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Characterizing Apparel & Fit for Virtual and Physical Worlds with Logic statements

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Abstract

This paper conceptualizes clothing fit and represents fit attributes in detail using Logic statements with either common logic symbols or uniquely defined symbols to indicate thought process and then expand to the implemented level of Fit. These Logic statements explain the relationships between body and fit in 3D and 2D along with 1D and 0D features and measures. This work introduces four assets: Human, Humanoid, Cover, and Coveroid; and the fit attributes depict the relationships of those assets. Subsequently,16 transforms are combined to broadly define technology offerings involving physical and virtual fit. Importantly, the Logic statements are shown to depict proposed relationships that determine *Intended Fit* and *Expected Fit*. Fit statements were expressed for both known and unknown parameters; therefore, it can simulate a Ready-to-Wear Use Case, and Bespoke to Made-to-Measure Use Cases. In addition, 2D and 3D fit landmarks are described in the form of geometric details, including body geometries and measurement locations for known and unknown Humans and Humanoids. This work has characterized the essential parameters of Design Realm, Production process impact, and underneath cover(s). The Design Realm has incorporated: Universal style tag requirements, Emotive Design, and Human shape-dependent parameters. Since the fit is impacted by time, 4D concepts can be incorporated into a virtual avatar, in which Planned Fit is described by Rigging. This work translates all the fit principles used in the apparel industry into logical statements for both mathematicians and digital tool developers. Consequently, this will augment software intended to automate Cover design and development.

Keywords: Clothing fit, Coveroid, Humanoid, Intended Fit, Expected Fit

1. Introduction

This paper illustrates the problem of Fit at a very conceptual level using logic and uniquely defined symbols to indicate a certain level of Fit. The focus is to translate the complex language of pattern makers into a mathematical language understood by programmers who are responsible for automating Made-to-Measure for mass customization. The logic statements will be accompanied by explanatory text.

Other authors have researched this problem at an applicable level and in the details of workflows or equations, whereas the Apparel industry has focused on the Concept of Fit. A Concept of Fit is a formal document that defines the fit criteria with official pass and fail definitions. The Concept of Fit and the Impact of Made-to-Measure will be explored in future papers. The Logic statements presented focus on the fact that 2D patterns for Covers contain both the portion related to a body shape and the garment design. The portion related to the body (or body blocks) is derived from a body shape, and a body block is embedded within the pattern.

This study excludes draped clothes that do not require a coveroid pattern such as Sarong, Chiton (from ancient Greece), and scarves as their shapes are determined by the person wearing the cover. In addition, that do not require a 2D form will not be included in this discussion; neither will soft tissue digital Humanoids, since they are in the process of being developed.

There are many aspects to material properties including physical and thermal parameters are not described in detail. For example, materials shrink, and stretch may vary during production and over the lifetime of the cover, however, these two aspects are not described in this work. For this paper, we are merely stating that the materials used in any cover impact the fit of that cover.

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1.1. True and Representations

The person has two versions: true (called Human) and representation. Any representation of a body is called a Humanoid. Garments, Footwear or Wearables can have two versions: true or a representation (e.g., digital, or physical models). True versions of Garments, Footwear or Wearables can be expressed as "Covers". Any representation of Cover (garments, footwear, or wearables) is called a Coveroid. All of these are considered Assets. Complete definitions are found in IEEE Assets and Transformations paper [1] with a summary shown in Table 1. In this paper, the four Assets are represented using different fonts. The Assets are related to each other by a process called Transformation which is a process that converts, (filters, simplifies, combines, extracts, etc.) data and then copies or moves that data to a destination.

Table 1. Four key Assets

Term	Description
Human	A natural living person will be shown in **Arial Black**
Humanoid	Any representation (non-human) that can manifest human-like characteristics, such as motion or shape or other physical attributes of a human. Physical 3D / Digital 3D representations will be shown as ***Harlow Solid Italic*** Representations / Digital versions 2D versions will be shown as *Imprint MT Shadow*.
Cover	Anything Human wears on or above the skin; for any reason, under any condition, for any time period. Physical 2D fabricated cover or physical material will be shown as in **Arial Rounded MT Bold**. NOTE —This includes the covers' material or components.
Coveroid	Any representation or digital version of any "Cover." Representations / Digital versions 2D versions will be shown as *Lucida Calligraphy*. Assembled 2D versions that are virtual will be shown in Comic Sans MS.

1.2. 2D objects and 3D objects in CAD environment

The Humanoid is considered a 3D mesh object within the CAD environment which can be rigged for movement. The Coveroid is considered a 2D object or 2D skin model as it is a thin shell or skin object. The 2D surface model can be rigged for movement or wrapped around a 3D object. A surface object can occupy a 3D space but is still considered a 2D object. Figure 1 is the black and white version of the figure from [1] and is shown for reference.

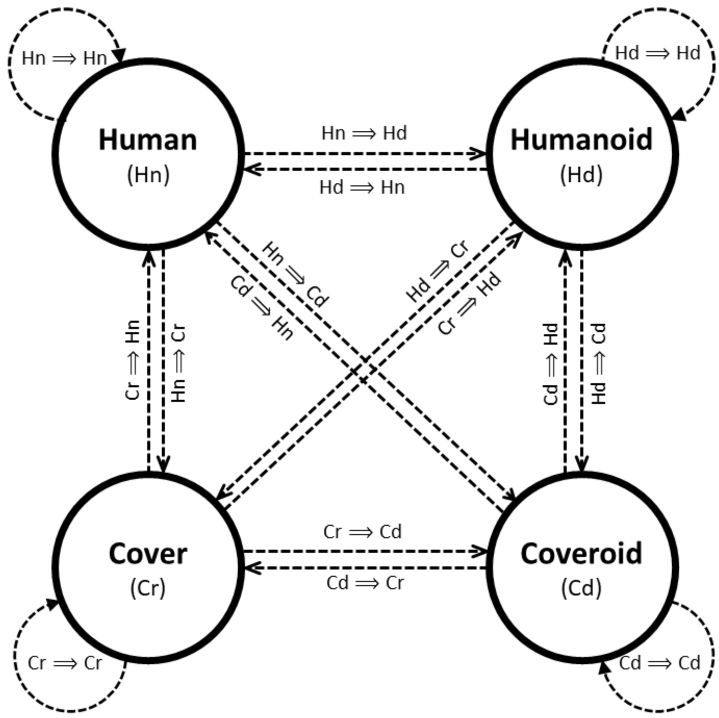

Figure 1 Diagram of Transformations between Assets

1.3. Logic symbols definitions

Table 2 depicts the symbols used in describing the logic statements, with standard ones from [2].

Table 2. Logic symbols

Symbol	Description
LS	Logic statement
≡	Both sides of the logic statements are logically "equivalent" or one side is "described by" other
{ , }	An unordered pair.
⓪	not worn
①	worn
∈	an "element of"
&	Both conditions must be met in logic statements.
\	depict "exclusion".
∀	To describe that this is a requirement for "*all".*
⊦	"derived from"
0	Subscript 0, implies "known"
n	Subscript n, implies "unknown"
•, ⎛, □	Body features such as points, curves, and surfaces
±	Amounts can be added or subtracted as required
⭮ , ⭯	To show assembled condition, virtual or physical (⭯)

2. Transformations

Beginning in the Physical world Hn ⟹ Cr

Assuming that Fit involves a Body and a Garment, this paper uses logic statements to express complex concepts in a shorthand notation. We start with the logic statement, Fit ≡ {Body, Garment} or F ≡ {B, G}. Expanding this statement to a more general statement to include human and cover, the statement changes to Fit ≡ {Human, Cover} or F ≡ {Hn, Cr}. Both terms are required: "There must be a human" *together with* "there must be cover" and being an unordered pair, it does not matter which comes first. The notation for a 3D Fit (physically) is **F**, the notation for a 3D Human is **Hn** and the notation for an assembled 2D Cover for the 3D physical world is **Cr**. In the 3D notation, the logic statement is shown as follows, when the Cover is being worn. In the physical world, as shown in LS 1, *Fit is described as the unordered pair of a Human and Cover when Cover is worn on a Human.*

Also, in the physical world, the *Cover is not worn on the Human*, is shown in LS 2. The Cover can be considered similar to a deflated balloon when not worn on the body, having a shape dependent on the method of storage. Just like a deflated balloon, its shape will be constrained by the amount of material used and the construction method.

F ≡ {**Hn** , **Cr**} when **Cr** ① **Hn** (LS 1)

Cr ⓪ **Hn** (LS 2)

2D Translation Hd ⟹ Cd, Cd ⟹ Cd

A Cover created in a 3D CAD environment is actually a 2D skin object that can be wrapped around a 3D solid object or a 3D mesh object. One requires patterns to create the geometry of the Covers by "fabric" that is either 2D material or 3D printed 2D material. Pattern makers take the design concepts and turn them into patterns that allow covers to be fabricated, 2D patterns will be the start of this exploration.

A lot of thoughtful planning goes into making a Cover to "Fit" a person. Regardless, actual fit is not expressly known; therefore, the "Fit" will be noted as "F". Patterns incorporate not only the amount of material required for fit, but also the shape required for the final Cover. In the 2D world, the Human becomes a Humanoid block, *Hd*. The Humanoid block is not a Human, but the form needed to fabricate a 3D Human body shape. In the 2D world, the Cover becomes the Coveroid pattern, noted as *Cd*. The Coveroid pattern is not a Cover, but the form needed to fabricate and assemble the 2D Cover.

The key difference between the physical 3D and 2D patterns is that **in the physical 3D world, Human and Cover are two separate items**. However, **in the 2D world, the 2D Humanoid block is embedded within the Coveroid pattern** or is an element of the Coveroid pattern, as shown in LS 3, *2D Humanoid Block is an element of the Coveroid pattern.*

$$\mathrm{Hd} \in \mathcal{Cd} \qquad \text{(LS 3)}$$

Parameters are used to create the Coveroid pattern. These are variables that can be constants or terms in a function that can describe the final cover shape in relation to the Humanoid block. The coveroid pattern is equivalent to a humanoid block and parameters, as shown in LS 4, *Coveroid pattern is described as 2D Humanoid block and Parameters.* These will be explained in more detail in the section on Parameters and noted as "$\mathcal{R}$".

$$\mathcal{Cd} \equiv \mathrm{Hd} \;\&\; \mathcal{R} \qquad \text{(LS 4)}$$

Fit in 3D is the interaction of Human and Cover, but in 2D, Fit (shown as "F") is implied by the Coveroid pattern, which has been described as the Body block and Parameters. Therefore, as in LS 5, *Fit is described as Coveroid pattern*, and also *is described as 2D Humanoid block and Parameters.*

$$\mathrm{F} \equiv \mathcal{Cd} \equiv \mathrm{Hd} \;\&\; \mathcal{R} \qquad \text{(LS 5)}$$

Based on previous statement, and by rearrangement of terms, other relationships can be developed, as shown in LS 6. The *2D Humanoid block is described as Fit excluding Parameters,* and also *is described by Coveroid pattern excluding Parameters* and LS 7. *Parameters are described as Fit excluding Humanoid block,* and also *are described by Coveroid pattern excluding Humanoid block.*

$$\mathrm{Hd} \equiv \mathrm{F} \setminus \mathcal{R} \equiv \mathcal{Cd} \setminus \mathcal{R} \qquad \text{(LS 6)}$$

$$\mathcal{R} \equiv \mathrm{F} \setminus \mathrm{Hd} \equiv \mathcal{C} \setminus \mathrm{Hd} \qquad \text{(LS 7)}$$

<u>CAD design or Multiple Covers, Hd ⟹ Cd, Cd ⟹ Cd</u>

The Humanoid block may be "on" a layer other than the Coveroid pattern in a CAD environment. However, the final Cover is designed with a known Human in mind, and as such that Humanoid block is taken into consideration for the coveroid pattern design and is, therefore "embedded within" the Coveroid pattern.

Cover can be part of the set of covers each with its own styling and parameters of which the Humanoid is still an element for any Coveroid pattern used to create the Cover(s). The future state of being worn, implies that a coveroid pattern is described as a humanoid block and parameters regardless of styling. To describe that this is a requirement for *all* Covers, LS 8 is used.

$$\forall \mathcal{Cd} \equiv \mathrm{Hd} \;\&\; \mathcal{R} \qquad \text{(LS 8)}$$

<u>Humanoid Block Hd ⟹ Hd</u>

A "sloper" is a Humanoid block [3], that is, "a sloper is a 2D version of the 3D form." Note that "Commercial pattern producers use slopers that fit the 'average' body shape" [3]. The Humanoid block, Hd, a 2D version of the 3D form, is calculated with the help of fitting aids such as darts, cutouts and curve generation and is derived from a 3D object. Note that the Humanoid block is considered a second skin. There is no compression of the body, no additional fullness or additional material to allow for the wearing of the Humanoid block on the body. Incorporating fitting aids into a calculation implies a particular body shape. The body shape shows the placement of body features or geometries such as shoulders, bust, waist and hips relative to each other along with their respective numerical values.

Using the expression that "a sloper is a 2D version of the 3D form", in logic terms, one can say that the 2D form *is derived from* the 3D form. This implies the 2D version of the 3D form can be expressed as LS 9, *2D Humanoid block is derived from 3D Humanoid shape.*

$$\mathrm{Hd} \equiv \vdash \boldsymbol{\mathcal{Hd}} \qquad \text{(LS 9)}$$

The ‘average’ body shape is from either a 3D CAD model or a mannequin representing the target market for which the designer or brand is designing. With the 3D CAD models or mannequins, the shape, location of measurements and measurements are *known*. These can be either measured manually or obtained from the computer. A known Humanoid block is noted as, Hd_0. Hd_0 is not the average Humanoid block or the sample size Humanoid block for the cover but the Humanoid block for which exists the information of the 3D Humanoid, $\mathcal{Hd}_0$, from which the humanoid block was derived. For example - if making a dress in sizes UK 2-12 based on an hour-glass body shape, and there exists only the CAD avatar or the mannequin for size 6, then this is the known Humanoid, $\mathcal{Hd}_0$, and grading of the Cover to the other graded sizes is based on rules dependent on the Cover. The only “known” Humanoid block, $\mathcal{H}_0$, has been derived from a size 6 hour-glass shaped mannequin, $\mathcal{Hd}_0$. If Hd_0 exists for all of these sizes, then it will be “known” for UK2, UK4, UK6, UK8, UK 10, and UK12. If there is direct information how the Humanoid block was derived for the Humanoid block embedded in the pattern, it is “known”. As shown in LS 10, *2D Known Humanoid block is derived from 3D Known Humanoid shape.*

$$\mathrm{Hd}_0 \equiv \vdash \mathcal{Hd}_0 \qquad \text{(LS 10)}$$

It is a given that the known 3D Humanoid, $\mathcal{Hd}_0$, will not be the same as any other (unknown) person who wears the Cover, noted as $\mathbf{H}_n$. An unknown Human has not been measured, or the shape and size are not known. That is, they could be a CAD or mannequin, or a body before scanning. However, it is assumed that the Unknown Human will be able to wear the Cover and the unknown Human is approximately the same general size and shape as the 3D Humanoid, such that the *Intended Fit is described as a Coveroid pattern,* also *described as known 2D Humanoid block and known Parameters* as shown in LS 11 .However, this is not the case and *the Intended Fit is described as Coveroid pattern,* also *is described as unknown 2D Humanoid block and unknown Parameter* as shown in LS 12.

$$\mathrm{F}_J \equiv \mathcal{Cd} \equiv \mathrm{Hd}_0 \ \& \ \mathcal{R}_0 \qquad \text{(LS 11)}$$

$$\mathrm{F}_J \equiv \mathcal{Cd} \equiv \mathrm{Hd}_n \ \& \ \mathcal{R}_n \qquad \text{(LS 12)}$$

Another goal would be to keep the known Parameters and change the *Intended Fit* to an *Expected Fit*, being noted as “ F_E” and the Proposed Coveroid pattern, being noted as “ G_P “. This could be considered a Customized Fit as the relationship between the Humanoid and Coveroid are maintained. The Fit has been adjusted for the Humanoid shape and this relationship is shown in LS 13, E*xpected Fit is described as Proposed Coveroid pattern*, *also is described as unknown 2D Humanoid block, and known Parameters.*

$$\mathrm{F}_E \equiv \mathcal{G}_p \equiv \mathrm{Hd}_n \ \& \ \mathcal{R}_0 \qquad \text{(LS 13)}$$

What are the Parameters? Hd ⟹ Cd

For this paper, Parameters, $\mathcal{R}$, has three main components for the Pattern producers. They are Design Realm “$\mathcal{D}$“, Production Process Impact “$\mathcal{P}$” and expected underneath Covers “$\mathcal{C}$”. The Design Realm “$\mathcal{D}$“ includes the universal style tag requirements “$\mathcal{U}$”, and expected emotive design “$\mathbf{E}\mathcal{D}$”, and the Humanoid shape dependent, “$\mathcal{S}$“. The Parameters’ relationships can be shown in LS 14, *Parameters are equal to Design Realm plus/minus Production Process Impact plus/minus plus/ minus underneath covers* and LS 15, *Design Realm are equal to Universal style tag requirements plus/minus emotive design plus/minus Humanoid shape dependent.*

$$\mathcal{R} = \mathcal{D} \pm \mathcal{P} \pm \mathcal{C} \qquad \text{(LS 14)}$$

$$\mathcal{D} = \mathcal{U} \pm \mathbf{E}\mathcal{D} \pm \mathcal{S} \qquad \text{(LS 15)}$$

The Universal style tag is already a method of classification and characterization of the Cover used by on-line search companies [4]. We used that taxology to describe the Cover. Basically, one can use the platforms' method of classification as a starting point in the Design Realm. Combining LS 14 and LS 15, then *Parameters are equal to Universal style tag requirements plus/minus emotive preference plus/minus Humanoid shape dependent plus/ minus Production Process Impact plus/ minus underneath Covers* becomes LS 16.

$$\mathcal{R} = \mathcal{U} \pm \mathbf{E}\mathcal{D} \pm \mathcal{S} \pm \mathcal{P} \pm \mathcal{C} \qquad \text{(LS 16)}$$

Let's explore three main components in more detail. Sometimes all of these components may be incorporated together as these may be coincident variables, rather than cumulative. In this paper, we will be discussing them individually in the following section. However, after consideration, the components will be as part of the Parameters, $\mathcal{R}$.

Design Realm, Hd ⟹ Cd

First component

The first component of the Design Realm includes Universal style tag requirements. Mathematically functions require certain defined inputs to obtain an output.

Universal style tags, $\mathcal{U}$, require function of intent "i", cover materials "M", fasteners "F" and Finishing methods "FG". The definitions for these are shown in Table 3.

Table 3. Universal style tag requirements

Notation	Description
i	intent of the cover (type and usage)
M	Materials in the cover (woven or knit). As noted earlier, the actual parameters of the materials are not covered in this discussion.
F	Appropriate selection of fasteners
FG	Finishing methods

The intent of the cover includes the cover type that is, pants, or shirt and the usage such as PPE, uniform. Intent is commonly considered the "planned end-use" of the cover.

Second component

The second component of Design Realm is the emotive preference, $\mathbf{E}\mathcal{D}$, of the cover. The emotive preference, $\mathbf{E}\mathcal{D}$, is a function of hygge "h", status "s", and become aligned with social "b". The definitions of each of these are shown in Table 4.

Table 4. Emotive preference inputs

Notation	Description
h	Hygge (comfort with warm feelings) (pronounced HEU- guh)
s	Status (does this Cover convey a status) *(status e.g., boss versus worker, middle class)*
b	Become Aligned with Social, (become aligned with social (or not) with socio-cultural group or societal expectations for the wearing occasion)

Third component

The third component of Design Realm is Humanoid shape dependent, $\mathcal{S}$, of the cover. The Humanoid shape dependent, S, is a function of Geometry "G0", expected kinematics "K0", aesthetics for body type "A_B", and materials "M". The definitions of each of these are shown in Table 5.

Table 5. Humanoid shape dependent inputs

Notation	Description
G0	Geometry of pattern
K0	Kinematics for expected body movement allowance (at each landmark)
A_B	Aesthetics for Body shape (based on style on body shape)
M_A	Amount of material in the cover (woven or knit)
F#	Length of opening (impacts number of fasteners or length of zippers)
FG#	Amount of Finishings (the amount of coating required, the amount of interface, etc.) (*the finishing method was listed already in* $\mathcal{U}$.)

The functional need for the cover and kinematics for the expected body movement allowance can vary depending on the activity the Human undertakes as shown in reference [5]. The numerical value obtained from the Parameters will vary at each Landmark. The definition of fitting types is specified in reference [6]. It is recommended that the coveroid design be evaluated over multiple humanoids that include variations of skin tone, hair styles, body shapes and activities.

Landmarks Hn ⟹ Hn, Hd ⟹ Hd

Body features or geometries are considered geometric details. Certain geometric details can be identified as Landmarks such as shoulders, bust, waist and hips and are noted as *LM*. Landmarks can be points, curves, or surfaces. The font used will be dependent on the 2D or 3D nature of the landmark. The location may be dependent on the method used to obtain them. Landmarks are determined from the Human first. Just like the Humanoid block, the 2D Landmark is derived from the 3D Landmark and must be derived on the Humanoid block and positioned appropriately.

Virtual Fabrication, Cd ⟹ Cd

Currently, virtual fabrication is optional, and this section is often skipped. Therefore, the thought process of assembly will be repeated in the Physical Fabrication section. It is recommended to read this section as logic statements will be explained in detail.

After the virtual patterns are made, and fabrication complete , everything is now "assembled". The 2D occupies 3D space and is considered a 2D fabricated item, necessitating changes to the logic statements. After assembly, the assembled Coveroid can be evaluated at the landmarks that have been specified. Using the same relationship of LS 11, that *Coveroid pattern, is described as known 2D Humanoid block and known Parameters* as shown in LS 17.

$$\mathcal{Cd} \equiv \mathrm{Hd}_0 \ \& \ \mathcal{R}_0 \qquad \text{(LS 17)}$$

Since the next step was to "assemble" the Coveroid, the logic statement will change to the assembled version. The Fit of the Cover is usually checked at the specified landmarks. Since the Fit is being compared with a 3D object of a Humanoid, Fit is a 3D item. Assembled versions are as shown in LS18, *3D Fit which is described by the assembled term of Intended Fit at Landmarks* and LS 19*, 2D Fabricated Coveroid is described by the assembled term of 2D Coveroid patterns.*

$$\mathcal{F} \equiv \circlearrowleft \mathrm{F}_{\mathrm{LM}} \qquad \text{(LS 18)}$$

$$\mathcal{C}\mathrm{d} \equiv \circlearrowleft \mathcal{Cd}_{\mathrm{LM}} \qquad \text{(LS 19)}$$

As shown in LS 20, *Coveroid is described by 3D Fit* and also *is described by the assembled term of (known Humanoid block derived from known Humanoid shape at each Landmark and known 2D Parameters at each Landmark)*

$$\mathcal{C}\mathrm{d} \equiv \mathcal{F} \equiv \circlearrowleft \mathrm{F}_{\mathrm{LM}} \equiv \circlearrowleft (\mathrm{Hd}_{0,\mathrm{LM}} \ \& \ \mathcal{R}_{0\mathcal{LM}}) \qquad \text{(LS 20)}$$

Using the distributive property, one would apply the "assembled" to the whole of derived Humanoid and Parameters, but we are going to separate the terms, as the Humanoid and Coveroid become two separate items when assembled and attached on 3D Humanoid. This is shown in LS 21, *Known 3D Fit* *is described by the assembled term of known Humanoid block derived from known Humanoid shape at each Landmark and assembled term of known 2D Parameters at each Landmark*

$$\mathcal{C}d_0 \equiv \mathcal{F}_0 \equiv \circlearrowleft \mathrm{F}_{\mathrm{LM}} \equiv \circlearrowleft (\mathrm{Hd}_{0,\mathrm{LM}}) \;\&\; \circlearrowleft (\mathcal{R}_{0\mathcal{LM}}) \quad \text{(LS 21)}$$

Since Hd was derived from $\mathcal{H}d$ as noted in LS 10, the first term will become $\mathcal{H}d$ again once it is assembled.

$$\mathcal{H}d_0 \equiv \circlearrowleft (\mathrm{Hd}_{0,\mathrm{LM}}) \equiv \circlearrowleft (\vdash \mathcal{H}d_{0,\mathrm{LM}}) \quad \text{(LS 22)}$$

What is the name of the second term of $\circlearrowleft (\mathcal{R}_{0\mathcal{LM}})$? Since we do not have a name for it as yet, it will be noted it as double ?? *which is described by assembled known 2D Parameters at each Landmark when the Coveroid is assembled and attached to Humanoid.* As shown in LS 23, there needs to be a comparison with the Humanoid.

$$\textbf{??} \equiv \circlearrowleft(\mathcal{R}_{0,\mathcal{LM}}),\ \text{when } \mathcal{C}d \text{ ① } \mathcal{H}d \quad \text{(LS 23)}$$

The question becomes what to name the assembled known 2D Parameters. In the Apparel industry, this is commonly called *Ease.* For this paper, we are not exploring the many definitions of Ease. We will note that Ease can exist as both 2D and 3D. It will be noted as "$\mathcal{E}$" for 2D digital/ representation and E for 3D. In addition, if we define *Ease as being the relationship between Humanoid shape and Coveroid when assembled and attached to the Humanoid*, then the assembling of the Parameters becomes 3D Ease. This is shown in LS 24, *Known 3D Ease is described by assembled known 2D Parameters at each Landmark when the Coveroid is attached to a known Humanoid.*

$$\mathrm{E}_0 = \circlearrowleft(\mathcal{R}_{0,\mathcal{LM}}),\ \text{when } \mathcal{C}d \text{ ① } \mathcal{H}d_0 \quad \text{(LS 24)}$$

Determination of 3D Ease in the virtual space is open for research. The difference between a digital Coveroid and digital Humanoid will be the differences in measures between the two items at designated locations and with designated offsets. For example, if the cover is worn on the shoulders, the offset of cover at those locations may only include the underneath covers. Material stretch may or may not have been modeled. The gravity may or may not have been modeled. However, the overlap of materials reflecting the fabrication method including the manufacturing tolerances will need to be modeled.

A logic statement for 3D Fit can be generated by combining the relevant terms. The 3D Fit can also be described as type of unordered pair, as the assembled Coveroid and Humanoid are two separate objects. In LS 25, *Known assembled Coveroid is described as assembled term of known Humanoid block derived from known Humanoid shape and known 3D Ease*. In LS 26*, 3D Fit is the unordered pair of a Humanoid and known assembled Coveroid.*

$$\mathcal{C}d_0 \equiv (\mathcal{H}d_{0,\mathrm{LM}} \;\&\; \mathrm{E}_{0,\mathcal{LM}}) \quad \text{(LS 25)}$$

$$\mathcal{F} \equiv \{\mathcal{H}d_0, \mathcal{C}d_0\} \quad \text{(LS 26)}$$

The 3D Fit can also be described as a type of unordered pair, as the assembled Coveroid and Humanoid are two separate objects. The combination of LS 25 and LS26 can be written as LS 27, *3D Fit is described as the unordered pair of a Humanoid and (known Humanoid and known Ease) when Coveroid is attached on known Humanoid at Landmarks.*

$$\mathcal{F} \equiv \{ \mathcal{H}d_0 , (\mathcal{H}d_{0,\mathrm{LM}} \;\&\; \mathrm{E}_{0,\mathcal{LM}})\} \text{ when } \mathcal{C}d \text{ ① } \mathcal{H}d_0 \quad \text{(LS 27)}$$

<u>Landmarks Cd ⟹ Cr</u>

As noted previously, there will be a small manufacturing tolerance which can be located at the landmarks. As shown in LS 28, *All Cover Landmarks are described as assembled known Intended 2D Fit at each Landmark with manufacturing tolerances for all points, curves, and surfaces*. Landmarks are usually noted as subscripts going forward. Since the location of the landmarks, have been incorporated into the design of the Cover, as shown in LS 29, *There exists Landmarks on Cover when it is not worn.*

$$\mathbf{LM}_0 \equiv \circlearrowleft \forall \vdash \mathcal{LM}_0 \pm \mathbf{t}, \text{ for all } \bullet \, (, \square \qquad \text{(LS 28)}$$

$$\exists \mathbf{Cr}_{,\mathbf{LM}} \text{ when } \mathbf{Cr} ⓪ \mathbf{Hn} \qquad \text{(LS 29)}$$

<u>Physical Fabrication, Cd ⟹ Cr</u>

The thought process of "assembly" is the same for the physical world as in virtual, even if the methods of "assembly" are very different. Similar to what was written before in LS 11, LS 21, and LS 22, patterns are made, and the physical is fabricated and "assembled. The 2D becomes physical 3D and the equations will change from virtual to physical.

$$\mathbb{F}_J \equiv \mathcal{Cd} \equiv \mathbb{Hd}_0 \;\&\; \mathcal{R}_0 \qquad \text{(LS 11)}$$

$$\mathcal{C}d_0 \equiv \boldsymbol{\mathcal{F}}_0 \equiv \circlearrowleft \mathbb{F}_{\mathbb{LM}} \equiv \circlearrowleft (\mathbb{Hd}_{0,\mathbb{LM}}) \;\&\; \circlearrowleft (\mathcal{R}_{0\mathcal{LM}}) \qquad \text{(LS 21)}$$

$$\boldsymbol{\mathcal{Hd}}_0 \equiv \circlearrowleft (\mathbb{Hd}_{0,\mathbb{LM}}) \equiv \circlearrowleft (\vdash \boldsymbol{\mathcal{Hd}}_{0,\mathbb{LM}}) \qquad \text{(LS 22)}$$

The previously mentioned "assembled" symbol will be used, it will be "bold". Unlike the virtual world, the methods of the assembly are fully understood and small manufacturing tolerance, "t", is included. After assembling, the coveroid becomes a **3D object** or the *assembled* **2D** Coveroid becomes an **assembled 2D** Cover. Thus, the 3D logic statements are of most concern. The manufacturing tolerance is in the Cover, the known Humanoid shape and known parameters are assembled into the Cover. This implies that similar logic statements can be utilized, with a physical notation. LS 11 will remain the same as it is in 2D. However, transformations will come into play. In the physical world, there will be a slight manufacturing tolerance when Covers are assembled. As shown in LS 30, Assembled 2D Cover transforms into a Cover, and Known Modeled Fit will transformed to the Intended Fit of a Cover.

$$\mathcal{C}d_0 \Rightarrow \mathbf{Cr},\; \boldsymbol{\mathcal{F}}_0 \Rightarrow \mathbf{F_J}, \qquad \text{(LS30)}$$

As shown in LS 31, *The Assembled cover which is described as 3D Intended Fit that is described as assembled known Intended 2D Fit at each Landmark with manufacturing tolerance.*

$$\mathbf{Cr} \equiv \mathbf{F_J} \equiv \circlearrowleft \mathbb{F}_{\mathbb{LM}} \pm \mathbf{t} \qquad \text{(LS 31)}$$

This allows us to modify LS 21 (along with LS 22) to the 3D physical version of LS 32*, The Intended Fit is described by a 3D Cover* and also *is described by the assembled term of known Body block derived from a known Humanoid shape at each Landmark and the assembled known 2D Parameters at each Landmark with manufacturing tolerance.* The physical Cover is based on the Humanoid that is utilized in the design.

$$\mathbf{F_J} \equiv \mathbf{Cr} \equiv \circlearrowleft(\vdash \boldsymbol{\mathcal{Hd}}_{0,\,\mathbb{LM}}) \;\&\; \circlearrowleft(\mathcal{R}_{0,\,\mathcal{LM}}) \pm \mathbf{t} \qquad \text{(LS 32)}$$

<u>Ease, Cover is Worn, Hn ⟹Cr, Hd ⟹ Cr, Cr ⟹ Hn, Cr ⟹ Hd</u>

Since the Cover is designed and assembled to be worn, it is the 3D physical logic statement that is of the most concern. The Cover can be "worn" on a mannequin (which is a physical Humanoid) or worn on a Human. Ease will still be defined *as being the relationship between Human or Humanoid and Cover when worn*, then the baking of the Parameters becomes 3D Ease shown as "**E**". The manufacturing tolerance will add in a small variance. This implies that LS 24 transforms into LS 33. It is also important to note in LS 33 that $\boldsymbol{\mathcal{Hd}} \neq \boldsymbol{\mathcal{Hd}}_0$, and $\mathbf{Hn} \neq \boldsymbol{\mathcal{Hd}}_0$ *The Humanoid or Human is not equal to the known Humanoid*. One is a 3D digital model, and one is a 3D physical model. If the

Humanoid is physical representation of the 3D digital model, then in LS 34, *3D Ease is approximately the assembled known 2D Parameters at each Landmark when the Cover is worn by known Humanoid with manufacturing tolerance.*

$E_0 = \circlearrowleft(\mathcal{R}_{0,\mathcal{LM}})$, when $\mathcal{C}d$ ① $\boldsymbol{\mathcal{Hd}}_0$ (LS 24)

$E = \circlearrowleft(\mathcal{R}_{0,\mathcal{LM}}) \pm \mathbf{t}$, when **Cr** ① **Hn** (LS 33)

$E \approx \circlearrowleft(\mathcal{R}_{0,\mathcal{LM}}) \pm \mathbf{t}$, when **Cr** ① $\boldsymbol{\mathcal{Hd}}_0 \pm \mathbf{t}$ (LS 34)

<u>3D world, Cover is Worn Hn ⟹Cr, Hd ⟹ Cr, Cr ⟹ Hn, Cr ⟹ Hd</u>

In the 3D world, LS 27 becomes a starting point from which a Human and Humanoid will wear the Cover. Every component is now 3D. As stated previously, the known 3D Humanoid is noted as, "$\boldsymbol{\mathcal{Hd}}_0$". The unknown Human will be noted as "$\mathbf{Hn}_n$", and an unknown Humanoid will be noted as "$\boldsymbol{\mathcal{Hd}}_n$. This person has **not** been measured by any method. From the Brands' point of view, the only information known is that this person has purchased the Cover It may be incorrect to assume the Cover is purchased by the intended wearer, or the ultimate wearer is known. Therefore, the Fit and Ease will not be known but the relationship is the same. These are shown in LS 35, *The Unknown Human is not equal to the known Humanoid* and LS 36, *The Unknown Humanoid is not equal to the known Humanoid.*

$\mathbf{Hn}_n \neq \boldsymbol{\mathcal{Hd}}_0$ (LS35)

$\boldsymbol{\mathcal{Hd}}_n \neq \boldsymbol{\mathcal{Hd}}_0$ (LS36)

These are now combined in LS 37 and LS 38. As shown in LS 37, *Fit is described as the unordered pair of a Human and (known Humanoid and known Parameters with manufacturing tolerance) when Cover is worn on Human*. As shown in LS 38*, Fit is described as the unordered pair of a Humanoid and (known Humanoid and known Parameters with manufacturing tolerance) when Cover is worn on unknown Humanoid.*

$\boldsymbol{\mathcal{F}} \equiv \{ \boldsymbol{\mathcal{Hd}}_0, (\boldsymbol{\mathcal{Hd}}_{0,\mathrm{LM}}$ & $E_{0,\mathcal{LM}})\}$ when $\mathcal{C}d$ ① $\boldsymbol{\mathcal{Hd}}_0$ (LS 27)

$\mathbf{F} \equiv \{ \mathbf{Hn}, (\boldsymbol{\mathcal{Hd}}_{0,\mathrm{LM}}$ & $E_{0,\mathcal{LM}} \pm \mathbf{t})\}$ when **Cr** ① **Hn** (LS 37)

$\boldsymbol{\mathcal{F}} \equiv \{ \boldsymbol{\mathcal{Hd}}_0, (\boldsymbol{\mathcal{Hd}}_{0,\mathrm{LM}}$ & $E_{0,\mathcal{LM}} \pm \mathbf{t})\}$ when **Cr** ① $\boldsymbol{\mathcal{Hd}}_n$ (LS 38)

Since the fabricated Cover can be measured, it becomes a known Cover with the manufacturing tolerance embedded in approximate design parameters as shown in LS 39. Even though the Cover can now be measured, the relationship of the unknown human to the known Humanoid is not known, implying Ease cannot be known. The logic statement format can be the same as before. The unknown Fits or Eases will not have the same values or landmarks. As shown in LS 40, *Unknown Fit is described as the unordered pair of an unknown Human and (known Humanoid and unknown Ease) when measured Cover is worn on an unknown Human* and in LS 41*, Unknown Fit is described as the unordered pair of an unknown Humanoid and (known Humanoid and unknown Ease) when Cover is worn on an unknown Humanoid.*

$\mathbf{Cr}_0 \approx (\boldsymbol{\mathcal{Hd}}_{0,\mathrm{LM}}$ & $E_{0,\mathcal{LM}})$ (LS 39)

$\mathbf{F}_n \equiv \{\mathbf{Hn}_n, (\boldsymbol{\mathcal{Hd}}_0$ & $E_n)\}$ when $\mathbf{Cr}_0$ ① $\mathbf{Hn}_n$ (LS 40)

$\mathbf{F}_n \equiv \{\boldsymbol{\mathcal{Hd}}_n, (\boldsymbol{\mathcal{Hd}}_0$ & $E_n)\}$ when $\mathbf{Cr}_0$ ① $\boldsymbol{\mathcal{Hd}}_n$ (LS 41)

Human and Unknown Human in 3D world, Hn ⟹Cr

In the 3D world, the Cover is dependent upon the 3D Human dimensions, and shape. In addition, the alignment of the human-to-cover shape may not be correct or in good alignment. The impact of soft tissue displacement while wearing the Cover, compression covers, and any cover designed to shape and conceal body shape is included in the 3D Human dimensions. The 3D Human dimensions, and shape as impacted by the cover, is noted as "**ĦHn**". The 3D alignment of Human shape-to-cover shape is noted as "**§Hn**". This can be impacted at each Landmark as well. As shown in LS 42, *Human is described by the set of Human dimensions and shape as impacted by cover along with 3D Alignment of human shape to cover shape when Cover is worn by that Human* and shown in LS 43, *Unknown Human is described by the set of Unknown Human dimensions and shape as impacted by cover along with Alignment of Unknown Human shape to cover shape when Cover is worn by that Human.* Landmark impact is shown in LS 44, *Unknown Human is described by the set of 3D Unknown Human dimensions and shape as impacted by cover along with 3D Alignment of Unknown Human shape to cover shape at each Landmark when Cover is worn by that Human.*

$$\mathbf{Hn} \equiv \{\mathbf{ĦHn}, \mathbf{§Hn}\} \text{ when } \mathbf{Cr} \text{ ① } \mathbf{Hn} \qquad \text{(LS 42)}$$

$$\mathbf{Hn}_n \equiv \{\mathbf{ĦHn}_n, \mathbf{§Hn}_n\} \text{ when } \mathbf{Cr} \text{ ① } \mathbf{Hn}_n \qquad \text{(LS 43)}$$

$$\mathbf{Hn}_{n,\mathbf{LM}n} \equiv \{\mathbf{ĦHn}_n, \mathbf{§Hn}_n\}_{\mathbf{LM}n} \text{ when } \mathbf{Cr} \text{ ① } \mathbf{Hn}_n \qquad \text{(LS 44)}$$

4D, the element of time

The element of time can be added to the logic statements. Since the output of the Fit can change over time, Fit is considered a function of time. Time can be considered in two different ways – continuous time (i.e., wearing a cover all day) and noted as " ʘt" or as static or fixed time "t". An example of fixed time includes 3D body scan at a given scan date and time stamp. Time at a fixed time introduces the aspect of body pose for assistance in Landmark determination and measurement. ʘt can be specified for a duration, from t_0 to $t_{specified}$.

4D, the element of time, Virtual Hd ⟹ Cd, Cd ⟹ Hd

Time can be applied to an avatar that is Rigged. In the virtual world, this is the animation of an avatar that is a known Humanoid. The interoperability of Rigging from various design software is an open issue and will not be addressed. Since the Coveroid is modeled as a 2D skin element, the Ease is noted in 2D. Rigging Fit adds in material physics (material stretch) and the effect of underneath covers, to closer reflect the physical world, requiring Ease to be modelled with its components. As shown in LS 45, *Rigging Fit is defined as known Humanoid and known Ease as a function of time for all Rigging Landmarks* and as shown in LS 46, *Rigging Fit is defined as known Humanoid and known Ease at a fixed (or known) time for all Rigging Landmarks*

$$\mathcal{F}_{R,\mathcal{LM}R}(ʘt) \equiv \mathcal{H}d_{0,\mathcal{LM}R}(ʘt) \,\&\, E_{0,\mathcal{LM}R}(ʘt) \qquad \text{(LS 45)}$$

$$\mathcal{F}_{R,\mathcal{LM}R}(t) \equiv \mathcal{H}d_{0,\mathcal{LM}R}(t) \,\&\, E_{0,\mathcal{LM}R}(t) \qquad \text{(LS 46)}$$

These logic statements can be used as tools for decision making as the parameters can be adjusted for product modelling. Since the Humanoid is known and Ease is known, this may be considered the 3D Planned Fit as shown in LS 47, *Planned Fit is described by Rigging Fit is defined as known Humanoid and known Ease at a fixed (or known) time for all Rigging Landmarks.*

$$\mathcal{F}_p \equiv \mathcal{F}_{R,\mathcal{LM}R}(t) \equiv \mathcal{H}d_{0,\mathcal{LM}R}(t) \,\&\, E_{0,\mathcal{LM}R}(t) \qquad \text{(LS 47)}$$

4D, the element of time, Physical Hn ⟹Cr, Cr ⟹ Hn, Hn ⟹ Hd

In the physical world, comfort is an issue for people as they breathe and move while wearing Covers. The environment can also impact a Human for example, the thermal impact of wearing the cover. Body shape changes over time as people age. These are not addressed in this paper.

It is well known that Fit of any Cover will be impacted by the material of the Cover, (noted as **ms** (ʘt)$_{0,LM_n}$), the age of Cover (as such as material wear and fatigue), stretch properties changing, the impact of care or washing, (noted as **ms**(ʘt)$_{W\ LM_n}$), and the amount of clothes underneath the Cover, (indicated as **c**(ʘt)$_{n,LM_n}$). In addition, the 3D Human shape can be impacted by the Cover along with the alignment of the Human with the Cover and the Designed-in Ease of the Cover being affected based on logic statements LS 40 and LS 43. This is the last logic statement of the paper, as shown in LS 48, *Unknown Fit for a person as a function of time is described as the set of Unknown Human dimensions and shape as impacted by cover along with Alignment of Unknown Human shape to cover shape & known Ease with manufacturing tolerance and known material stretch and unknown material wear and thickness of underneath covers at each Landmark when Cover is worn as a function of time by that Human.*

F(ʘt)$_{n,LM_n}$ ≡ {Ħ**Hn**$_n$, §**Hn**$_n$}(ʘt)$_{LM_n}$ ($\mathcal{Hd}_0$ & E$_0$(ʘt)$_{,LM_0}$ ± **t** & (**ms**(ʘt)$_{0,LM_n}$ & **ms**(ʘt)$_{W,LM_n}$) & **c**(ʘt)$_{n,LM_n}$ when **Cr** ① **Hn**$_n$(ʘt) (LS 48)

3. Conclusion

Logic statements were developed in this study to conceptualize the clothing fit attributes in detail. This work bridges the knowledge between creatives and techies; therefore, it is helpful to apply these expressions in developing the relevant software tool development to make Made-to-Measure or mass customization possible. The work also explores the physical world of Humans and Covers, their interrelationship, the wearer's preference and how the virtual world differs, but generally, aligns with the physical world.

Future work should include better virtual modeling of Fit such that material stretch, physics of gravity and the overlap of materials reflecting the method of fabrication including the manufacturing tolerances are modeled. The virtual modeling should have Fit aligned with the landmarks of the Humanoid and Coveroid while including the element of time.

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