage gate process could be applied by manufacturers developing military uniforms incorporating new technologies and thus review and prioritize the opportunities. The market opportunity along with how the technology fits within the core competencies of the company can be reviewed monthly. Thus if a company has 30-40 concepts they can be narrowed down by the process to top 10 and from there the company can focus on the top three to five.

The Voice of Customer (VOC) is an integral part for uniform development in the military. Here the consumers are the soldiers who wear the uniforms in the battlefields, so there input is important to make improvements in the uniforms which would add to their comfort and the ease of use. For Example: The Army Combat Uniform (ACU) with a new Universal Camouflage "pixilated" scheme is the uniform of choice by the overwhelming majority of the Army's leaders and soldiers, developed with direct and continuous input from army soldiers. It has been designed for functionality and ergonomics, and to enhance soldiers' performance and safety (Army Reserve Magazine, 2004).

The forces of the United States military are located in nearly 130 countries around the world performing a variety of duties from combat operations, to peacekeeping, to training with foreign militaries. There are environmental and climatic differences between the regions where the army troops are deployed. For example: The climate in Iraq is dry and arid where the average temperatures range from 48 ^{0}C to below freezing. The western and southern areas are desert regions having dry and dusty winds (Global Security.org, 2008). Conversely, Vietnam has a tropical monsoon climate with average humidity of 84% throughout the year. It has coastal plains and mountain peaks with tropical forests as opposed to the deserts in Iraq. Figure 18 shows the differences in the environmental conditions between Iraq and Vietnam and also, the difference in uniforms used by the soldiers.

Figure 18. The photographs above show the difference in environment between Iraq (left) and Vietnam (right).

Source: Google images

The following are the examples of military uniforms which have different designs and thus different functions.

- *Army Combat Uniform (ACU)*: The ACU consists of a jacket, trousers, and patrol cap in universal camouflage pattern, moisture wicking T-shirt, and Army Combat Boots (temperature and hot weather). The component materials are 50% cotton, 50% nylon that is treated to be wrinkle-free. It has 37 coat sizes and 36 trouser sizes.
- *Generation III Extended Cold Weather Clothing System (GEN III ECWS)*: GEN III ECWS was designed to be functional in multiple cold weather climates and activities. It consists of a versatile, multi-layered insulating system that allows the soldier to adapt to varying mission requirements and environmental conditions. New materials offer a greater range of breathability and environmental protection providing greater versatility in meeting soldiers' needs. There are 12 components of the GEN III ECWCS that include a lightweight shirt and drawers, fleece cold weather jacket, wind cold weather jacket, soft shell jacket and trousers, extreme cold/wet weather jacket and trousers, extreme cold weather parka, and trousers. It weighs 12.85 lbs and has sizes small-regular, medium-regular, large-regular, large-long, extra large-regular and extra large-long.
- *Improved Outer Tactical Vests (IOTV)*: These are three pounds lighter than the conventional outer tactical vests and provide better performance and comfort while protecting the soldier against bullets and fragments. The additional features include side access to facilitate medical treatment without removing the vest, channels for communication equipment cables, mesh lining for better ventilation, adjustment

straps for customized fit, etc. It weighs 30 pounds and has 11 sizes ranging from X-small through XXXX-large.

- *Advanced Combat Helmet (ACH)*: The ACH enhances ballistic protection, stability and comfort without degrading vision or hearing. Its shell is made of Aramid fabric; chinstrap features cotton/polyester webbing. It is currently available is four sizes (small, medium, large and X-large) which weigh 2.93 pounds, 3.06 pounds,3.31 pounds and 3.80 pounds respectively.

Testing

In case of military uniforms for the *testing* stage the manufacturers do not need to launch the uniforms in the market so there are no test markets available. Instead they provide the samples to the DoD which would test the uniforms. Sometimes for testing the general properties the uniforms are tested according to the ASTM standards and for testing more specific properties the DoD uses its own set of standards. The testing is done at the Natick Soldier RD&E Center, MA. The DoD has specifications for each and every component, construction and pattern of the uniforms.

The Textile Protection and Comfort Center (TPACC) at College of Textiles, NCSU does perform tests on military uniforms. The various tests that are performed at TPACC include human subject testing, comfort work test and physiological tests. These tests are carried out at the environmental conditioning lab where the testing conditions can be matched with those conditions under which the uniforms would be used by the soldiers. The testing requirements vary according to the camp and type of mission.

The uniforms are also field tested during which the soldiers use the new uniforms at the war ground. The feedback is then studied and needed changes are made. For example: The Navy's new BDU was tested over two years before being made official BDU for Navy. Also, for field testing the ACU, 21 uniforms were delivered to Stryker Soldiers at the Joint Training and Readiness Center, who were then deployed to Iraq. Sgt. 1st Class Jeff Myhre, the Clothing and Individual Equipment noncommissioned officer in charge was among a team who visited Iraq to get more feedback from the soldiers. They would talk to soldiers' right after they completed a mission while the benefits of the uniform were still fresh in their minds. The team wanted to know how the uniform helped the mission. They made modifications in the final version of the uniform from the feedback of the soldiers in combat (Triggs, 2004).

Introduction

In case of military uniforms the introduction stage which is basically the product launch in the market does not exist as the uniforms will be directly supplied to the U.S. military through the DoD once they pass the testing stage, so there is no need for marketing or promotion for the uniforms. The other reason why the military uniforms are not marketed is because it is a matter of the nation's safety. The uniform functions and features are trade secrets of the DoD.

Product Life Cycle Management

The product life cycle for military uniforms follows a different life-cycle then the ideal path. In case of military uniforms introduction stage could be inception of new design idea for the uniform. This is generally done at the DoD, Defense Supply Center (DSCP) or the Natick Soldier RD&E Center. The military uniforms do not have competition as in case of other products as a new design of military uniform is introduced only if there is a need to improve the functional characteristics of the present one. The issue of *life cycle management* for military uniforms arises only if there is change in the uniform designs or application of new technology in the uniforms and only under the circumstances of new additions the current uniforms are replaced be new ones. Also if the forces are deployed in a country with different environmental conditions then the uniforms need to be redesigned. There may be a lag between the idea inception and product inception stage because there are strict regulations regarding the material used for military uniforms.

According to the Berry Amendment the military uniform must be 100% U.S. material up to the finished product. This means in case of Poly/Wool material the sheep wool must be from the U.S. A few products such as Rayon are not made in the U.S. and have been waived (Office of Textiles and Apparel, 2008). But, there is competition for the manufacturers of these military uniforms. The contracts given by the DoD for manufacture of the uniforms are governed by the bid process, thus, the pricing of the garments under the bidding process is the number one criteria. When all other governing factors are equal the DoD compares the price of the uniforms for issuing the contract.

The soldiers initially get four pairs of uniforms from the military services, but after the use of these initial pairs of uniforms it is the responsibility of the soldier to buy new uniform and also laundering the uniforms. Thus, from the soldiers' point of view it is important that the military uniforms have better life and durability. The uniforms should have better wash fastness and should not wear out due to laundering. Taking this into consideration the new ACU has patches and tabs that are affixed to the uniform with Velcro to give the wearer more flexibility and to save the soldier money. Soldiers can take the name-tapes and patches off their uniforms before laundering, which will add to the lifecycle of the patches.

Use of Nonwovens for Manufacturing the ACU

Research Objective: *Discuss the materials identified as an opportunity for changes in the ACU and thus study the opportunity identification phase for ACU.*

A nonwoven fabric is a two dimensional (2D) textile material which does not involve conventional weaving or knitting. Instead, a web of loose fibers is made and bonded by a variety of technologies to make a strong fabric. According to the Association of the Nonwovens Fabrics Industry (INDA), nonwovens are a sheet, web, or bat of natural and/or man-made fibers or filaments, excluding paper, that have not been converted into yarns, and that are bonded to each other. Therefore, the nonwoven technology allows the fibers to be constructed to fabric in an economical, rapid and more versatile way (Block, 1974). Nonwoven fabrics are highly engineered fabrics that may be a single-use fabric with limited life or a very durable fabric depending on the end-application. In combination with other materials they can provide a spectrum of products with diverse properties for military clothing. For applications in military uniforms, a fabric should meet certain requirements such as superior strength, comfort, protection against chemical biological (CB) warfare, flame resistance (FR), and many more (Uddin, 2006). Nonwovens, being highly engineered, can combine all these properties in one fabric. If nonwoven manufacturing techniques are selected correctly, the resultant fabric can easily match the required standards, and development of cost effective durable FR nonwoven uniforms protecting soldiers against CB warfare agents can be achieved.

The current utility fabrics used for military uniforms are woven fabrics consisting of 50% nylon and 50% cotton. Woven fabric manufacturing comprises three main steps: spinning, weaving and finishing which in turn consist of as many as fourteen sub-steps (some of which cannot be performed under a single roof). This makes the complete process, time consuming as well as expensive (Szczesuil and Narayanan, 2008). On the contrary, nonwoven fabric processes are brief having five steps: opening, blending, carding/web formation, bonding and finishing, and thus they tend to be less expensive. Woven fabric is composed of large yarns having twisted strands which fail to give a compact structure to the fabric. The loose structure leads to poor insulation, filtration and barrier properties. As opposed to this, nonwoven fabrics are produced by bonding finer individual fibers thus providing a condensed structure which can lead to better insulation, filtration and barrier properties. Also, nonwoven fabric processes involve new technologies and innovations in which the U.S. leads. Producing military uniforms using nonwoven fabrics instead of woven fabrics will make domestic mass production of defense materials much easier (Szczesuil and Narayanan, 2008).

Some of the recent developments in military clothing include progress in minimizing weight and maximizing wear and comfort. The Natick Soldier RD&E is currently researching developing and incorporating enhanced nonwoven composite fabrics for military uniforms. This proposed composite nonwoven military uniform fabric possesses high strength, softness, improved abrasion resistance, air permeability and printability for the camouflage pattern. The lighter weight and higher breathability can lead to potential reduction in heat stress and also adds to the comfort properties of the fabric.

This nonwoven fabric designed for the military uniforms has a composite multilayer structure which provides enhanced water absorbency inside for sweat absorption and exterior water repellency for rain protection. This nonwoven fabric can also be treated with fire retardant chemicals which impart characteristics such as self-extinguishing, char formation and low smoke generation to the fabric (Winterhalter, 2008).

Smart Textiles for the Army Combat Uniforms

Research Objective: Discuss the materials and technologies identified as an opportunity for changes in the ACU and thus study the opportunity identification phase for ACU.

Since the Vietnam War, in the last forty years, many improvements have been made in the U.S Army's combat uniforms to provide better functionality, comfort and protection to the soldiers. The modern warfighting scenarios and environments that the soldiers face include domestic and foreign terrorism, peace keeping, nation building, low and high density conflicts, special operations, military operations in urban terrain and worldwide climatic conditions (Tassinari and Leitch, 2004). Smart textiles can provide protection to safeguard the troops in these modern battlefield environments. Potential enhancements the U.S. army is currently evaluating are use of smart textiles to serve as backbone for electronics, optics and other sensors.

The future warrior systems would be equipped with head-up display, wireless weapons, global positioning systems, chemical and biological threat detectors, battery power, etc. All these systems would assist the soldier in situational awareness and understanding by providing functions like physiological status monitoring, sensing battlefield hazard, battlefield surveillance, mobility enhancement, threat responsive protection, combat ID, real time communication and lightweight and low cube power generation.

Nanotechnology will also play a major role in the development of new generation army uniforms. The Institute for Soldier Nanotechnologies (ISN) at Massachusetts Institute of Technology (MIT) was founded in 2002 by a $50 million, five year contract with the U.S. Army Research Office (ARO) to develop and exploit nanotechnology applications in Army to improve the survivability of soldiers (Institute for Soldier Nanotechnologies, 2008). The ultimate goal of ISN is to help Army to develop a battlesuit that provides high tech capabilities as well as will be light weight and comfortable.

DARPA also focuses on research in the area of smart textiles. DARPA’s mission is to maintain the technological superiority of the U.S. military by revolutionary, innovative and high-payoff research ideas that bridge the gap between fundamental discoveries and their military use (Defense Advanced Research Projects Agency, 2008).

The Natick Soldier RD&E Center partners with the U.S Army Integrated Logistics Support Center- Soldier, Biological Chemical (ILSC-SBC), the U.S Army Natick Soldier RD&E Center and the U.S Army Product Manager Clothing and Individual Equipment (CIE) for research and development activities. To maximize the soldier's survivability, mobility, sustainability, combat effectiveness these organizations collaboratively work for providing uniforms that offer ballistic protection and are safe and durable (The U.S Army Soldier Systems RD & E, 2008).

Bio-feedback and Wearable Health Monitoring

The bio-monitoring products that are textiles based are expected to find applications in the medical, public safety, military and sports market. These biofeedback and health monitoring systems are designed to monitor the physical well-being and other vital signs such as heart rate, caloric consumption and temperature of the wearer. Sensatex developed a SmartShirt System that incorporated new technologies from textile engineering, wearable computing and wireless data transfer (Sensatex, 2008). This system collects, transmits and analyses the personal health and lifestyle of the user. This system was developed by interconnecting and networking the information processing devices within the fabric.

The SmartShirt detected the penetration of a projectile in the garment, monitored the soldier's vital signs and also alerted the medical triage units stationed near the battlefield. The soldier's vital signs that were measured and monitored included heart rate, respiration rate, body temperature and caloric burn. The readouts were provided through a wristwatch, Personal Digital Assistant (PDA), or voice synthesis and then transmitted wirelessly to a personal computer and finally, the internet (The U.S Army Soldier Systems RD & E, 2008).

In the past, nylon Lycra textile has proven to be an excellent substrate for strain gauge sensors for biofeedback health monitoring systems as compared to other textile materials available commercially (Munro, 2008). This textile substrate has been proved to exhibit low resistive forces which help in effective functioning of the sensors and the material does not impede body movement too. Since the proposed ACU design uses nylon nonwoven fabric for the ACU, the biofeedback monitoring systems can be incorporated in the future ACU leading to better monitoring of the soldier's status in the battlefield and also helping the medical staff to locate the soldier's wound quickly amid the battlefield chaos.

Application of RFID Technology to the ACU

Radio frequency identification or RFID is the process and physical infrastructure by which a unique identifier, within a predefined protocol definition, is transferred from a device to a reader via radio frequency waves. RFID plays an important role in implementation of knowledge-enabled logistic support system for military operations through fully automated and visible management of resources. Implementation of RFID technology would have many unique benefits to combat and rescue operations. In the modern battlefield scenario better and faster use of combat information would be the key deciding factor. Network centric joint warfare system would be one of the essentials of modern warfighting. This could be possible using RFID technology because during the combat operations of tactical or strategic nature it will be possible for the commanders to monitor the terrain and movement of the soldiers continuously thus giving more accurate and responsive command to direct the troops to achieve the mission. The RFID tags were carried by the soldiers during the operation Iraqi Freedom. These tags enabled the radar to detect the soldiers' location and also allowed the commanders to see their troops closing in on their objective real time. Thus RFID technology may lead to more comprehensive decisions and thus decrease in casualties (Banks, Hanny, Pachano and Thompson, 2007).

Elliot, Ellis, Skaggs and Nguyen (2008) from TDA Research Inc., are in process of developing chemical warfare (CW) agent sensors based on RFID tag. This sensor will not only warn the individual soldiers but will also warn the commanders of an existing CW threat. Thus, it could be used for communicating with and alerting other soldiers' during the future network centric warfare system. These sensors can be very practical and economical solution to the individual chemical detection challenges that the military is currently facing.

Concept Screening Matrix

Research Objective: Compare the potential design and the current ACU using a concept evaluation matrix

In the previous chapters' the uniform requirements for current combat conditions have been explained. Also, the ideas of using nonwovens, smart textiles, RFID technology and incorporating self-cleaning feature for chemical-biological defense for manufacture of ACU have been proposed. In this section, we have developed a concept screening matrix that compares the current ACU for its properties and functionality with a new design for the ACU. The concepts for the new design of the ACU are based on the requirements for the uniform after interviewing researchers from the Natick Soldier RD&E Center. Also, the concept screening matrix is developed on basis of a survey where the respondents were people working in the field of military textiles and specifically in the area of army uniforms.

The concept screening matrix rates the new design with the current ACU on basis of the selection criteria (mobility, functionality, communications, ergonomics, durability, design) that are listed along the left-hand side of the screening matrix. If the interviewee considered the current ACU performed satisfactorily but there is a possibility of improvement than it was given a “0”, but if the current ACU does not meet a particular criterion than a relative score of “-” was assigned in the corresponding cell. If the current ACU performed extremely well and no further improvement was required than a relative score of “+” was placed in the corresponding cell. A final score was recorded by adding the plusses and the minuses. It can be seen from Table 5 that the new design has a score of 7, whereas the current ACU has a score 0. So, we can confirm that there is much scope for improvement the current design and thus improving the functionality of the current ACU.

Table 5. Concept Screening Matrix

Selecting Criteria	Current ACU	New Design for ACU
Mobility		
Flexibility	0	+
Lightweight	+	0
Communications		
RFID, Bluetooth, GPS Technologies	0	+
Functionality		
Flame resistant	+	+
Protection against Chemical Biological Warfare Agents *i.e.* Self-cleaning, Self-detoxifying, Anti-microbial Effects, Seam-sealing, etc.	-	+
Protection against Physical Attack	+	+
Stand-off Chemical/ Biological/ Nuclear Warfare Detection	-	+
Ergonomics		
Comfort/ Feel such as Breathability	0	0
Durability		
Wash Fastness	0	+
Design		
Camouflage (invisibility during the day)	0	0
Stealth (invisibility at night)	0	0
Sum +'s **Sum 0's** **Sum –'s**	3 7 2	7 3 0
Net Score	**1**	**7**

On basis of the concept scoring matrix and interviews the following could be summarized:

- The current ACU has adequate flexibility but additional flexibility for the areas like shoulders, elbows, knees and seat is desirable.
- Weight of the current ACU is ideal for multi-environment combat fields, but if the new design weighs lighter and also provides satisfactory environmental protection than such a feature would be desirable.
- The current ACU does not have an RFID sensor, but this feature should be incorporated in the new design only if the sensor does not add too much additional weight to the uniform and also is not too much expensive. Also, this should not result in advantage for the enemy for tracking the US army troops.
- The army has two ACU designs. The standard ACU is not fire resistant while the FR ACU used for combat deployment is fire resistant.
- The current ACU is not protected against the chemical-biological warfare agents neither it is anti-microbial, superhydrophobic or self-cleaning. All these properties are desirable and could be added to the new design if they are durable and do not affect the comfort characteristics of the uniform.
- The current ACU is durable for 25 industrial launderings but the desired goal is to make the ACU durable upto 50-100 launderings.

Concept Scoring Matrix

Research Objective: Compare the potential design and current ACU using a concept evaluation matrix

In the concept screening method, each criterion was given equal weight and the design concept was ranked. The concept scoring matrix prioritizes criteria according to the relative level of importance that each criterion plays for success of the final design. The concept scoring matrix uses a weighted sum for comparison of design concepts, thus providing more refined comparisons. The criteria with higher level of importance receive a higher weight percentage of the total score.

The concept scoring matrix is set up similar to the screening matrix, with the criteria listed on the left hand side. Under the “weight” column each criterion is given a value on the basis of its importance such that the total weight for all the criteria sums upto 100. The current ACU and the new design have been rated on a scale of 1-10 based on the potential of each to meet a particular criterion. The higher the score, the better the uniform meets the criterion. For production cost a lower rating implies the cost of production is higher and vice-e-versa. For manufacturability, a higher rating implies ease of manufacture. The “weighted score” is calculated by multiplying the rating by the criteria weight and dividing it by 10. The total score for each concept is the sum of the weighted scores. A uniform design with a higher total score implies that it is better than the other uniform design.

Table 6. Concept Scoring Matrix

Selection Criteria	Weight	Current ACU		New Design for ACU	
		Rating	Weighted Score	Rating	Weighted Score
Mobility	**15**				
Flexibility	7.50	7	5.25	8	6.00
Lightweight	7.50	5	3.75	6	4.50
Communications	**5**				
RFID, Bluetooth, GPS Technologies	5.00	0	0.00	7	3.50
Functionality	**35**				
Flame resistant	15.00	9	13.50	9	13.50
Protection against Chemical Biological Warfare Agents *i.e.* Self-cleaning, Self-detoxifying, Anti-microbial, Seam-sealing.	15.00	0	0.00	9	13.50
Stand-off Chemical/ Biological/ Nuclear Warfare Detection	5.00	0	0.00	6	3.00
Ergonomics	**15**				
Comfort/ Feel such as Breathability	15.00	6	9.00	6	9.00
Durability	**20**				
Mechanical Properties of Clothes	10.00	5	5.00	5	5.00
Durability against washing	10.00	6	6.00	7	7.00
Design	**5**				
Camouflage	5.00	6	3.00	6	6.00
Others	**5**				
Production Cost	2.50	3	0.75	6	1.50
Manufacturability	2.50	7	1.75	6	1.50
Total	**100.00**		48.00		74.00

The concept scoring matrix as shown in Table 6 was developed based on personal communication and surveys answered by researchers working at Natick Soldier RD&E Center, MA. It was determined that comfort, flame resistance, self-cleaning, anti-microbial and protection against chemical-biological warfare agents are the most important characteristics required for the ACU deployment uniform. So, these criteria were given a higher weight of 15. Mobility which included two features lightweight and flexibility was also recognized as an important feature for the ACU. Thus, mobility was given a combined rating of 15 with each flexibility and lightweight having weight 7.5. Durability and mechanical properties of the uniform should have the same performance after several wash cycles. So, the overall property of durability is given a weight of 20 with mechanical properties of fabric and durability against washing given a weight of 10 each.

The current ACU and the new design for the ACU were rated by personnel from Natick, MA as a part of survey that was done for this research in February 2009. It was observed from the survey results that the current ACU has superior flame resistance but it lacks the chemical-biological warfare protection, anti-microbial, self cleaning features. Thus, the new design for the ACU should incorporate all these additional features and functionalities and retain the same superior performance of flame resistance characteristic that the current ACU has. After comparison on basis of the concept screening matrix it can be seen that the new design has a total score of 74 compared to the total score of 48 for the current ACU. The new design aims at providing all these essential features to the ACU which will improve the uniform functionality and provide additional protection to the soldiers during combat.

Preparation of Superhydrophobic and Superoleophobic Surface

Research Objective: Propose a method for preparing superhydrophobic and superoleophobic surface and prepare a prototype sample showing superhydrophobic and superoleophobic characteristics.

From the concept scoring matrix it can be seen that the current ACU scores low because it lacks certain functional features such as anti-microbial, superhydrophobicity, protection against chemical-biological defense .

The following section shows the results of tests carried on current uniform for superhydrophobicity and superoleophobicity. Also, the results for tests carried on the NYCO and nonwoven fabric surfaces that have been treated for superhydrophobicity and superoleophobicity are discussed.

Testing the Current ACU for Superhydrophobicity and Superoleophobicity

To test the superhydrophobicity and superoleophobicity of a garment the water and organic solvent (dodecane) droplets contact angle with the fabric surface respectively were measured. For a fabric surface to be superoleophobic or superhydrophobic, both the dodecane and water contact droplet angles with the fabric surface should be above 150^{o}.

Table 7 gives the contact angle measurements after 20 wash cycles for the nylon cotton (50/50) blended fabric (NYCO) that is currently being used for manufacturing the ACU.

Table 7. Contact angle measurements for NYCO fabric that is currently used for the ACU

No. of wash cycles	No washing	5	10	15	20
Water Contact angle (^{o})	151	147	138	136	124
Dodecane contact angle (^{o})	84	Dodecane droplet absorbed completely by fabric			

For any fabric surface to be superhydrophobic, the contact angle of water droplet with that surface should be greater than 150^o. The current ACU is not treated for superhydrophobicity, but has a wrinkle resistant finish; this is the reason due to which the contact angle of water before washing is 151^o. Also, the contact angle for dodecane is 84^o before the first wash cycle. This shows that the current ACU does not have superoleophobic properties. One cycle of the accelerated AATCC wash test method 61 No. 2A is equivalent to 5 home laundering washes. The contact angle decreases after washing which shows that the fabric is losing the finish and also superhydrophobicity after the first wash cycle. The dodecane is completely absorbed by the fabric after the first wash cycle.

On measuring the contact angles after washing for the current ACU fabric with water and dodecane, it was deduced that the current ACU lacks both superhydrophobicity which leads to self-cleaning clothing and superoleophobicity which protects the soldiers against the chemical-biological warfare.

Testing Nonwoven Fabric Treated with Fluoroamine

On basis of research carried by Lee et al. (2005), the nonwoven fabric was treated with 1H,1H-perfluorooctylamine according to the method explained in experimental section. The water and organic solvent (dodecane) droplets contact angle with the fabric surface were measured. The results for the same are seen in Table 8 below.

Table 8. Contact angle measurements for nonwoven fabric treated with fluoroamine

Contact Angle (^{o})	
Water	**Dodecane**
158	140
156	142
156	138

From the contact angle measurements it can be seen that though the fabric surface has become superhydrophobic (the contact angle for water droplet is >150^{o}), and results similar to Lee et al. (2005) were obtained, but, the surface does not have superoleophobic properties (the contact angle for dodecane droplet is <150^{o}). So, we cannot use treatment with fluoroamine to make the surface both superhydrophobic and superoleophobic. Thus, a substitute method of treating the surface with 1H,1H,2H,2H-Perfluorodecyltrimethoxysilane was developed which imparted both superhydrophobic and superoleophobic properties to the fabric.

Testing the Treated Nonwoven Fabric for Superhydrophobicity and Superoleophobicity

The nonwoven fabric was treated with 1H,1H,2H,2H-Perfluorodecyltrimethoxysilane according to the method explained in the experimental section, and was tested for superhydrophobic and superoleophobic behavior. The water and organic solvent (dodecane) droplets contact angle with the fabric surface were measured for 25 wash cycles as well before washing. In Figure 19 we can see the images of the water and dodecane droplets on the nonwoven fabric treated with 1H,1H,2H,2H-Perfluorodecyltrimethoxysilane. Both the droplets sit almost spherically on the fabric surface. This shows that the fabric has low affinity for both water and dodecane. Table 9 gives the contact angle measurements for the treated nonwoven fabric upto 25 cycles of washing.

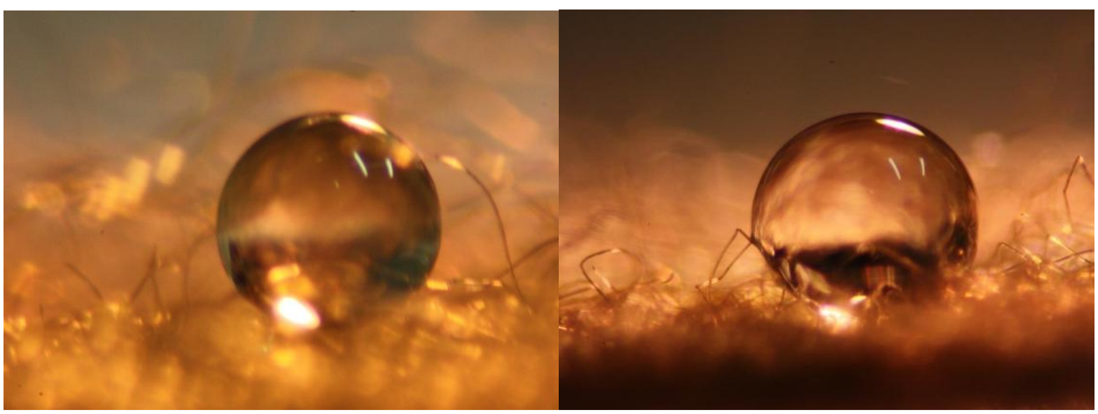


Figure 19. 2 µl water (left) and dodecane (right) droplet on 1H, 1H, 2H, 2H Perfluorodecyltrimethoxysilane -grafted-PAA-grafted-nylon nonwoven fabric

Table 9. Contact angle measurements for nonwoven fabric treated with 1H,1H,2H,2H-Perfluorodecyltrimethoxysilane

No. of wash cycles	No washing	5	10	15	20	25
Water Contact angle (^{o})	168	150	←	Not stable		→
Dodecane contact angle (^{o})	153	←		Not stable		→

Initially, both the water and dodecane contact angles were recorded to be above 150^o. This shows that the surface attained both, superhydrophobicity and superoleophobicity. But, after 5 cycles of washing though the water contact angle is 150^o, the dodecane was absorbed by the fabric surface at some positions and had a contact angle of over 100^o at some positions. For 10 and above wash cycles both water and dodecane were absorbed by the surface. So, though this method of treatment for making the surface superoleophobic and superhydrophobic was successful, there is a need to improve the durability of chemical finish for washing.

Testing the Treated NYCO Fabric for Superhydrophobicity and Superoleophobicity

The NYCO fabric that is being currently used for manufacture of ACUs was treated with 1H,1H,2H,2H-Perfluorodecyltrimethoxysilane according to the method explained in the experimental section, and tested for superhydrophobic and superoleophobic behavior. The water and organic solvent (dodecane) droplets contact angle with the fabric surface were measured for 25 wash cycles as well as before washing.

Table 10. Contact angle measurements for NYCO fabric treated with 1H,1H,2H,2H-Perfluorodecyltrimethoxysilane

No. of wash cycles	No washing	5	10	15	20	25
Water Contact angle (^{o})	155	148	137	134	115	115
Dodecane contact angle (^{o})	140	137	137	134	133	130

For the NYCO fabric treated for superhydrophobicity and superoleophobicity, it was observed that the water contact angle was 155^o and the dodecane contact angle was 140^o. After 25 wash cycles only slight decrease can be seen in the dodecane contact angle, while for water the contact angle after 25 wash cycles is 115^o. Thus it can be deduced that treatment with 1H,1H,2H,2H-Perfluorodecyltrimethoxysilane on the NYCO fabric is durable after 25 wash cycles.

The water and dodecane contact angle readings recorded during these experiments for both nonwoven and NYCO fabrics are much higher than the contact angle measurements recorded by Jiang et al. (2005) after treatment of cotton fabric with FPAQ. Also, the degree of superhydrophobicity and superoleophobicity is similar to that obtained by Willis (2008) using pulsed electrical discharges. The method proposed in this research is better than using pulsed electrical discharges or plasma treatment as it is cost effective. But, this method needs to be standardized to achieve even and more durable superhydrophobic and superoleophobic surface.

Prototype Sample Fabric Testing

The following tests were carried out on the nylon-6 nonwoven fabric that was used for making the prototype sample.

ASTM D3822

Standard Test Method for Tensile Properties of Single Textile Fibers

This test provides a method for measuring the breaking force and elongation at break of single textile fibers and thus, calculating the fiber breaking tenacity, fiber modulus and the breaking toughness. The testing was carried out at 70^{o}F and 65% relative humidity. The mean value of fiber modulus of the nylon-6 fiber used for making the prototype sample is 16.99 gf/denier and the mean value of fiber tenacity is 4.44 gf/denier. The fiber toughness of the nylon-6 fiber used is 2.19 gf/denier. The values for the nylon-6 fiber specimens used for making the prototype sample can be seen in Table 11.

Table 11. Results for ASTM D3822

Specimen #	Fiber Modulus gf/denier	Fiber Tenacity gf/denier	Fiber Toughness gf/denier
1	15.08	4.80	2.65
2	19.57	4.32	1.57
3	19.66	4.10	1.97
4	20.66	4.23	1.71
5	13.29	4.39	2.51
6	16.17	3.76	1.41
7	18.00	4.05	1.37
8	17.42	5.73	3.72
9	13.06	4.53	2.78
Mean	**16.99**	**4.44**	**2.19**
Std. Dev.	**2.78**	**0.57**	**0.79**

ASTM D1117

Standard Test method for determining Trapezoidal Tear strength for Textile Nonwoven Fabrics

Table 12. Results for ASTM D1117 in machine and cross direction

Specimen #	Peak Load Machine Direction Lbf	Peak Load Cross Direction lbf
1	28.68	42.89
2	33.00	43.84
3	33.33	48.20
4	32.19	38.63
5	26.85	41.44
Mean	**30.81**	**43.00**
Std. Dev.	**2.88**	**3.51**

This test gives the trapezoidal tear of the nonwoven fabric in the machine and crossed direction. The test was carried at a grip pressure of 80 psi and crosshead speed of 12 in/min with the jaw face size of 1” x 3” at lab conditions of 70^{o}F and 65% relative humidity.

The values of peak load for this test for both machine and cross direction can be referred from Table 12. The mean values for peak load for the nylon-6 fabric used for the prototype sample are 30.81 lbf in machine direction and 43.00 lbf in cross direction.

ASTM D5034

Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Test)

The grab test determines the effective strength of the fabric; considering the strength of the yarns in a specific width together with the fabric assistance from the adjacent yarns. The test was carried at a grip pressure of 80 psi and crosshead speed of 12 in/min with the jaw face size of 1” x 3” at lab conditions of 70^{o}F and 65% relative humidity.

The values of peak load for this test for both machine and cross direction can be referred in Table 13. The mean values for peak load for the nylon-6 fabric used for the prototype sample are 29.51 lbf in machine direction and 41.67 lbf in cross direction.

Table 13. Results for ASTM D5034 in machine and cross direction

Specimen #	Peak Load Machine Direction lbf	Peak Load Cross Direction lbf
1	27.19	40.55
2	30.65	41.09
3	27.60	46.36
4	31.40	42.91
5	30.70	37.44
Mean	**29.51**	**41.67**
Std. Dev.	**1.96**	**3.28**

Comparison of Nonwoven Fabric vs. the ACU Physical Requirements

The tearing strength and breaking strength requirements for the ACU from Table 2 with the results obtained in Tables 12 and 13 for the nonwoven fabric used for preparation of prototype sample can be compared. The minimum tearing strength required for the ACU is 4.0 pounds in both the warp and filling direction. From Table 12 we can see that the tear strength in machine direction is 30.81 Lbf and that in the cross direction is 43.00 Lbf. So, the tearing strength for the nonwoven fabric higher is than the tearing strength requirement for the ACU.

The minimum requirement for breaking strength for the ACU is 100 pounds in warp direction and 80 pounds in filling direction. From Table 13 we can see that breaking strength is machine direction is 29.51 Lbf and that in the cross direction is 41.67 Lbf. These values are less than the minimum requirement for the ACU. But, the nonwoven fabric used for the prototype sample that has been tested is a single pass hydroentangled fabric. In common practice a double pass hydroentangled fabric is used for making garment purposes. So, a double pass nonwoven fabric will have better breaking strength than the nonwoven fabric tested during this research. A double pass hydroentangled fabric will meet or even surpass the minimum requirements for the breaking strength for the ACU.

Also, Szczesuil and Narayanan (2008) have discussed how hydroentangled nonwoven fabrics can be fabricated to be lighter in weight and thinner than the current woven fabric used and exhibit higher breaking, tearing and elongation characteristics as well as have improved air permeability. So, it can be concluded that nonwovens could provide equivalent or even better physical properties to the ACU than a woven fabric.

Computer Aided Manufacturing (CAM)

Research Objective: Suggest a model for mass customization of the ACUs

The process of mass customization based on 2D intelligent design starts from the customer's requirements. Figure 20 represents a roadmap of intelligent design and manufacturing system helping mass customization of military uniforms. First, the soldier provides personality requirements such as the style requirements (various uniform styles are required depending on the soldier posts and work) and body size to the intelligent design module. Second, the soldier gets the 2D style that has been designed and then, the soldier gives an evaluation about the style. If the soldier is satisfied with the style, the style will be accepted and he continues with the third step. If not satisfied with the style, the soldier can put it away or adjust it again. Third, the accepted style will be sent to the specialist pattern design module and the pattern will be generated automatically. Finally, the customized uniform is ready to be manufactured. After planning CAM, the fabric needs to be cut and assembled. For many military uniforms, ultrasonic seaming is preferred to prevent intrusion of chemical biological (CB) warfare agents.

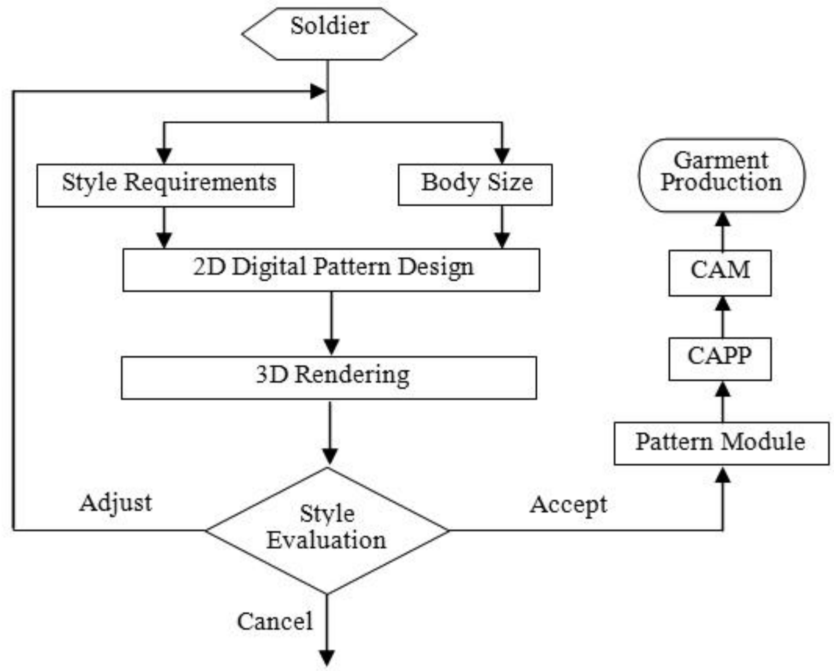


Figure 20. Process of mass customization based on intelligent design and manufacturing.

Ultrasonic Sewing

Research Objective: Study of novel sewing techniques for manufacture of ACUs

Ultrasonic bonding uses high frequency vibrations which create a rapid buildup of heat forms a finished seam or sealed edge without melting or affecting the base materials. Materials that are 100% synthetic or blends up to 40% natural fibers are suited for ultrasonic and are easily bonded using ultrasonic bonding (Sonobond Ultrasonics, 2009). Ultrasonic bonding technology can be used as a tool of garment construction. If traditional sewing machines are used to produce garments with nonwoven fabrics having fine filament webs, the needle of the sewing machines may lead to entanglement of the fibers in the nonwoven fabric during its up-down sewing motion. More importantly, conventional sewing leaves holes where chemical or biological agents can penetrate. If an automatic cutting machine connected to CAD pattern software has ultrasonic bonding unit beside the blade, the garment can be cut and assembled without sewing steps.

The most labor intensive steps during product formation are cutting and sewing (Isaccs, 2005). It can be seen from Table 3 in Chapter 2 that the compensation costs in the apparel manufacturing industry are on an increase too. So, it is important to cut down the labor requirements during garment manufacturing. The multi-functional equipment (ultrasonic cutting and bonding machine) is expected to require fewer workers since it is completely automated. The advanced technology proposed in this research would make the complete process of nonwoven garment manufacturing cost-effective. At this point, the final garment is ready to be packaged and shipped. To get here, the soldier has input his design criteria; a pattern has been created by CAD; and the soldier has approved the design which then moves through CAM to the final product. In the CAM process, nonwoven fabric has been automatically cut and ultrasonically seamed for a customized fit and mission specific criteria.

Preparation of Prototype Sample

A 2D pattern of the ACU jacket was prepared using Gerber Acumark® Software. The final pattern design can be seen in following figures.

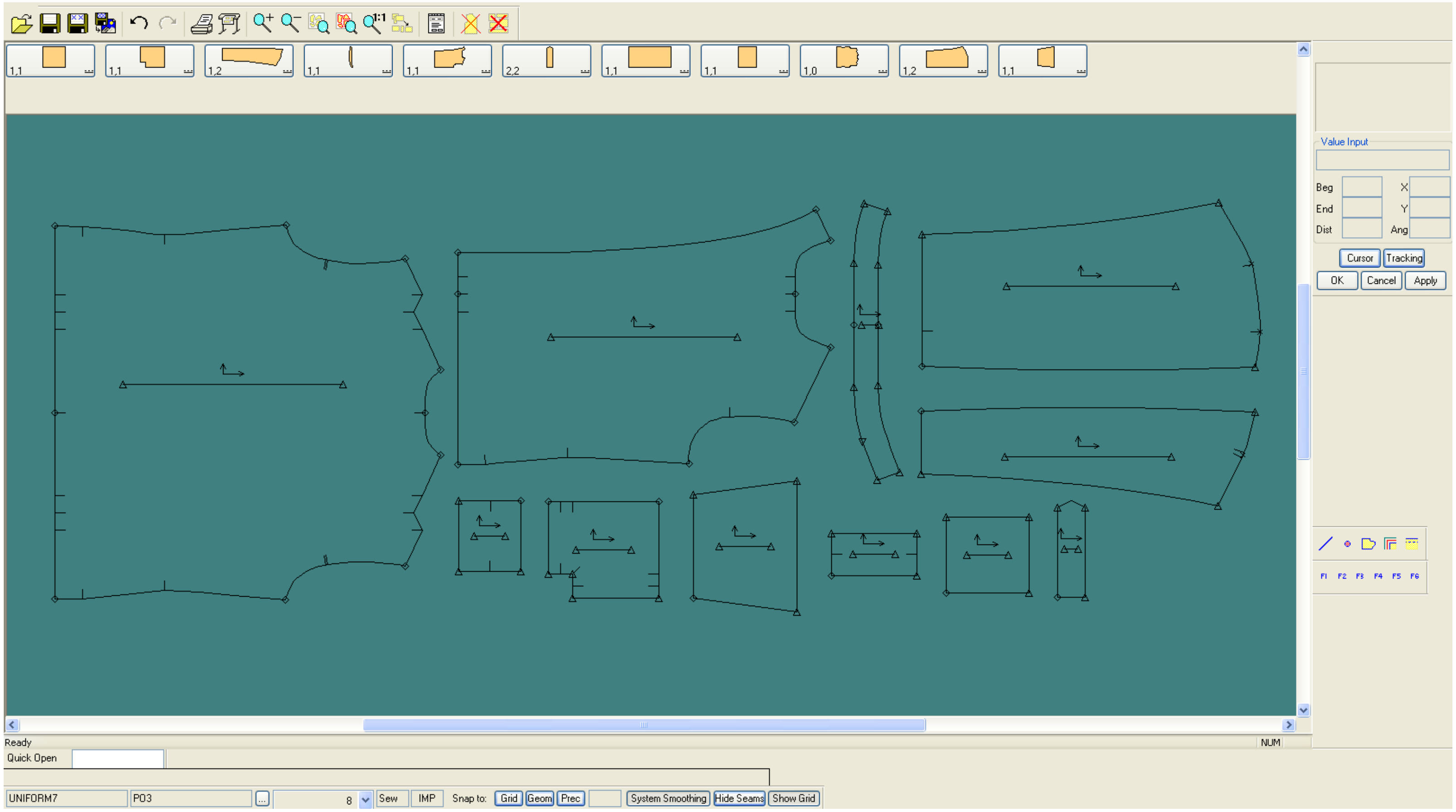


Figure 21. Pattern layout for ACU jacket using Gerber Acumark® software

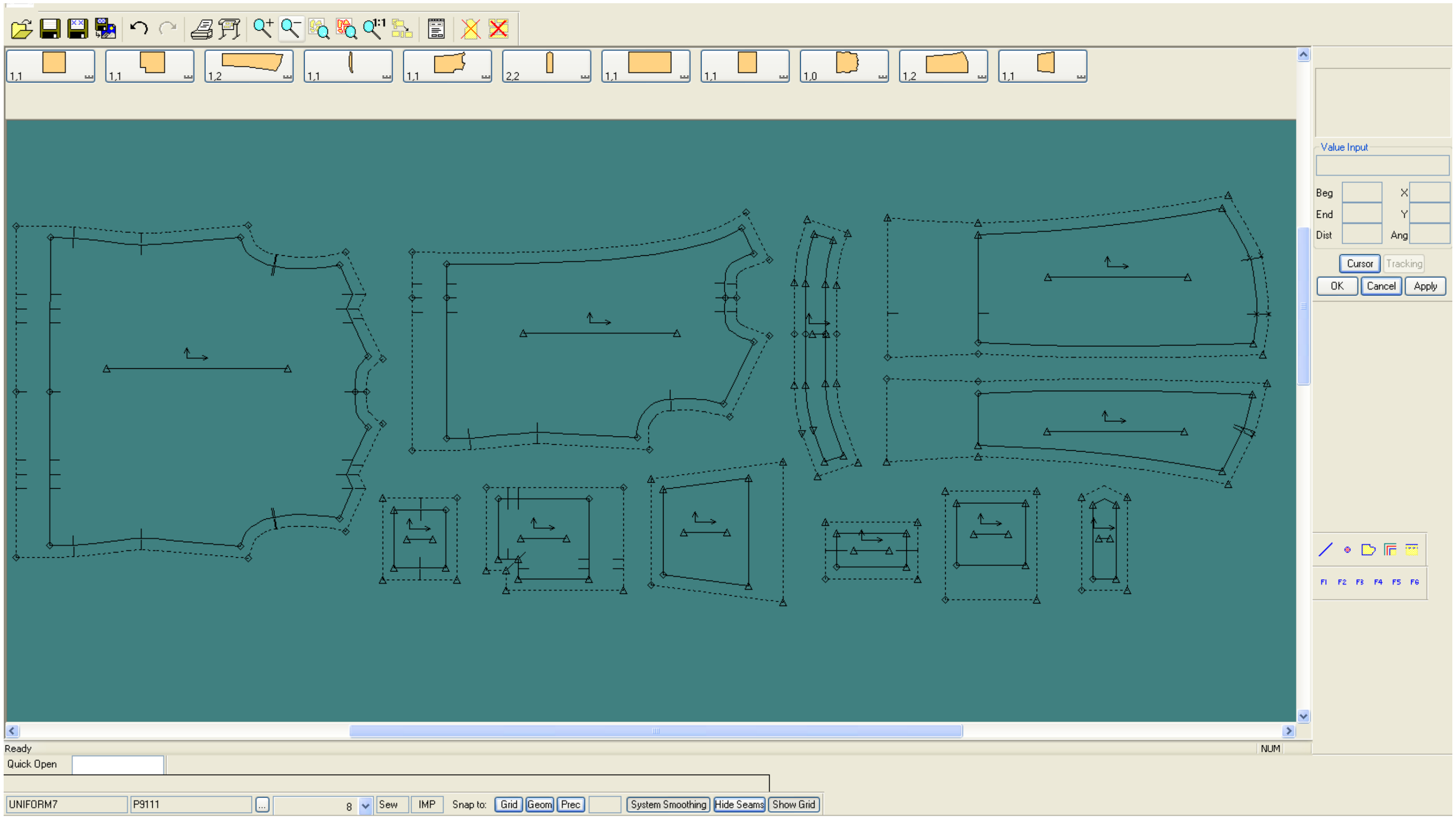


Figure 22. Pattern Layout with seam allowance for ultrasonic sewing

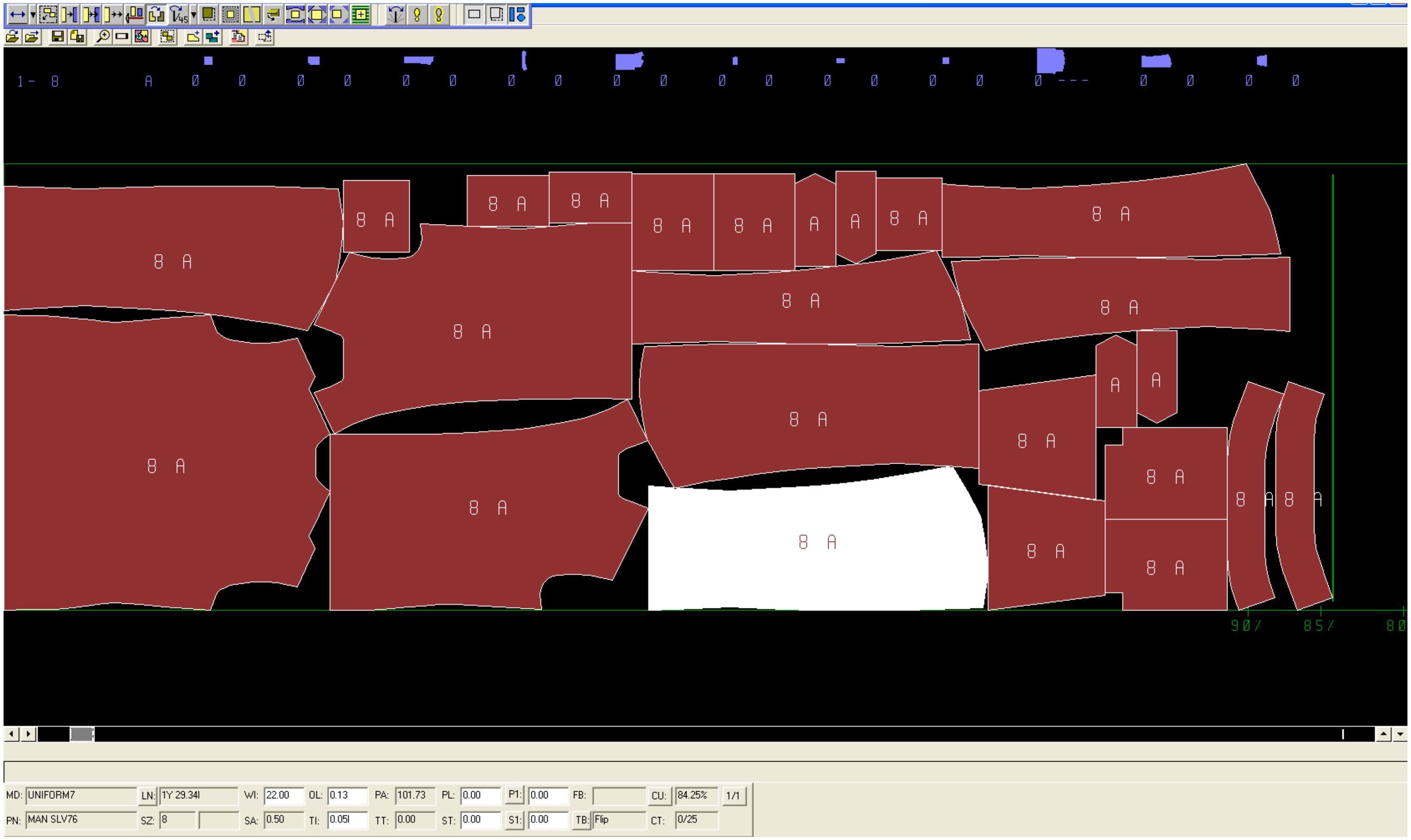


Figure 23. Pattern layout for cutting machine

After the patterns for the ACU jacket were ready, the nylon-6 nonwoven fabric was treated with different chemicals for making the fabric anti-microbial, superhydrophobic and superoleophobic according to the procedures explained in section “preparation of prototype sample” in Chapter 3. After the fabric treatment is completed the garment patterns are cut using an automated sewing machine. The garment was then sewn using the Sonobond ultrasonic sewing machine. One of the sleeves of the prototype sample that was treated with chemicals for the anti-microbial and superhydrophobicity and superoleophobicity, also has an inner layer of carbon black fabric for additional protection against the chemical-biological warfare agents.

Pictures of the final garment can be seen below:

Figure 24. Pictures of prototype sample

House of Quality Matrix (HQM)

Research Objective: Use the above results to develop a House of Quality Matrix as a future guide for selection of technologies to be incorporated in the ACUs.

The HQM is a convenient diagram to help link engineering variables to the detailed customer needs. In the center of the house, a "relationship matrix" indicates how each engineering characteristic affects each customer need. The HQM represents engineering tradeoffs with a "roof" matrix that links each engineering characteristic with every other engineering characteristic. The roof matrix helps to balance engineering changes to ensure that important customer benefits are not adversely affected.

Figure 25 shows the basic framework of the House of Quality Matrix that was used to develop the HQM for this study.

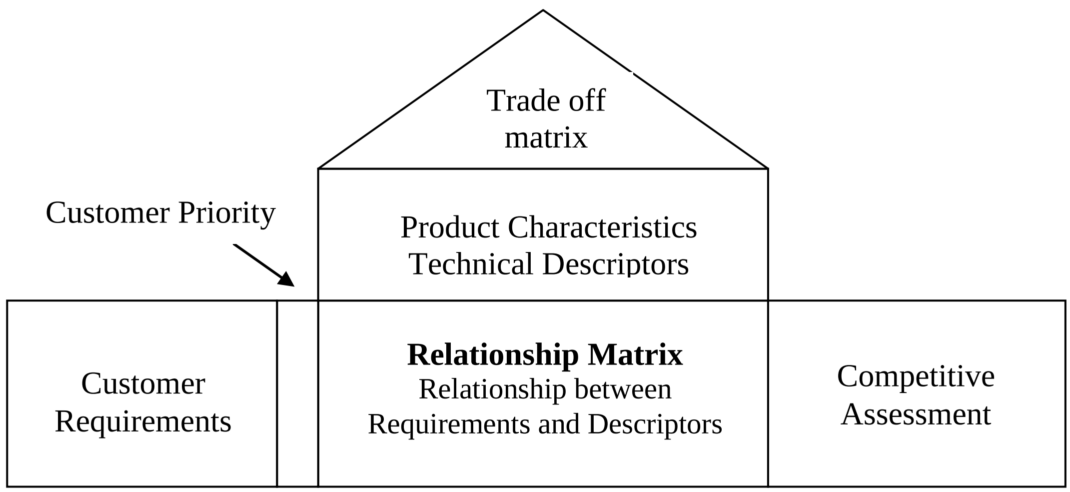
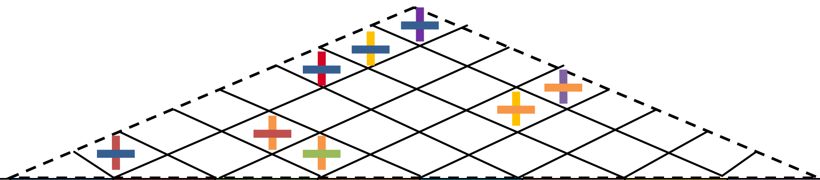


Figure 25. Basic framework for the House of Quality Matrix

Source: "QFD Matrix" Kumar, D., Crocker, J., Chitra, T., Saranga, H. (2006), *Reliability and Six Sigma*, Springer.



Technical Descriptors → / Customer Requirements ↓	Meets government and non-government standards	Flame resistant finish	Treatment for making the surface oleophobic	Fabric selection	Sensor and RFID technology	Mass customization	Sewing technology	Physical properties of fabric	Customer importance
Comfortable	■		●	▲		▲	■		**4**
Protective against chemical and biological warfare agents			▲	▲				●	**4**
Flame resistant	■	▲		▲				●	**5**
Flexible	■	●	●	▲		●	■	●	**3**
Light weight	●	●	●	▲	●				**3**
Durable	▲	▲	▲	▲	▲				**5**
Protective against physical attack				▲			■	▲	**2**
Provides better communication and tracking					▲				**1**
Cost		●	●	●	▲	■	▲		**4**

Figure 26. House of Quality Matrix for the ACU design process

The HQM shown in Figure 26 was developed specific to the Army Combat Uniforms. The relationship between the customer requirements and technical descriptors is explained with help of three symbols: ● for weak relationship, ■ for medium relationship and ▲ for strong relationship.

The HQM can be considered as an extension of the research carried out by Augustyn et al. (2008). Instead of focusing only on the elements affecting the soldier's performance due to the use of chemical-biological defense equipment, the HQM explains the relationship between different factors associated with the complete ACU design process.

The customer importance column on extreme right gives the importance of different functions and features of the ACU according to the soldiers' requirements. The grading numbers from 1 through 5 were used to indicate rating of 1 for least important and 5 for very important. These were decided using the concept scoring matrix as basis. The competitive assessment (extreme right column in Figure 25) is not included in Figure 26 as the competitive assessment between the current ACU and new design is already done with the help of concept scoring matrix (Table 6).

From Figure 26 it can be deduced that most of the customer requirements have a strong relationship with "fabric selection". Thus, selecting the right fabric would be first step for proposing an ideal combat uniform. Also, it can be seen that the durability of the uniform is greatly affected with the types of finishes or additional features. Cost is also a factor that is weakly associated with the features added to the ACU.

The roof of the HQM, gives the interrelationship between the technical descriptors. Figure 26 depicts that the type of finishes applied (either for flame resistant or for superhydrophobicity) are interrelated with the fabric. The fabric type also has a correlation with the sewing technology that can be used and the physical properties of the fabric.

The HQM proposed in Figure 26 is aims at providing a systematic approach for future design development for the ACUs. The future soldier requirements are complex and are dependent on military textiles and creation of soldier clothing. The HQM provides a method for management of the complexity, inter-relationships or dependencies present within the elements associated with the design process of the ACU. The design process of the ACU is of critical importance because it involves clothing systems that require meeting high-level of performance under many major threats and also provide comfort and flexibility to the soldiers simultaneously. The future military uniforms need to lightweight, flexible and perform different functions and be versatile. With the advent of new materials and technologies for manufacture of the ACUs, new characteristics and features can be added to the ACUs to improve comfort, functionality and protection. The HQM will thus provide a basic framework showing the intricacies and dependencies of the different elements involved in the ACU development. The HQM proposed in Figure 26 suggests that for developing a high-performance ACU which would be an ideal combat uniform both materials and technology considerations are important alongside with the features such as comfort and flexibility to enhance soldier performance during combat.

Chapter 5

Summary, Conclusions, Recommendations

Summary

Textiles have been used for military purposes since long time, but there are many exciting areas in this field that continue to develop and improve. With the ever changing defense domain and technological advances of the warfare weapons, it has become an imperative to incorporate latest advances from the field of textiles in army uniforms to protect the soldier from both predictable and unpredictable sources of life threats. These changes are intended to make the uniform more effective and functional, lighter in weight or less costly. The purpose of this research was to study the process of new product design for military uniforms and then narrow down the focus to identify opportunities for technological innovations that could be incorporated in the Army Combat Uniforms (ACU) to improve their functionality and manufacturing and thus specifically examine and identify the opportunity and design phases for the ACU.

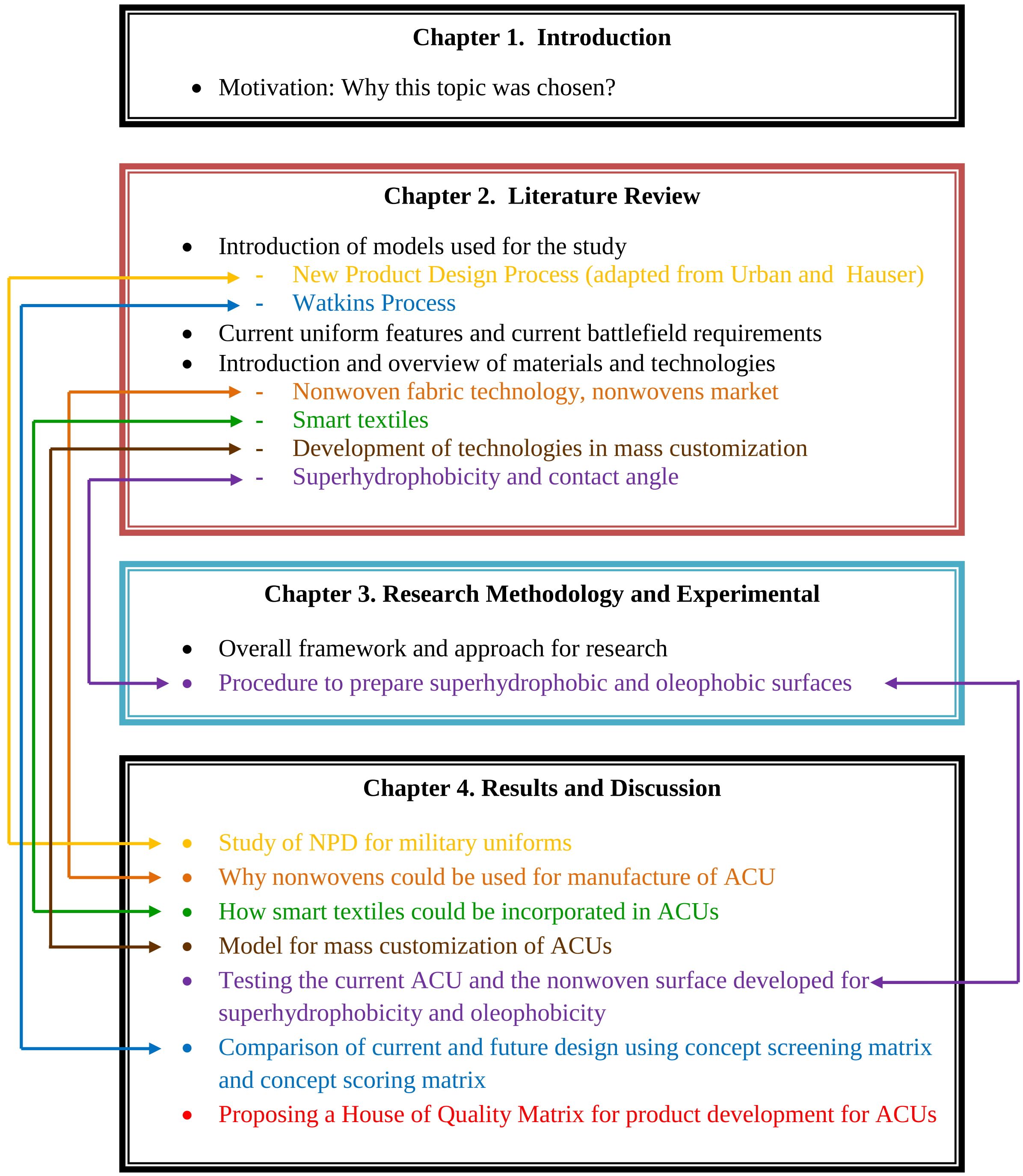


Figure 27. Summary

Figure 27 gives a brief overview of the overall research and shows the thought process that led to the final result of developing a House of Quality Matrix for product development of the ACUs. The figure also shows how the literature reviewed in Chapter 2 ties up with the final results and forms a basis for the same.

As phase I of this research, the new product design process (adapted from Urban and Hauser) was studied for military uniforms. Phase II of the research used the Watkins design process as the basic framework to study the opportunity identification step for design (functionality) changes that could be added to the ACU. During this phase requirements for the ACU according to the current battlefield conditions and the features of the current ACU were thoroughly studied. The new materials and technologies that could be incorporated in the ACU were proposed and explained. Experiments were performed to develop a superhydrophobic and superoleophobic surface that can protect the soldiers from chemical-biological warfare agents. The House of Quality Matrix was developed for future product development for the ACUs.

Conclusions

This study proposes the use of nonwovens as the fabric for manufacturing the ACUs. Also, mass customization and ultrasonic sewing technologies have been suggested as manufacturing technologies for the ACU. Application of smart textiles to the future ACU was also studied as a part of this research and a method to produce superhydrophobic and superoleophobic surface was recommended.

The current ACUs are made of NYCO fabric which is a 50% nylon- 50% cotton woven fabric. The current uniform has good mechanical properties and flame resistance. It also provides comfort and flexibility to the soldiers during different combat operations. During this research it was found that as the soldiers face new threats, the current uniform needs additional functional characteristics. These were protection against chemical-biological warfare agents, anti-microbial properties and incorporation of smart textiles that will facilitate physiological monitoring of the soldier during combat and also help tracking the soldier.

This research used the New Product Design model (adapted from Urban and Hauser) for studying the NPD process for military uniforms. The introduction and product life-cycle stages of the NPD model used cannot be effectively applied to the NPD process for military uniforms. But, this model serves as a basic platform for ideating various possibilities in the opportunity identification stage that could lead to new design of the ACUs. The Watkins Process was used during this research for exploring the opportunities for adding functional characteristics to the ACU. It is an effective process for identifying, analyzing and implementing new materials and technologies for developing the high performance ACU.

In this research nonwoven fabric was proposed for manufacture of the ACU, since the nonwoven fabric technology is simple and less time consuming than the woven fabric manufacturing. Also, the selection of appropriate nonwoven fabric would provide mechanical properties equivalent or better than the current NYCO fabric. A method to make the garment superhydrophobic and superoleophobic is suggested which would lead to protection against chemical and biological (chem.-bio) warfare agents. The contact angle measurement for samples prepared showed that this method is an effective means of imparting both superhydrophobicity and superoleophobicity to the surface. This research also recommends the use of ultrasonic sewing technique for manufacture of the ACU which would lead to better chemical-biological defense. The intelligent design model based on mass customization developed, aims at providing uniforms with better fit and comfort and also targets at reducing the uniforms cost by adapting automated processes that would require less labor-force.

The concept evaluation matrices provide the level of importance of different criteria for the army and also give a brief overview of the features absent in the current ACU. The new design proposed for the ACU and the current ACU are compared using the concept scoring matrix. The House of Quality Matrix serves as a model showing the complexity involved in the design process of the ACUs. It shows the interdependencies of different elements that are part of this design process.

This research recommends different materials and technologies that can be incorporated in the manufacture of the future ACU making it more functional and cost effective. Use of nonwovens, mass customization and ultrasonic sewing technology for manufacture of the ACU are the suggested materials and technologies that would enhance the production process of the ACU. The procedure recommended to produce a superhydrophobic and superoleophobic fabric surface is effective and durable for both nonwovens and NYCO fabric. All these technologies aim at protecting the soldiers against the modern warfighting threats and enhance their performance during combat.

Recommendations

The new product design process maps the path from reviewing the current state of research in the field of military uniforms to overcome the shortcomings of the current products, thus, approaching the set target of new uniform design. Soldiers rely on their clothing for protection as well as life support. As the saying goes, “Necessity is the mother of invention”, the soldiers’ require new functional characteristics in their uniforms to surmount the climatic conditions during their combat. New uniform designs need to be introduced for the same. Thus, incorporating anti-microbial, superoleophobic and superhydrophobic properties and retaining the flame retardancy in the ACU would be a positive change in the design leading to better protection of the soldiers against the chemical-biological warfare agents. Blended nonwoven fabric with better mechanical properties than the NYCO fabric that is being currently used can be used for manufacturing the future ACU.

The House of Quality Matrix developed as the final component of this research integrates the requirements of the ACU and the complexity of incorporating these functions in the ACU. This matrix in recommended as a guide that would help for any new product design or development process related to the ACU.

This research provides documentation regarding different features that could be added to the future ACU to make it an ideal combat uniform. Also, the procedure to develop an superoleophobic surface which helps soldiers protect against the chemical-biological warfare agents has been documented.

Future Work

The final prototype sample prepared from the nonwoven fabric had an added functionality of protection against the chemical-biological warfare agents. Due to time constraints only one additional feature could be added to the Army Combat Uniform (ACU). So, we suggest the some avenues for future research.

Selective tests were carried out for testing the nonwoven fabric used for making the prototype sample. In future, the nonwoven fabric could be examined for all properties required according to the US Army Standards. In addition to these lab tests, the nonwoven fabric garment, incorporated with all additional functionalities, should be tested using wear tests to assure the same performance results at the garment level, and for evaluation of comfort and fit of the garment. The procedure for preparing superoleophobic surfaces was standardized at the lab-scale. This method could be optimized for industry purposes with further research. Table 14 gives an overview of the path forward that could be an extension of this research.

Table 14. Path forward

Research Area	Path forward
Smart Textiles	A prototype sample that incorporates smart sensors and bio-feedback system in an ACU should be prepared
Mass customization model	The CAD model proposed should be developed and applied to the process of ACU manufacturing
Fabric selection	The nonwoven fabric selected for ACU manufacturing should have equal or better physical properties than the NYCO fabric that is currently used
Flame Resistance	The prototype sample prepared in this research used a 100% nylon nonwoven. For better flame resistance a nylon nonwoven blended fabric having flame retardant properties should be used.
Chemical-biological warfare	The method proposed for preparation of oleophobic surfaces was tried on lab-scale. This method should be standardized for better durability and commercialized.

With the current economic recession there is an environment of uncertainty in the U.S apparel industry. But, the stimulus package passed recently has a special amendment that will help the apparel industry to prosper. This Kissell amendment also has a rule specific to military uniforms and related to their domestic production. Since, this research proposed the idea of use of nonwovens and mass customization for manufacture of the ACUs to increase the domestic production of the ACU and also to decrease the production costs inspite of domestic production, the following section gives a brief overview of the Kissell Amendment in the stimulus package and how the proposed research favors this rule.

Stimulus Package

On February 13, 2009 Congress passed the $787 billion stimulus package. This package includes a “buy American” law that was sponsored by North Carolina Rep. Larry Kissell. This law was designed to help create and preserve thousands of jobs in the textile industry (NC congressman's 'buy American' provision enacted, 2009). According to Auggie Tantillo, executive director of the American Manufacturing Trade Action Coalition, every $100 million spent annually under the Kissell Amendment, will create or preserve 5,000 jobs in the textile industry. A recent study cited that 33% more manufacturing jobs will be created with exclusively domestic production. The “buy American” law also expands a rule that military uniforms be made and assembled in the United States. The Kissell amendment also includes textiles worn and used by the Transportation Security Administration (TSA) officers. The rule also applies to not just clothing but all textile products such as body armor, holsters and conveyor belts (Morrissey, 2009).

The use of nonwoven fabrics for manufacture of the ACU will lead to increase in the domestic production of the military uniforms as nonwovens production in the U.S. is on an increase. Also, the mass customization model could be effectively applied to the manufacturing process of the ACU as the military uniforms need to be assembled in the U.S. under the Kissell amendment. So, the materials and production technologies proposed in this research could be commercialized for effective application of the Kissell rule.

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APPENDICES

APPENDIX A: SURVEY INSTRUMENTS

APPENDIX A1: SURVEY INSTRUMENT-1

Introduction

The aim of this survey is to get information about the current Army Combat Uniform (ACU). The features and functionality of the current ACU form an important basis of our research**.** We would like to know the features present in the current ACU and the features that need to be added in the High Performance Army Combat Uniform (HPACU) to improve its performance. Also, the level of importance that army gives to each of these features while designing an ACU needs to be established for adding functional properties to the new uniform.

In the first part of this survey you need to answer a few questions which would help us determine the features present in the current ACU and also the features that need to be added to the HACU to make it an ideal combat uniform.

In the second part of this survey, we would like to know the weights or rating for each of these features according to their level of importance. Please give a rating on scale of 10 for each feature and then rate the current ACU on a scale of 10 explaining the extent to which the current ACU satisfies that functional need.

Part 1: Concept Screening Matrix

Do you think the current uniform has adequate flexibility for easy soldier movements?

>>

Do you think the ACU should be lighter in weight?

>>

Does the current uniform have RFID sensor technology for soldier identification and tracking? If no, do you think the HPACU should have this technology?

>>

Is the current ACU flame resistant? If no, do you think the HPACU should have this technology?

>>

Is the current ACU protective against the chemical- biological warfare agents? If no, do you think the HPACU should have this technology?

>>

Is the current ACU super- hydrophobic (i.e. self cleaning or water repellant)? If no, do you think the HPACU should have this technology?

>>

Does the current ACU have anti-microbial properties? If no, do you think the HPACU should have this technology?

>>

Does the current ACU have chemical-biological or nuclear warfare detection sensors? If no, do you think the HPACU should have this technology?

>>

Is the current ACU breathable and comfortable?

>>

The current ACU is durable for how many wash cycles? The HPACU should be durable for how many washes?

>>

After how many month(s)/year(s) do the soldiers' have to buy a new uniform for themselves?

>>

Does the current uniform has the property "stealth" i.e. make the uniforms harder to be detected by all means than conventional uniforms by employing a combination of features to reduce visibility in the visual, audio, infrared, and radio frequency spectrum? If no, do you think the HPACU should have this technology?

>>

Concept Scoring Matrix

- Please fill in the value on a scale of 10 for assigning a level of importance to the selection criteria.
- In the rating column please rate in the current ACU on a scale of 10 for these selection criteria.

Selection Criteria	Weight	Current ACU Rating
Mobility		
Flexibility	?	?
Lightweight	?	?
Communications		
RFID, Bluetooth, GPS Technologies	?	?
Functionality		
Flame resistant	?	?
Protection against Chemical Biological Warfare Agents *i.e.* Self-cleaning, Self-detoxifying, Anti-viral, Anti-bacterial Effects, Seam-sealing, etc.	?	?
Protection against Physical Attack	?	?
Stand-off Chemical/ Biological/ Nuclear Warfare Detection	?	?
Ergonomics		
Comfort/ Feel such as Breathability	?	?
Durability		
Mechanical Properties of Clothes	?	?
Durability against washing		
Design		
Camouflage	?	?
Stealth	?	?
Others		
Production Cost	?	?
Manufacturability	?	?
Total	**100**	

APPENDIX A2: SURVEY INSTRUMENT-2

Concept Screening Matrix

- In the table below please select **Y** implying **"Yes"** or **N** implying **"No"** for the feature in the current Army Combat Uniform (ACU). In the suggested design column select **Y** or **N** for features you would want to be present in the suggested design for ACU.

Selecting Criteria	Current ACU	Suggested Design
Mobility		
Flexibility	Y/N	Y/N
Lightweight	Y/N	Y/N
Communications		
RFID, Bluetooth, GPS Technologies	Y/N	Y/N
Functionality		
Flame resistant	Y/N	Y/N
Protection against Chemical Biological Warfare Agents ***i.e.*** **Self-cleaning, Self-detoxifying, Anti-viral, Anti-bacterial Effects, Seam-sealing, etc.**	Y/N	Y/N
Protection against Physical Attack	Y/N	Y/N
Stand-off Chemical/ Biological/ Nuclear Warfare Detection	Y/N	Y/N
Ergonomics		
Comfort/ Feel such as Breathability	Y/N	Y/N
Durability		
Mechanical Properties of Clothes	Y/N	Y/N
Design		
Camouflage (invisibility during the day)	Y/N	Y/N
Stealth (invisibility at night)	Y/N	Y/N

Concept Scoring Matrix

- Please fill in the numbers assigning an importance value in the “Weight” column.
- After giving the weights, please give ratings on each criteria.

Selection Criteria	Weight	Current ACU	Future ACU
		Rating	Rating
Mobility			
Flexibility	?	?	?
Lightweight	?	?	?
Communications			
RFID, Bluetooth, GPS Technologies	?	?	?
Functionality			
Flame resistant	?	?	?
Protection against Chemical Biological Warfare Agents *i.e.* Self-cleaning, Self-detoxifying, Anti-viral, Anti-bacterial Effects, Seam-sealing, etc.	?	?	?
Protection against Physical Attack	?	?	?
Stand-off Chemical/ Biological/ Nuclear Warfare Detection	?	?	?
Ergonomics			
Comfort/ Feel such as Breathability	?	?	?
Durability			
Mechanical Properties of Clothes	?	?	?
Design			
Camouflage (invisibility during the day)	?	?	?
Stealth (invisibility at night)	?	?	?
Others			
Production Cost	?	?	?
Manufacturability	?	?	?
Total Score	100		

APPENDIX B: SURVEY RESULTS

APPENDIX B1: SURVEY RESULT-1

Part 1: Concept Screening Matrix

Do you think the current uniform has adequate flexibility for easy soldier movements?

>>yes

Do you think the ACU should be lighter in weight?

>>yes

Does the current uniform have RFID sensor technology for soldier identification and tracking? If no, do you think the HPACU should have this technology?

>>no/no. Put the technology be on load carriage equipment or ballistic vest. Do not need it on every uniform. Too expensive for each uniform

Is the current ACU flame resistant? If no, do you think the HPACU should have this technology?

>> The Army has 2 ACUs. The standard ACU is a 50/50 nylon/cotton ripstop; Fire resistant ACU (FR ACU) is Defender M fabric

ACU No

FR ACU yes

Is the current ACU protective against the chemical- biological warfare agents? If no, do you think the HPACU should have this technology?

>>No/yes

Is the current ACU super- hydrophobic (i.e. self cleaning or water repellant)? If no, do you think the HPACU should have this technology?

>>no/yes, however Soldier will complain if perspiration does not wick away from body. Or is trapped inside ACU.

Does the current ACU have anti-microbial properties? If no, do you think the HPACU should have this technology?

>>No/no

Does the current ACU have chemical-biological or nuclear warfare detection sensors? If no, do you think the HPACU should have this technology?

>>no/no. put sensors on ballistic vest or load carriage equipment. Don't belive we need the expense of sensors on each uniform

Is the current ACU breathable and comfortable?

>>yes/yes

The current ACU is durable for how many wash cycles? The HPACU should be durable for how many washes?

>>25/50

After how many month(s)/year(s) do the soldiers' have to buy a new uniform for themselves?

>>6 mos

Does the current uniform has the property "stealth" i.e. make the uniforms harder to be detected by all means than conventional uniforms by employing a combination of features to reduce visibility in the visual, audio, infrared, and radio frequency spectrum? If no, do you think the HPACU should have this technology?

>>yes for visual audio (if you mean quiet), yes for IR, and no for radio frequency. Don't need radio frequency.

Part 2: Concept Scoring Matrix

Selection Criteria	Weight	Current ACU
		Rating
Mobility		
Flexibility	10	10
Lightweight	10	8
Communications		
RFID, Bluetooth, GPS Technologies	1	1
Functionality		
Flame resistant	10	10 (FR ACU) 3 (ACU)
Protection against Chemical Biological Warfare Agents *i.e.* Self-cleaning, Self-detoxifying, Anti-viral, Anti-bacterial Effects, Seam-sealing, etc.	8	1
Protection against Physical Attack	8	2
Stand-off Chemical/ Biological/ Nuclear Warfare Detection	1	1
Ergonomics		
Comfort/ Feel such as Breathability	8	4
Durability		
Mechanical Properties of Clothes	10	5
Durability against washing	10	5
Design		
Camouflage	10	5
Stealth	10	5
Others		
Production Cost	10	4 (FR ACU) 9(ACU)
Manufacturability	10	10

APPENDIX B2: SURVEY RESULT-2

Part 1: Concept Screening Matrix

Do you think the current uniform has adequate flexibility for easy soldier movements?

>>Yes, however, added flexibility can be achieved by inserting compressible materials to critical areas such as shoulders, elbows, knees and seat.

Do you think the ACU should be lighter in weight?

>>Current weight is ideal for a multi environment combat field. However, if at lower weigh we can achieve equal environmental protection then this would be desirable.

Does the current uniform have RFID sensor technology for soldier identification and tracking? If no, do you think the HPACU should have this technology?

>>No. But at low weigh low cost it would be desirable. However, please be certain that this and other capabilities will not result in an advantage to the enemy.

Is the current ACU flame resistant? If no, do you think the HPACU should have this technology?

>>We have two versions the ACU and the FR ACU for combat deployment.

Is the current ACU protective against the chemical- biological warfare agents? If no, do you think the HPACU should have this technology?

>>It isn't. The threat from Chem-Bio agents requires a whole system approach, if you can insert at some level some chem.-bio protection it would be a positive thing. But think about comfort…

Is the current ACU super- hydrophobic (i.e. self cleaning or water repellant)? If no, do you think the HPACU should have this technology?

>>It isn't. If you can achieve self cleaning and DWR it would be great, but again, make sure these capabilities don't have an adverse effect on comfort or otherwise no one will accept the HPACU.

>>it is not, we have environmental clothing for weather

Does the current ACU have anti-microbial properties? If no, do you think the HPACU should have this technology?

>>It doesn't. anti-microbial protection must be defined. Are you trying to address smell, skin sensitivity, etc??? all things being equal a level of durable anti-microbial would be welcomed.

Does the current ACU have chemical-biological or nuclear warfare detection sensors? If no, do you think the HPACU should have this technology?

>>No. However, sensor technology is a desirable objective, as long as it doesn't add weight or reduces comfort …

Is the current ACU breathable and comfortable?

>>Current ACU is not very breathable. However it is comfortable under a temperate/cold terrain…somewhere between 35F to 80F.

The current ACU is durable for how many wash cycles? The HPACU should be durable for how many washes?

>> Threshold 25 industrial launderings – Objective 50- 100 launderings

After how many month(s)/year(s) do the soldiers' have to buy a new uniform for themselves?

>>In the field 140-180 days, In Garrison 6 months to a year

Does the current uniform has the property “stealth” i.e. make the uniforms harder to be detected by all means than conventional uniforms by employing a combination of features to reduce visibility in the visual, audio, infrared, and radio frequency spectrum? If no, do you think the HPACU should have this technology?

>>Current camouflage specifications address visual, and NIR wavelengths. Any tangible improvements towards better counter-surveillance protection are welcomed.

Part 2: Concept Scoring Matrix

Selection Criteria	Weight	Current ACU
		Rating
Mobility	8	7
Flexibility	7	8
Lightweight	8	5
Communications	5	0
RFID, Bluetooth, GPS Technologies	1	0
Functionality		
Flame resistant	10	9
Protection against Chemical Biological Warfare Agents *i.e.* Self-cleaning, Self-detoxifying, Anti-viral, Anti-bacterial Effects, Seam-sealing, etc.	5	0
Protection against Physical Attack	5	0
Stand-off Chemical/ Biological/ Nuclear Warfare Detection	4	0
Ergonomics	10	8
Comfort/ Feel such as Breathability	10	7
Durability	8	6
Mechanical Properties of Clothes	9	5
Durability against washing	9	7
Design	8	6
Camouflage	9	6
Stealth	5	0
Production Cost	7	8
Manufacturability	7	5

APPENDIX B3: SURVEY RESULT-3

Part 1: Concept Screening Matrix

Do you think the current uniform has adequate flexibility for easy soldier movements?

>>I do, the uniform has adequate flexibility

Do you think the ACU should be lighter in weight?

>> I think it should actually be a heavier weight to increase durability

Does the current uniform have RFID sensor technology for soldier identification and tracking? If no, do you think the HPACU should have this technology?

>> If it could be very small and light weight

Is the current ACU flame resistant? If no, do you think the HPACU should have this technology?

>>the version issued for deployment is FR

Is the current ACU protective against the chemical- biological warfare agents? If no, do you think the HPACU should have this technology?

>>It is not. Would probably make the uniform heavy and eliminate breathability

Is the current ACU super- hydrophobic (i.e. self cleaning or water repellant)? If no, do you think the HPACU should have this technology?

>>it is not, we have environmental clothing for weather

Does the current ACU have anti-microbial properties? If no, do you think the HPACU should have this technology?

>>it does not, could be an interesting addition, although with t-shirt and shorts underneath, it is not against the skin in most areas

Does the current ACU have chemical-biological or nuclear warfare detection sensors? If no, do you think the HPACU should have this technology?

>>This would also be an interesting addition, if it could be light weight

Is the current ACU breathable and comfortable?

>>very much so

The current ACU is durable for how many wash cycles? The HPACU should be durable for how many washes?

>> I believe 25 cycles currently, this seems to be good

After how many month(s)/year(s) do the soldiers' have to buy a new uniform for themselves?

>>in combat about every 140-180 days, back in garrison about every 6 months to a year

Does the current uniform has the property "stealth" i.e. make the uniforms harder to be detected by all means than conventional uniforms by employing a combination of features to reduce visibility in the visual, audio, infrared, and radio frequency spectrum? If no, do you think the HPACU should have this technology?

>>they are resistant to certain wavelength IR, anything in this area would be interesting

Part 2: Concept Scoring Matrix

Selection Criteria	Weight	Current ACU
		Rating
Mobility	4	3
Flexibility	4	3
Lightweight	3	3
Communications	0	0
RFID, Bluetooth, GPS Technologies	2	0
Functionality	7	6
Flame resistant	9	9
Protection against Chemical Biological Warfare Agents *i.e.* Self-cleaning, Self-detoxifying, Anti-viral, Anti-bacterial Effects, Seam-sealing, etc.	6	0
Protection against Physical Attack	5	0
Stand-off Chemical/ Biological/ Nuclear Warfare Detection	5	0
Ergonomics	9	7
Comfort/ Feel such as Breathability	9	7
Durability	9	5
Mechanical Properties of Clothes	9	5
Durability against washing	9	6
Design	8	7
Camouflage	9	6
Stealth	5	0
Others		
Production Cost	5	7
Manufacturability	5	7

APPENDIX B4: SURVEY RESULT-4

Part 1: Concept Screening Matrix

Do you think the current uniform has adequate flexibility for easy soldier movements?

>> Yes

Do you think the ACU should be lighter in weight?

>> No

Does the current uniform have RFID sensor technology for soldier identification and tracking? If no, do you think the HPACU should have this technology?

>>Yes.

Is the current ACU flame resistant? If no, do you think the HPACU should have this technology?

>> There are two versions – standard, non-FR and FR

Is the current ACU protective against the chemical- biological warfare agents? If no, do you think the HPACU should have this technology?

>> No. It would be nice to have, but may be cost prohibitive.

Is the current ACU super- hydrophobic (i.e. self cleaning or water repellant)? If no, do you think the HPACU should have this technology?

>> No, but it is water repellant. It would be nice to have, but may be cost prohibitive.

Does the current ACU have anti-microbial properties? If no, do you think the HPACU should have this technology?

>> No. It would be nice to have

Does the current ACU have chemical-biological or nuclear warfare detection sensors? If no, do you think the HPACU should have this technology?

>> No. It would be nice to have, but may be cost prohibitive

Is the current ACU breathable and comfortable?

>>Yes

The current ACU is durable for how many wash cycles? The HPACU should be durable for how many washes?

>> I don't know

After how many month(s)/year(s) do the soldiers' have to buy a new uniform for themselves?

>> I don't know

Does the current uniform has the property "stealth" i.e. make the uniforms harder to be detected by all means than conventional uniforms by employing a combination of features to reduce visibility in the visual, audio, infrared, and radio frequency spectrum? If no, do you think the HPACU should have this technology?

>> Yes

Part 2: Concept Scoring Matrix

Selection Criteria	Weight	Current ACU
		Rating
Mobility		
Flexibility	9	9
Lightweight	9	9
Communications		
RFID, Bluetooth, GPS Technologies	10	10
Functionality		
Flame resistant	10	8
Protection against Chemical Biological Warfare Agents *i.e.* Self-cleaning, Self-detoxifying, Anti-viral, Anti-bacterial Effects, Seam-sealing, etc.	5	1
Protection against Physical Attack	1	1
Stand-off Chemical/ Biological/ Nuclear Warfare Detection	5	1
Ergonomics		
Comfort/ Feel such as Breathability	10	10
Durability		
Mechanical Properties of Clothes	9	9
Durability against washing	8	8
Design		
Camouflage	10	10
Stealth	10	10
Others		
Production Cost	8	8
Manufacturability	9	9

APPENDIX B5: SURVEY RESULT-5

Part 1: Concept Screening Matrix

Selecting Criteria	Current ACU	Suggested Design
Mobility		
Flexibility	Y	Y
Lightweight	Y	Y
Communications		
RFID, Bluetooth, GPS Technologies	N	Y
Functionality		
Flame resistant	N	Y
Protection against Chemical Biological Warfare Agents *i.e.* Self-cleaning, Self-detoxifying, Anti-viral, Anti-bacterial Effects, Seam-sealing, etc.	N	Y
Protection against Physical Attack	N	N
Stand-off Chemical/ Biological/ Nuclear Warfare Detection	N	Y
Ergonomics		
Comfort/ Feel such as Breathability	Y	Y
Durability		
Mechanical Properties of Clothes	Y	Y
Design		
Camouflage (invisibility during the day)	Y	Y
Stealth (invisibility at night)	N	Y

Part 2: Concept Scoring Matrix

Selection Criteria	Weight	Current ACU	Future ACU
		Rating	Rating
Mobility			
Flexibility	4	3	9
Lightweight	4	3	9
Communications			
RFID, Bluetooth, GPS Technologies	0	0	10
Functionality			
Flame resistant	7	6	8
Protection against Chemical Biological Warfare Agents *i.e.* Self-cleaning, Self-detoxifying, Anti-viral, Anti-bacterial Effects, Seam-sealing, etc.	9	1	8
Protection against Physical Attack	6	0	1
Stand-off Chemical/ Biological/ Nuclear Warfare Detection	5	0	1
Ergonomics			
Comfort/ Feel such as Breathability	9	7	10
Durability			
Mechanical Properties of Clothes	9	5	9
Design			
Camouflage (invisibility during the day)	9	6	8
Stealth (invisibility at night)	8	7	10
Others			
Production Cost	5	5	10
Manufacturability	7	6	8

APPENDIX B6: SURVEY RESULT-6

Part 1: Concept Screening Matrix

Selecting Criteria	Current ACU	Suggested Design
Mobility		
Flexibility	Y	Y
Lightweight	Y	Y
Communications		
RFID, Bluetooth, GPS Technologies	N	N
Functionality		
Flame resistant	N	Y
Protection against Chemical Biological Warfare Agents ***i.e.*** **Self-cleaning, Self-detoxifying, Anti-viral, Anti-bacterial Effects, Seam-sealing, etc.**	N	Y
Protection against Physical Attack	N	N
Stand-off Chemical/ Biological/ Nuclear Warfare Detection	N	Y
Ergonomics		
Comfort/ Feel such as Breathability	Y	Y
Durability		
Mechanical Properties of Clothes	Y	Y
Design		
Camouflage (invisibility during the day)	Y	Y
Stealth (invisibility at night)	N	N

Part 2: Concept Scoring Matrix

Selection Criteria	Weight	Current ACU	Future ACU
		Rating	Rating
Mobility			
Flexibility	4	5	9
Lightweight	4	6	9
Communications			
RFID, Bluetooth, GPS Technologies	0	0	10
Functionality			
Flame resistant	7	8	8
Protection against Chemical Biological Warfare Agents *i.e.* Self-cleaning, Self-detoxifying, Anti-viral, Anti-bacterial Effects, Seam-sealing, etc.	9	0	9
Protection against Physical Attack	6	0	1
Stand-off Chemical/ Biological/ Nuclear Warfare Detection	5	0	1
Ergonomics			
Comfort/ Feel such as Breathability	9	7	10
Durability			
Mechanical Properties of Clothes	9	5	9
Design			
Camouflage (invisibility during the day)	9	6	8
Stealth (invisibility at night)	8	7	10
Others			
Production Cost	5	5	10
Manufacturability	7	6	8