Automated Concept Generation Based On Function-Form Synthesis

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PRESENTATION OVERVIEW

Research Motivation
- Challenges for generating design concepts

Related Research
- Engineering design methodologies relating to concept generation

Methodology
- Creating a database of products
- Identifying candidate source products with functional similarities
- Creating tangible design concepts
  - Combine source product forms
  - Combine source product functions

Application
- Generating a design concept for a hybrid marine model

Conclusion
Research motivation
Design factors in product design


**Demand** = \( f(\text{product}, \text{price}, \text{time}) \)

“Optimize Price while Maximizing Utility”
Design factors in product design

- **Lower product differentiation** → results in lower competitive edge

<table>
<thead>
<tr>
<th></th>
<th>a1</th>
<th>a2</th>
<th>a3</th>
<th>a4</th>
<th>...</th>
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</thead>
<tbody>
<tr>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

*Shaked and Sutton, 1982*

- **Higher product differentiation** → may increase a company’s competitive edge

<table>
<thead>
<tr>
<th></th>
<th>a1</th>
<th>a2</th>
<th>a3</th>
<th>a4</th>
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<td>✓</td>
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<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

*Shooter and Simpson, 2006*
Research Questions

How can designers explore potentially relevant attributes from large scale data in timely efficient manner?
### Hypothesis

The research hypothesis is established as follows:

\[ \Delta(Y) = R - S \]

\[ \Delta(X) = R - C \]

\[ \Delta(X) < \Delta(Y) \]
Related Research
<table>
<thead>
<tr>
<th>Models</th>
<th>Definitions</th>
<th>Limitations</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Domain Predictive Morphing</td>
<td>Generate design concepts by partially changing current products</td>
<td>Design fixation occurs</td>
<td>[12-21]</td>
</tr>
<tr>
<td>Design by Analogy</td>
<td>Discover novel design concepts by exploring analogy across designers’ knowledge/ product descriptions for reducing design fixation</td>
<td>Require experts knowledge to discover concepts</td>
<td>[25-30]</td>
</tr>
<tr>
<td>Bio-Inspired Design</td>
<td>Discover novel design solutions by taking account into biological domains as design sources</td>
<td>Require deep understanding of Biological domains</td>
<td>[22,23], [31-33]</td>
</tr>
<tr>
<td>Functional Model</td>
<td>Generate functional structure based on design concepts from previous sections</td>
<td>Require to select candidate modules with designers’ functional knowledge</td>
<td>[34-46],</td>
</tr>
</tbody>
</table>
Knowledge Gap

Step 1: Identify customer needs
- Experts knowledge
- Search competitive products

Step 2: Gathering ideas
- Generate initial design concepts
  - Sketch forms
  - Describe general functions

Step 3: Detail design
- Functional modelling
  - Design structure matrix

Step 4: Prototypes
  - Mockups

Step 5: Hsiao and Chou, 2004

Related research
Methodology
The initial step of product design

Designers describe requirements in texts
Overall process of the proposed methodology

**Step 1. Collect product data to create database of products**
- Acquire functional description (text)
- Acquire 3D form of product (3D mesh)

**Step 2. Search products that satisfy the design requirements**
- Identify the product $i$ that satisfies most of the requirements in terms of function
- Identify the product $i'$ that satisfies the rest of requirements in terms of function

**Step 3. Create distinctive design concepts from the source products**
- Integrate functions of the products and reduce common functions from product $i'$
- Integrate 3D forms of the products by morphing each source product

http://www.engr.psu.edu/datalab/
Collect product data to create database of products

**Function:**
representing the objective of a design artifact.

**Form:**
representing the geometric surface of a design artifact.

<table>
<thead>
<tr>
<th>ID</th>
<th>Product Name</th>
<th>Form data (3D mesh)</th>
<th>Function data (text)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Camera</td>
<td>![Camera Image]</td>
<td>Live view shooting, Zoom, White balance, Focus</td>
</tr>
<tr>
<td>2</td>
<td>Cell phone</td>
<td>![Cell Phone Image]</td>
<td>Voice communication, GPS navigator</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>n</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Overall process of the proposed methodology

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Identify the Product $i$ that satisfies most of the requirements in terms of function

Collecting descriptions

A functional description

A database containing functions of product

<table>
<thead>
<tr>
<th>ID ($i$)</th>
<th>Product</th>
<th>Description ($d_i$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Camera</td>
<td>Encodes digital image and... store... memory...</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>n</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Identify the Product $i$ that satisfies most of the requirements in terms of function

Product ($i=1$) | Description ($d_{i=1}$)
---|---
Camera | Encodes digital image and... store...

<table>
<thead>
<tr>
<th>$t_{1,1} = \text{image}$</th>
<th>$t_{1,2} = \text{encode}$</th>
<th>...</th>
<th>$t_{1,F}$ = ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(t_{i,f}</td>
<td>d_i) = 0.16299$</td>
<td>$P(t_{i,f}</td>
<td>d_i) = 0.10111$</td>
</tr>
</tbody>
</table>

\[ P(t_{i,f} | d_i) = \sum_{f=1}^{F} P(t_{i,f} | q_f) P(q_f | d_i) \]  

(1)

where,

$t_{i,f}$: the functions that can found in a textual description of product ($i$)

$d_i$: the textual description of product ($i$)

$q_f$: $f^{th}$ function (paragraph) in the textual description of product ($i$)

$F$: the maximum number of functions of product ($i$)
Identify the Product $i$ that satisfies most of the requirements in terms of function $t_r$:

$$\text{Sim}(t_r, t_{i,f}) = \frac{t_r \cap t_{i,f}}{t_r \cup t_{i,f}}$$ (2)

$t_{i,f}$: the functions that can be found in a textual description of product $(i)$
$t_r$: the terms that can be found in designers’ requirements.
Overall process of the proposed methodology

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Identify the Product $i'$ that satisfies most of the requirements in terms of function

$$t_{r'} = t_r \cap (t_r \cap t_{i',f})^c \quad (3)$$

$t_r'$: the rest of terms that can be found in the requirements.

$$\text{Sim}(t_{r'}, t_{i',f}) = \frac{t_{r'} \cap t_{i',f}}{t_{r'} \cup t_{i',f}} \quad (4)$$

$t_{i',f}$: the functions that can be found in a textual description of product ($i'$)
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http://www.engr.psu.edu/datalab/
Integrate functions of the products and reduce common functions from product $i'$

$$F(T_I) = t_I \cup t_{i,f'}$$  \hspace{1cm} (5)

where,

$$F(t_I) = (t_{i,f} \cup t_{i',f}) \cap (t_{i,f'} \cup t_{i',f'})^c$$ \hspace{1cm} (6)

$T_I$ the integrated *functional* terms from each product $t_i$: the *functional* terms having no common *functional* terms between each product

subject to,

$$t_{i,f'} \subseteq t_{i,f}$$  \hspace{1cm} (7)

$$t_{i,f'} \subseteq t_{i,f} \cap t_{i',f}$$  \hspace{1cm} (8)

$$t_{i',f'} \subseteq t_{i',f}$$  \hspace{1cm} (9)

$$t_{i,f'} \subseteq t_{i,f} \cap t_{i',f}$$  \hspace{1cm} (10)
Overall process of the proposed methodology

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Integrate 3D forms of the products by morphing each source product. Generate Reeb graph for each source and target 3D model [44].

Similarity ratio = the number of matched points in the level sets / the number of larger data sets.
Integrate 3D forms of the products by morphing each source product

Generate an intermediate model

Source model  Intermediate model  Target model
Case Study
Design Scenario

Designers want to explore additional domains to search novel design concepts that can lead to the development of novel differentiated products in the marine domain.
Design Scenario

*Designers have described the functional requirements for novel product domains*

- It will be a vehicle
- It will operate over water
- It will not be influenced by waves
- It will operate over land
- It will move with stability
- It will be able to use the ground effectively
- It will be able to fly
New Product Development
- data collection

Form:

Digital camera  Cell phone  Hovercraft  Motorcycle  Airplane

Function:
“A digital camera has a compressor and decompressor to provide for raw sensor data to be stored more compactly prior to image processing...”

“The cellular phone system according to the present invention separates one or more of such components...”
New Product Development
- Search candidate products

Functional probabilities (%) from each product corresponding to the requirements

<table>
<thead>
<tr>
<th>Product</th>
<th>Requirements (t_r)</th>
<th>vehicle</th>
<th>water</th>
<th>wave</th>
<th>land</th>
<th>stability</th>
<th>ground-effect</th>
<th>flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>requirements</td>
<td></td>
<td>0%</td>
<td>0%</td>
<td>1%</td>
<td>6%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0%</td>
<td>0%</td>
<td>2%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
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<td>0%</td>
<td>0%</td>
<td>1%</td>
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<td></td>
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<tr>
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<td>3%</td>
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<td>0%</td>
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<tr>
<td></td>
<td></td>
<td>0%</td>
<td>0%</td>
<td>9%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>4%</td>
</tr>
</tbody>
</table>
## New Product Development
- Search candidate products

### Functional similarity between the requirements and products

**Product (i)**

<table>
<thead>
<tr>
<th>Functional similarity</th>
<th>5% (1/14)</th>
<th>0% (0/25)</th>
<th>21% (5/22)</th>
<th>13% (3/19)</th>
<th>4% (3/67)</th>
</tr>
</thead>
<tbody>
<tr>
<td>vehicle</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>water</td>
<td></td>
<td></td>
<td>t\textsubscript{i},t\textsubscript{f} ✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>wave</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>land</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>stability</td>
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<tr>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>t\textsubscript{i'},t\textsubscript{f} ✓</td>
</tr>
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New Product Development
- Functional concept generation

Common functions between the products

Parent products overlapped functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Hovercraft</th>
<th>Airplane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>2%</td>
<td>7%</td>
</tr>
<tr>
<td>Propeller</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>Aerodynamics</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Maneuverability</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>Absorber</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>Cargo</td>
<td>1%</td>
<td>1%</td>
</tr>
</tbody>
</table>

The functional concepts for novel product domain = the hovercraft’s 22 functions + airplane’s 61 functions
New Product Development
- Form concept generation

Hovercraft

Design concept of the hybrid marine model

Morph

Airplane

Case study
New Product Development - verification

Form and function similarity between wig and models

<table>
<thead>
<tr>
<th>Form similarity (x)</th>
<th>Function similarity (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x = 61%</td>
<td>y = 30%</td>
</tr>
<tr>
<td>x = 17%</td>
<td>y = 23%</td>
</tr>
<tr>
<td>x = 47%</td>
<td>y = 9%</td>
</tr>
</tbody>
</table>
Conclusions
Summary

Differentiated design concepts are generated from source products by reducing their similarity during the combination process in terms of *form* and *function*.

The experiment of the methodology demonstrates the possibility of an automated concept generation process that combines different products that satisfy designers’ requirements.
Future work
Future work

Improving the generated concepts into detailed engineering specifications by employing function-behavior-structure (FBS) model

Analyzing the interaction between *form* and *function* by related domain expertise will provide sophisticated design concepts to designers
Q & A
References


