Reduction of Complexity through the Use of Geometric Functional Periodicity

Reference:

Chapter 7 of

Nam P. Suh, *Complexity: Theory and Applications*, Oxford University Press, 2005

Definition of Complexity

Complexity is defined as a measure of uncertainty in satisfying the FRs.

According to this definition,

complexity is a *relative* quantity.

Four Different Kinds of Complexity

- **Time-Independent *Real* Complexity**
- **Time-Independent *Imaginary* Complexity**

- **Time-Dependent *Combinatorial* Complexity**
- **Time-Dependent *Periodic* Complexity**

“Complexity” can be reduced by taking the following actions:

- Reduce Time-Independent Real Complexity
- Eliminate Time-Independent Imaginary Complexity
- Transform Time-Dependent Combinatorial Complexity into Time-Dependent Periodic Complexity

Important concept: Functional Periodicity

Functional Periodicity

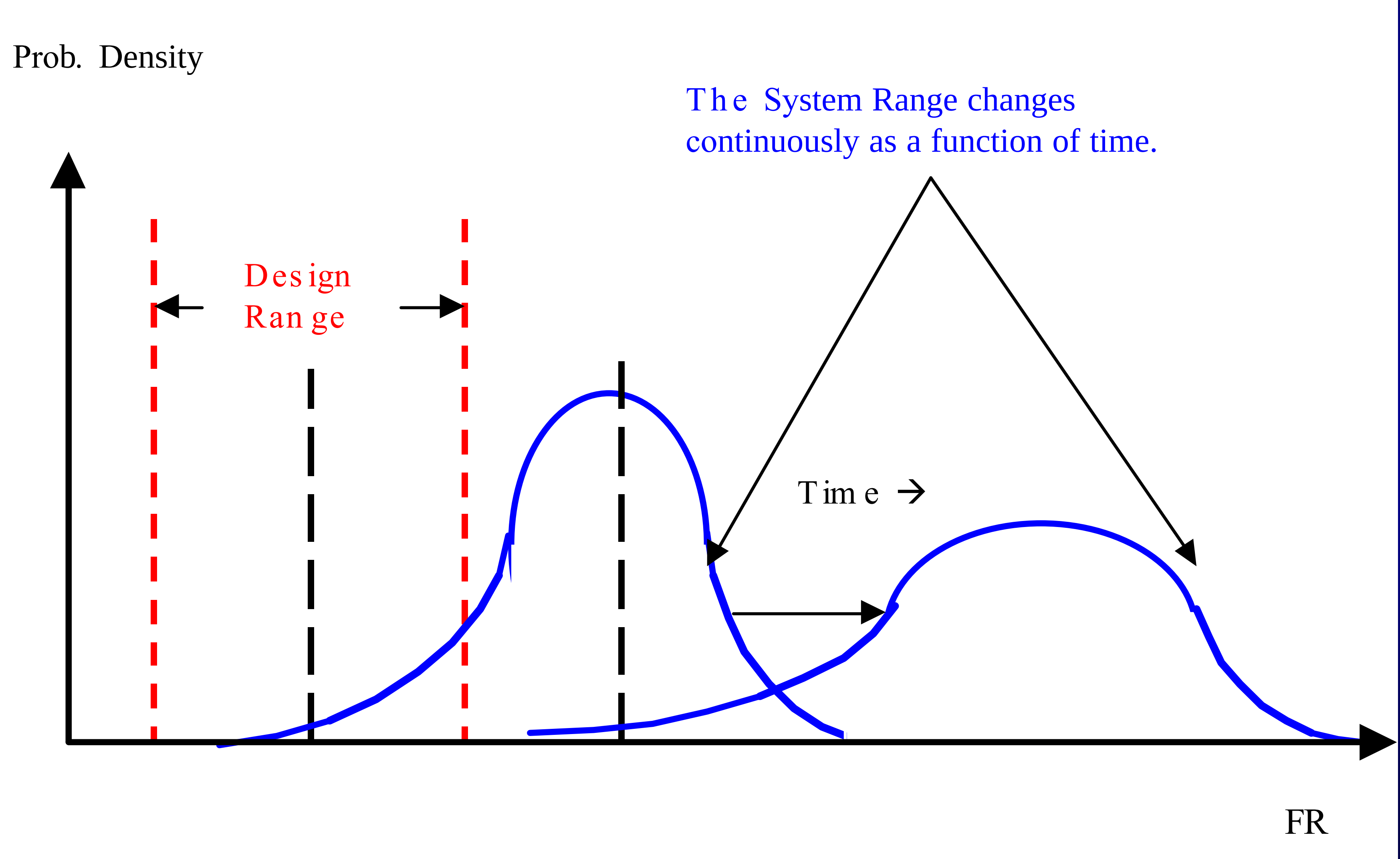
- Temporal periodicity
- Geometric periodicity
- Biological periodicity
- Manufacturing process periodicity
- Chemical periodicity
- Thermal periodicity
- Information process periodicity
- Electrical periodicity
- Circadian periodicity
- Material periodicity

Time-Dependent Combinatorial Complexity

Time-dependent combinatorial complexity arises because the future events occur in unpredictable ways and thus cannot be predicted.

For example, it occurs when the system range moves away from the design range as a function of time.

Time-Dependent Combinatorial Complexity



"Complexity" can be reduced by taking the following actions:

- **Reduce Time-Independent Real Complexity**
- **Eliminate Time-Independent Imaginary Complexity**
- **Transform Time-Dependent Combinatorial Complexity into Time-Dependent Periodic Complexity**

Reduction of Combinatorial Complexity

How?

Through
“*Re-initialization*” of the system
by defining
a “*Functional Period*”.

Note: Functional period is defined by a repeating set of functions, not by time period, unless “time” is a set of functions.

Transformation of Time-Dependent Combinatorial Complexity

- **Basic Idea**
  1. Make sure that the design satisfies the Independence Axiom.
  2. Identify a set of FRs that undergoes a cyclic change and has a functional period.
  3. Identify the functional requirement that may undergo a combinatorial process
  4. $$T\langle C_{com}(FR_i)\rangle \Rightarrow \langle C_{per}(FR_i)\rangle$$
  6. "Reinitialization"
  5. Set the beginning of the cycle as t=0

Functional Periodicity

- The functional periodicity are the following types:

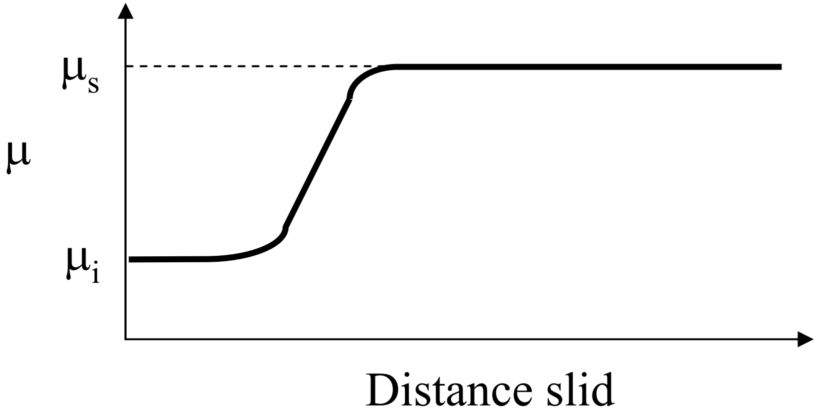
(1) Temporal periodicity
(2) Geometric periodicity
(3) Biological periodicity
(4) Manufacturing process periodicity
(5) Chemical periodicity
(6) Thermal periodicity
(7) Information process periodicity
(8) Electrical periodicity
(9) Circadian periodicity
(10) Material periodicity

Example: Design of Low Friction Sliding Surfaces

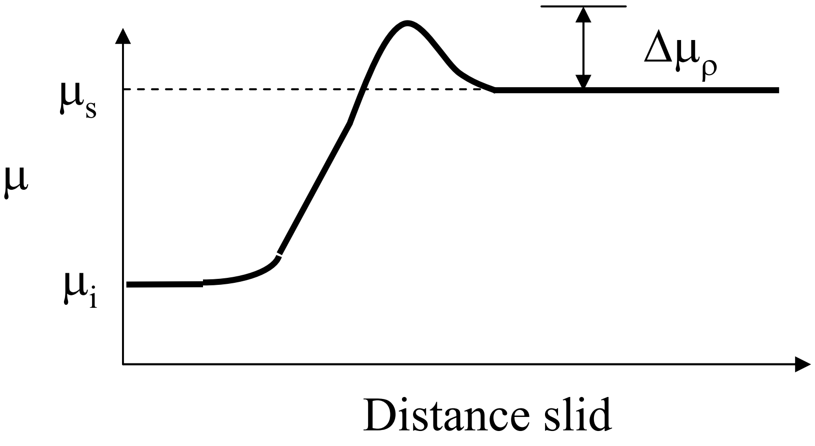
Consider the following task:

Reduce friction between two sliding surfaces under load

Coefficient of friction versus sliding distance

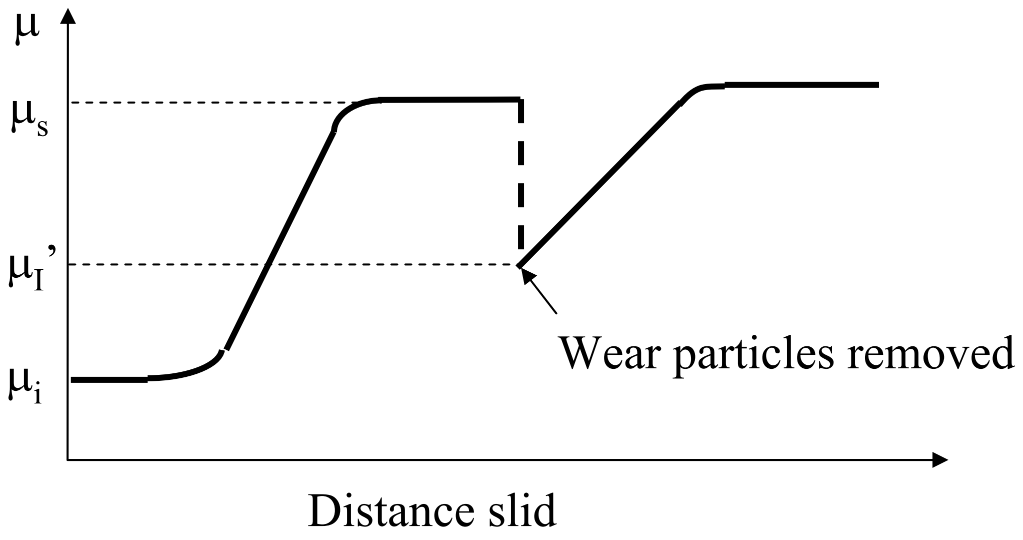


(a)



(b)

Effect of removing wear particles for an Armco iron slider sliding against an Armco iron specimen



Friction Space

Friction at Dry Sliding Interface
Plowing Mechanism

Friction at Dry Sliding Interface
Particle Agglomeration

Why do particles agglomerate?

Friction at Dry Sliding Interface
Height of Agglomerated Particles

Friction at Dry Sliding Interface
Friction Coefficient and the Number of Agglomerated Particles

Friction at Dry Sliding Interface
Reduction of Friction by Elimination of Particles

Design of Low Friction Sliding Surfaces without Lubricants

- What are the FRs?

- What are the constraints?

Design of Low Friction Sliding Surfaces without Lubricants

FR_1 = Support the normal load

FR_2 = Prevent particle generation

FR_3 = Prevent particle agglomeration

FR_4 = Remove wear particles from the interface

- Constraint: No lubricant

Design of Low Friction Sliding Surfaces without Lubricants

Figures removed for copyright reasons.
See Figure 7.11 and 7.13 in [Complexity]:
Suh, N. P. *Complexity: Theory and Applications*. New York, NY: Oxford University Press, 2005. ISBN: 0195178769.

DP_1 = Total contact area of the pad, A

DP_2 = Roughness of the planar surface of pads, R

DP_3 = Length of the pad in the sliding direction, λ

DP_4 = Volume and depth of the pocket for wear particles, V

Design of Low Friction Sliding Surfaces without Lubricants

The design equation:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & x & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & x & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} A \\ R \\ \lambda \\ V \end{Bmatrix}$$

Design of Low Friction Sliding Surfaces without Lubricants

Test Results:

Friction at Dry Sliding Interface
Undulated Surface for Elimination of Particles

Friction at Lubricated Interface

Effect of Boundary Lubrication

$\sim \mu \sim 0.1$

- Cause?
  - Plowing

- What is the role of a lubricant?
  - Lower shear stress
  - Transport particles
  - Prevent particle agglomeration
  - Prevent adhesion

Geometric Functional Periodicity to Decrease Face Seal Wear

Figures removed for copyright reasons.
See Figure 7.16 through 7.21 in [Complexity].

FRs of Face Seal

- ***FRs***

FR1 = Support the normal load

FR2 = Prevent particle migration across the seal

FR3 = Prevent agglomeration of particles in the seal/metal interface

FR4 = Provide lubricant to the interface

FR5 = Prevent the flow of the lubricant out of the sealed area

FR6 = Delay the initiation of the wear process

DPs of Face Seal

- *DPs*

  DP1 = Total Area of the pad, A

  DP2 = Seal lip

  DP3 = Diameter of the pad, λ

  DP4 = Lubricant

  DP5 = Length of the sealed tip, L

  DP6 = Seal material

Design Matrix for Face Seal Wear

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & X \\ 0 & X & 0 & 0 & 0 & x \\ 0 & 0 & X & 0 & 0 & x \\ 0 & 0 & 0 & X & 0 & 0 \\ 0 & x & 0 & 0 & X & x \\ 0 & 0 & x & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \end{Bmatrix}$$

Reduction of Wear of Pin-Joints By the Introduction of Geometric Functional Periodicity

Drive sprockets, idlers, rollers, Grouser shoes

FRs and DPs of Conventional Pin-Joints

- ***FRs***

FR1 = Carry the load

FR2 = Allow rotational motion about the axis of the bushing

FR3 = Minimize friction force

FR4 = Minimize wear

- ***DPs***

DP1 = Shaft/bushing dimensions

DP2 = Clearance between the shaft and the bushing

DP3 = Clearance between the shaft and the bushing

DP4 = Material properties

Friction in Geometrically Confined Space

FRs and DPs of Pin-Joints with Geometric Functional Periodicity

- ***FRs***

FR1 = Carry the load

FR2 = Allow rotational motion about the axis of the bushing

FR3 = Minimize friction force

FR4 = Minimize wear

- ***DPs***

DP1 = Dimensions of the pin and the bushing structure

DP2 = Cylindrical pin/bushing joint

DP3 = Low-friction system

DP4 = Wear-minimization system

FRs and DPs of Pin-Joints with Geometric Functional Periodicity

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \end{Bmatrix} = \begin{bmatrix} X000 \\ 0Xxx \\ 00Xx \\ 000X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \end{Bmatrix}$$

Decomposition of FR3 and DP3 of Pin-Joints with Geometric Functional Periodicity

- ***FR3s***

FR31 = Remove Wear Particles from the interface

FR32 = Apply lubricant

- ***DP3s***

DP31 = Particle removal mechanism

DP32 = Externally supplied grease

FRs and DPs of Pin-Joints with Geometric Functional Periodicity

$$\begin{Bmatrix} FR31 \\ FR32 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ x & X \end{bmatrix} \begin{Bmatrix} DP31 \\ DP32 \end{Bmatrix}$$

Decomposition of FR3 and DP3 of Pin-Joints with Geometric Functional Periodicity

- *FR31s (Remove wear particles from the interface)*

FR311 = Prevent particle agglomeration

FR312 = Do not allow the increase in the normal force due to the presence of particles at the interface

FR313 = Trap wear particles

- *DP31s (Particle removal mechanism)*

DP311 = The length of the pad on the liner that actually comes in contact with the pin

DP312 = Flexible ring

DP313 = The indented part of the undulated surface

Decomposition of FR3 and DP3 of Pin-Joints with Geometric Functional Periodicity

Figure removed for copyright reasons.
See Figure 7.22 in [Complexity].

FRs and DPs of Pin-Joints with Geometric Functional Periodicity

$$\begin{Bmatrix} FR\,311 \\ FR\,312 \\ FR\,313 \end{Bmatrix} = \begin{bmatrix} X\,00 \\ xX\,0 \\ 00\,X \end{bmatrix} \begin{Bmatrix} DP\,311 \\ DP\,312 \\ DP\,313 \end{Bmatrix}$$

Decomposition of FR3 and DP3 of Pin-Joints with Geometric Functional Periodicity

- *FR4s (Minimize wear)*

FR41 = Prevent particle penetration into both surfaces

FR42 = Minimize the shear deformation of the pin and the flexible liner

- *DP4s (Wear-minimization system)*

DP41 = Hardness ration of the two materials

DP42 = Coating of the pin with a thin layer of low shear strength material

FRs and DPs of Pin-Joints with Geometric Functional Periodicity

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR311 \\ FR312 \\ FR313 \\ FR32 \\ FR41 \\ FR42 \end{Bmatrix} = \begin{bmatrix} X\,0000000 \\ 0\,XxxxX\;\,00 \\ 00\,X\,00000 \\ 00\,xX\,0000 \\ 0000\;\,X\,000 \\ 0000\;\,xX\,00 \\ 000000\;\,X\,0 \\ 00000\;\,X\,0\,X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP311 \\ DP312 \\ DP313 \\ DP32 \\ DP41 \\ DP42 \end{Bmatrix}$$

Pin-Joint Design

Figures removed for copyright reasons.
See Figure 7.25 and 7.26 in [Complexity].

Geometric Functional Periodicity for Electrical Connectors

Electrical Connectors

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See Figure 7.29 in [Complexity].

Conventional Electrical Connectors

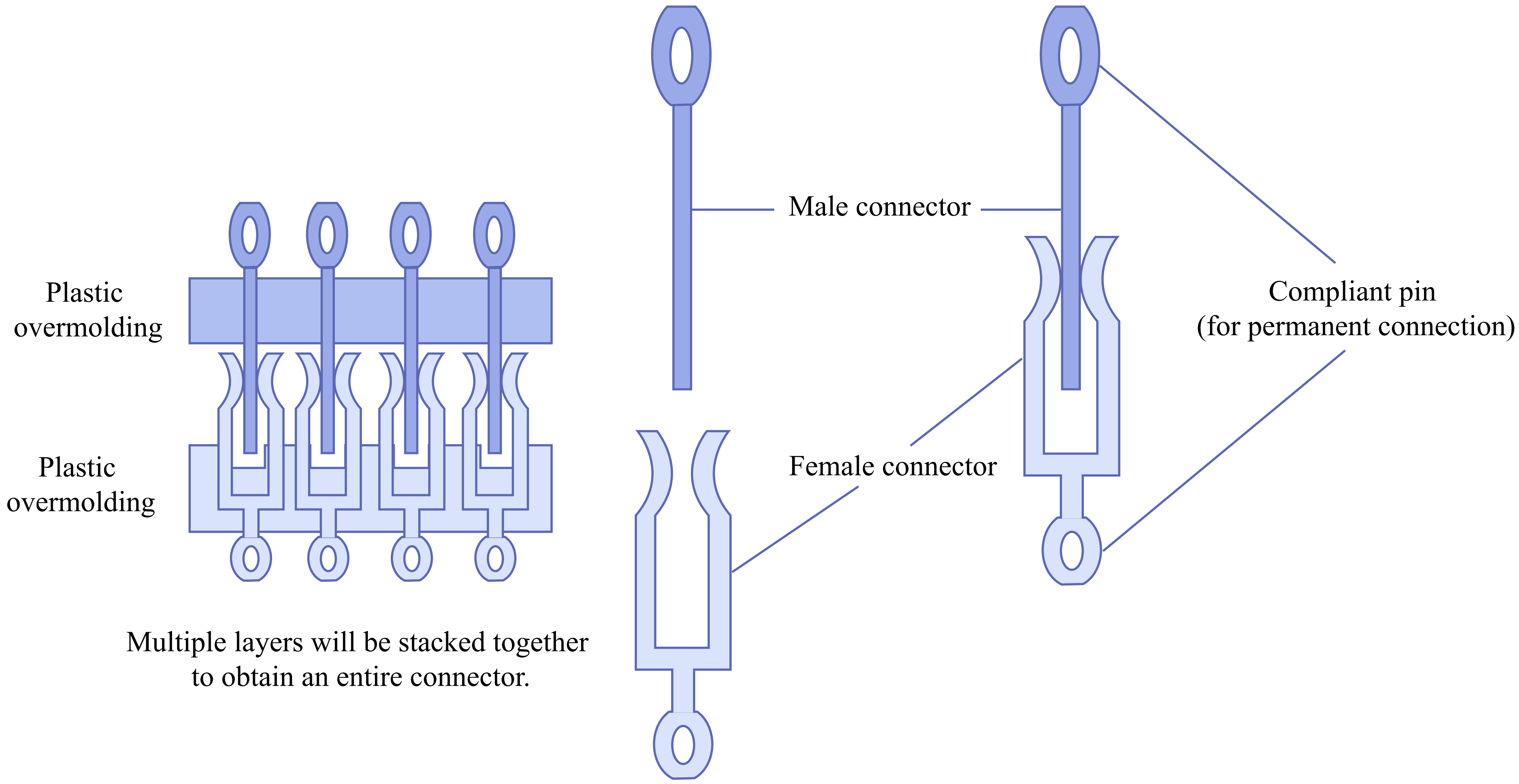


Figure by MIT OCW.

FRs of a Data Electrical Connector

FR1 = Mechanically connect and disconnect electrical terminals

FR2 = Control contact resistance (should be less than 20mΩ)

FR3 = Prevent the cross-talk (i.e., interference) between the connections

Subject to the following constraints (Cs):

C1 = Low cost

C2 = Ease of use

C3 = Long life (> million cycles)

C4 = Maximum temperature rise of 30 ^{o}C

C5 = Low insertion force

FRs of a Power Electrical Connector

FR1 = Mechanically connect and disconnect electrical terminals

FR2 = Control contact resistance (should be less than 20mΩ)

FR3 = Maximize power density

Subject to the following constraints (Cs):

C1 = Low cost

C2 = Ease of use

C3 = Long life (> million cycles)

C4 = Maximum temperature rise of 30 ^{o}C

C5 = Low insertion force

DPs of a Data Electrical Connector

DP1 = Cylindrical assembly of the woven tube and the pin

DP2 = Locally compliant electric contact

DP3 = Number of conducting wires

Decomposition of FR1 (Mechanically connect and disconnect electrical terminals) and DP1 (Cylindrical assembly of the woven tube and the pin)

FR11 = Align the rod axially inside the tube

FR12 = Locate the axial position of the rod in the tube

FR13 = Guide the pin

DP11 = Long aspect ratio of the rod and the tube

DP12 = Snap fit

DP13 = Tapered tip of the pin

Decomposition of FR2 (Control contact resistance to be less than 20mΩ) and DP2 (Locally compliant electric contact)

FR21 = Prevent oxidation of the conductor

FR22 = Remove wear particles

FR23 = Control line tension/deflection of the non-conducting fiber

DP21 = Gold plated metal surface

DP22 = Space created in the crevices between fibers

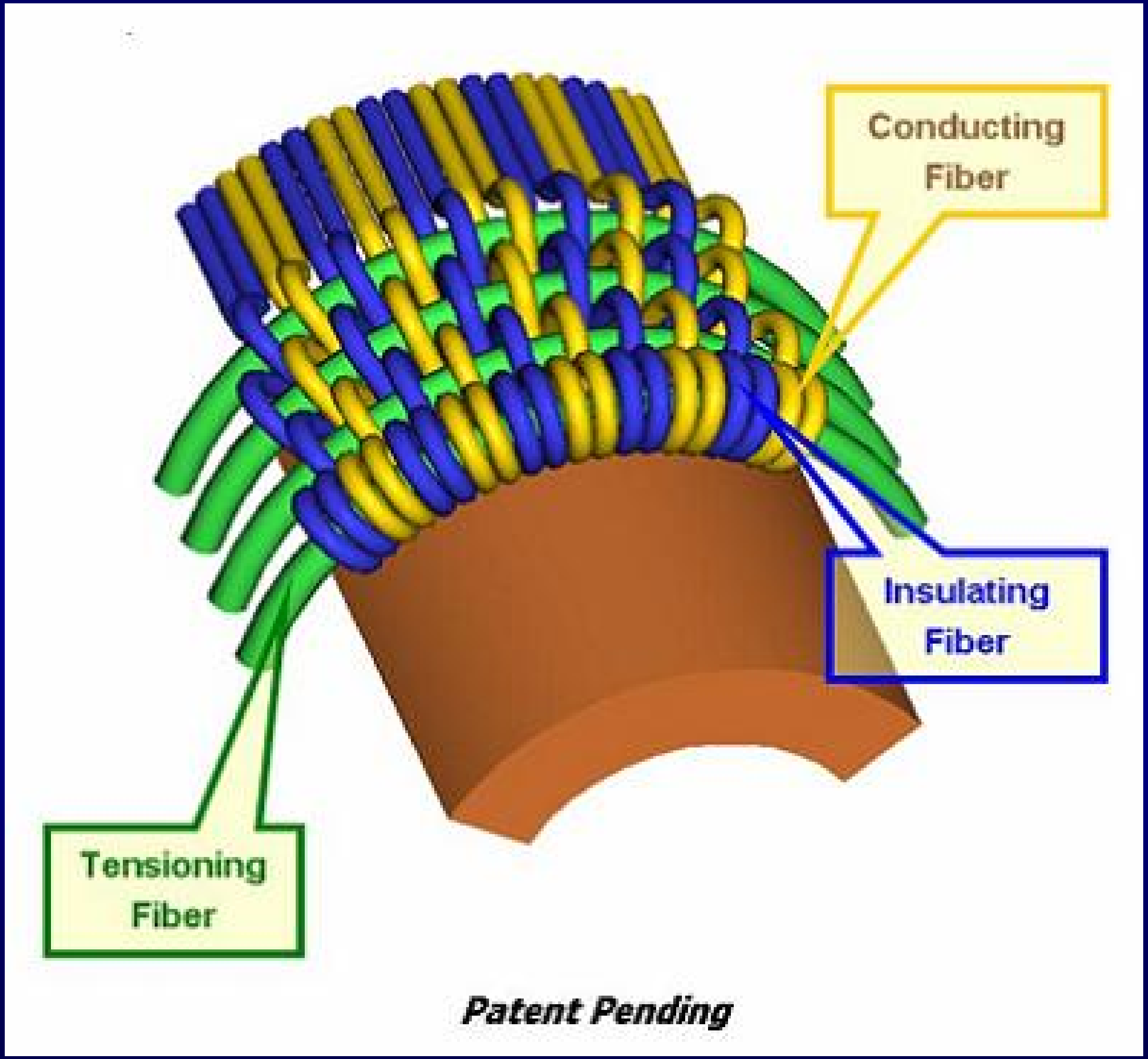
DP23 = Spring

Design Matrix

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X00 \\ XX0 \\ 0XX \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix}$$

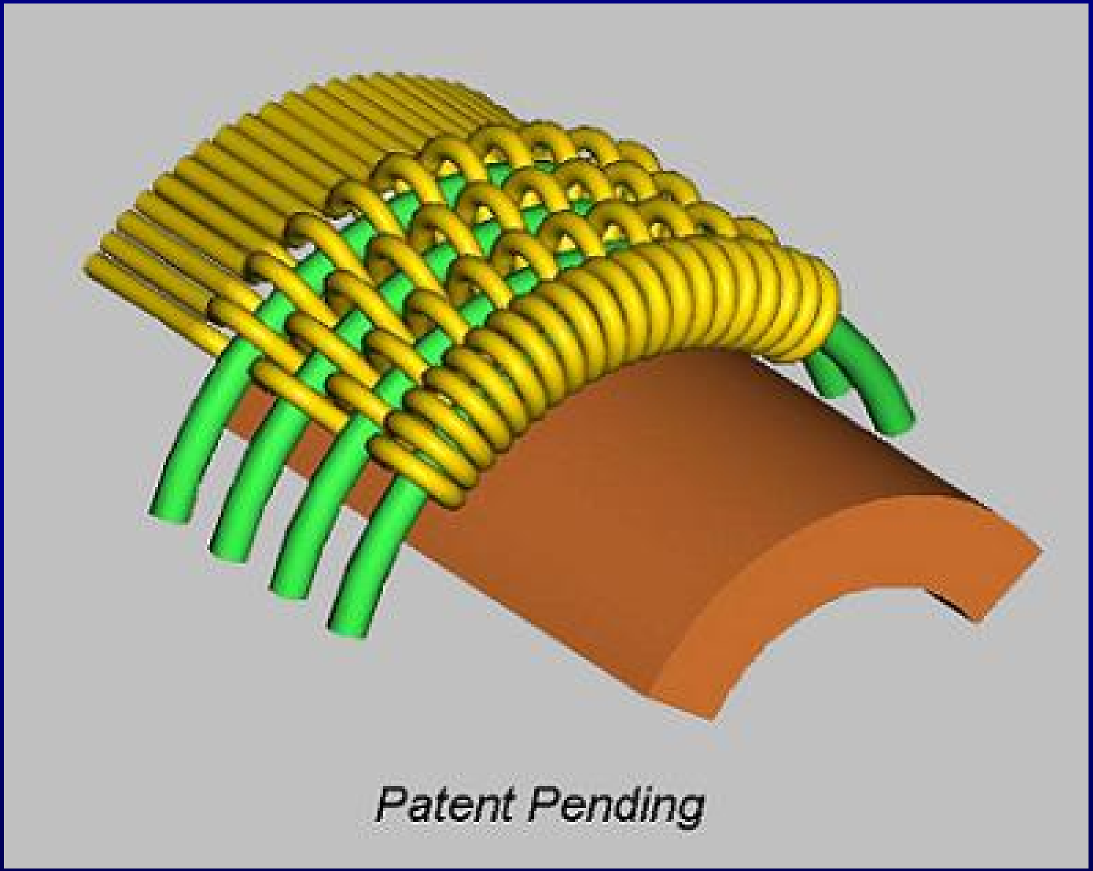
Tribotek Electrical Connectors

(Courtesy of Tribotek, Inc. Used with permission.)



Tribotek Electrical Connectors

(Courtesy of Tribotek, Inc. Used with permission.)



Performance of “Woven” Power Connectors

- Power density => 200% of conventional connectors
- Insertion force => less than 5% of conventional connectors
- Electric contact resistance = 5 m ohms
- Manufacturing cost -- Flexible manufacturing
- Capital Investment

Tribotek, Inc.

Busbar Application Embedded Configuration

- **Features…**
  - ***LowR 125* socket**
  - **Press-Fit into busbar**
  - **130 A**
- **Benefits…**
  - **Highest current density**
  - **Low insertion force**
  - **Low contact resistance, min voltage drop**
  - **Available in various contact sizes**

Figures removed for copyright reasons.

Tribotek, Inc.

Busbar Application - Mounted Configuration

Figures removed for copyright reasons.

- **Features…**
  - ***LowR 125* socket**
  - **Press-Fit onto busbar**
  - **130 A**
- **Benefits…**
  - **Highest current density**
  - **Low insertion force**
  - **Low contact resistance, min voltage drop**
  - **Available in various contact sizes**