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DEFINING SIMILARITY BETWEEN DESIGN CONCEPT SKETCHES BASED ON PHYSICAL QUANTITY AND GEOMETRY

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Abstract

In this paper, we propose a definition of similarity among design concept sketches from the viewpoint of behavior and structure for case-based design aid, such as retrieval of sketches relevant to a designer's current design problem or extraction of sharable design knowledge by classifying accumulated sketches. First, we analyze design concept sketches and formalize geometry with physical quantities (e.g., an arrow with 'Pa' representing pressure application) as a 'behavior line'. Then we introduce an objective and quantitative definition of similarity among sketches based on physical quantities, geometries, projection, and geometric and causal relations. We implemented the proposed method as a computer program written in Common Lisp, and examine its efficacy and feasibility by applying the method to the retrieval and classification of some example sketches.

Keywords: Design information management, knowledge management, classification and retrieval, computer-aided design, case-based reasoning, behavior line.

1. Introduction

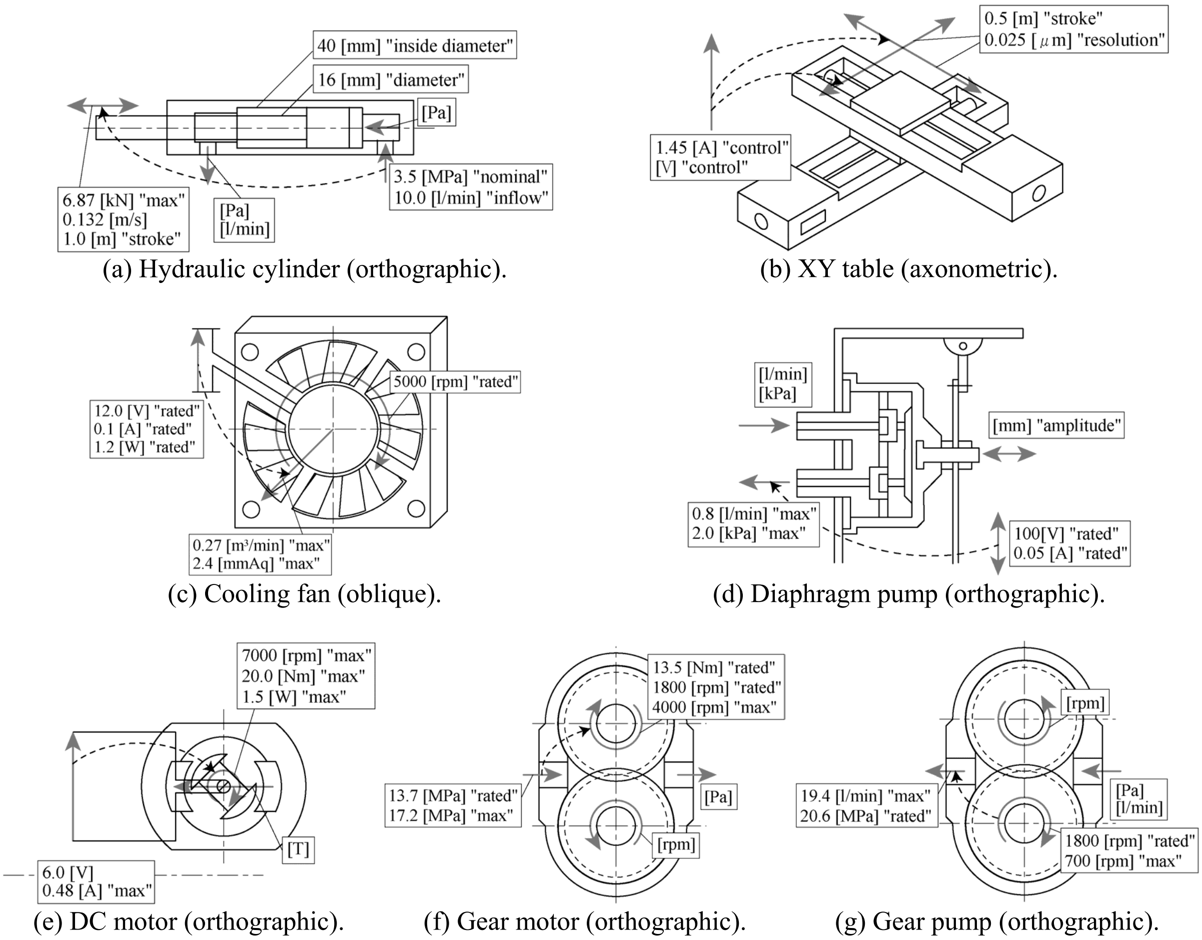
Defining similarity between design concept sketches according to their contents should enable designers to retrieve sketches or catalogues [1] relevant to their current design problems and obtain design information and knowledge, and to extract potential similarity from designs, which may lead to sharable design knowledge extraction or product modules standardization. To define similarity among engineering designs for physical phenomena, textual similarity in information retrieval in general and shape similarity [2] are not sufficiently descriptive. In studies on case-based design aid (e.g., [3]), design similarity was estimated by comparing named corresponding attributes (e.g., 'transmit-dead-load'). That approach is effective when we can expect exact attribute name correspondence within the same designer group, product family, domain and organization. Relevant design knowledge and information, however, may exist in different designer groups, products and domains. Therefore, a more general and objective similarity definition that covers a wider range of design cases across differences among designers, products, domains and organizations is necessary. We propose a general and objective definition of similarity among sketches based on physical quantities [4] and geometry, and examine its efficacy and practicability.

2. Design concept sketch

2.1 Definition of design concept sketch

We examine sketches like that in Figure 1, which are typically drawn in the conceptual design phase, with the following characteristics.

- A sketch is recorded as 2-D CAD data. Shapes are represented geometrically. Sketches may be drawn in different projections.
- Physical phenomena are represented geometrically as well as by physical quantities (for example, solid arrows in Figure 1).
- Geometric relations are represented by drawing geometries precisely or by indicating them with data when the sketch is roughly drawn.
- Causal relations between physical quantities should be specified (like dashed arrows in Figure 1). For example, sketches of a hydraulic gear pump and a hydraulic gear motor both represent physical quantities such as torque, rotation, pressure and flow. Without indicating the cause and the effect, the pump and the motor might not be distinguishable.



(a) Hydraulic cylinder (orthographic). (b) XY table (axonometric). (c) Cooling fan (oblique). (d) Diaphragm pump (orthographic). (e) DC motor (orthographic). (f) Gear motor (orthographic). (g) Gear pump (orthographic).

Figure 1. Examples of design concept sketches used in this research.

2.2 Representation of design concept sketch

In this research, we define a design concept sketch by a hierarchical data structure as follows:

- sketch (projection, size, drafting elements, geometric relations, causal relations),
- drafting element (element type, geometry, direction, physical quantities),
- physical quantity (magnitude, unit),
- geometric relation (relation type, drafting element 1, drafting element 2),
- causal relation (drafting element for cause, drafting element for effect).

Although text strings can be included and displayed as keywords for a sketch, a drafting element and a physical quantity, they are not used in similarity definition at present. In the following sections, we first describe our basic idea of similarity definition between physical quantities, and then define similarity between sketches in a parts-to-whole order.

3. Similarity between physical quantities

In this research, a physical quantity is represented not by a word such as "force" but by a magnitude and unit representation such as '0.3 m^3/s' and '100 VA'. This enables us to calculate similarity between physical quantities (i.e., physical phenomena) in a general and objective manner using quantity dimension space as described below [4].

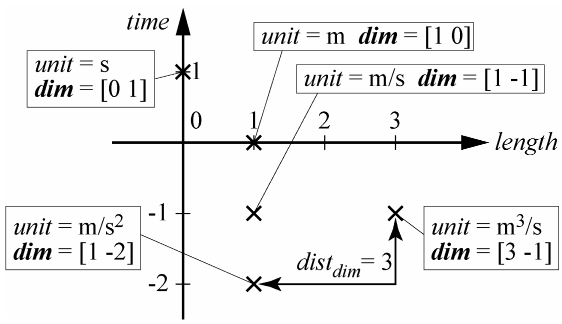
3.1 Unit dimension similarity

In SI units, all units are composed of the nine fundamental units 'm', 'kg', 's', 'A', 'K', 'mol', 'cd', 'rad' and 'sr'. These nine units can define orthogonal axes to define a mathematical space, which we call "quantity dimension space". A unit dimension of a quantity is a nine dimensional vector in this space:

$$\boldsymbol{dim} = [\, d_1 \;\; d_2 \;\; d_3 \;\; d_4 \;\; d_5 \;\; d_6 \;\; d_7 \;\; d_8 \;\; d_9 \,]$$
$$= [\, \textit{length} \;\; \textit{mass} \;\; \textit{time} \;\; \textit{electric-current} \;\; \textit{thermodynamic-temperature} \;\; \textit{amount-of-substance} \;\; \textit{luminous-intensity} \;\; \textit{plane-angle} \;\; \textit{solid-angle} \,]$$

For example, the unit 'N' for force is $mass^1 * length^1 * time^{-2}$ and thus $\boldsymbol{dim}$ = [1 1 -2 0 0 0 0 0 0]. Here, we define the similarity sim_{qdim} ($0 < sim_{qdim} <= 1$) between quantities q_i and q_j by their unit dimensions $\boldsymbol{dim}_i$ and $\boldsymbol{dim}_j$, based on city-block distance $dist_{dim}$ (Figure 2(a)), by equation (1). f_{ds} ($0 < f_{ds} <= 1$) is a function to map the distance or difference x ($0 <= x$) to a similarity. h and p are constants that determines the x required to make the similarity 1/2 and that represents the declination of the curve, respectively. c_{qdim} ($0 <= c_{qdim} <= 1$) is a function based on cos θ of the two vectors with some conditional arrangements, and the value is 0 when the two dimension vectors are orthogonal. Figure 2(b) shows examples of sim_{qdim} between some basic units.

$$dist_{dim}(\boldsymbol{dim}_i, \boldsymbol{dim}_j) = \sum_{k=1}^{9} | d_{ki} - d_{kj} |$$
$$sim_{qdim}(\boldsymbol{dim}_i, \boldsymbol{dim}_j) = f_{ds}\left(dist_{dim},\ 2,\ 1\right) \cdot c_{qdim}(\boldsymbol{dim}_i, \boldsymbol{dim}_j) \qquad (1)$$
$$f_{ds}\left(x, h, p\right) = 1 / \left(1 + \left(x / h\right)^p\right)$$



(a) Depicted two dimensionally for comprehensiveness.

	N	kg	s	m^3/s	m/s^2	m/s	m
m	0.23	0	0	0.38	0.5	0.67	1
m/s	0.43	0	0.28	0.5	0.67	1	
m/s^2	0.67	0	0.24	0.40	1		
m^3/s	0.27	0	0.20	1			
s	0.17	0	1				
kg	0.23	1					
N	1						

(b) Calculated unit dimension similarity.

Figure 2. Quantity dimension space and similarity.

3.2 Physical quantity similarity with magnitude

To compare magnitudes mag_i and mag_j of physical quantities q_i and q_j, we define magnitude similarity sim_{qmag} ($0 <= sim_{qmag} <= 1$) by equation (2). Then total similarity between physical quantities sim_q ($0<=sim_q<=1$) is defined as a weighted sum ($0<=w_q<=1$, presently $w_q=0.9$ is used) of dimension and magnitude similarities. Magnitude similarity is considered only when unit dimensions are equal. At present, we do not use 0 for magnitude.

$$sim_{qmag}(mag_i, mag_j) = f_{ds}\left(\left| \log_{10}|mag_i| - \log_{10}|mag_j| \right|,\ 0.5,\ 3\right)$$

$$sim_q(q_i, q_j) = \begin{cases} w_q \cdot sim_{qdim}(\boldsymbol{dim}_i, \boldsymbol{dim}_j) + (1-w_q)\cdot sim_{qmag}(mag_i, mag_j) & (sim_{qdim}=1) \\ w_q \cdot sim_{qdim}(\boldsymbol{dim}_i, \boldsymbol{dim}_j) & (sim_{qdim}<1) \end{cases} \tag{2}$$

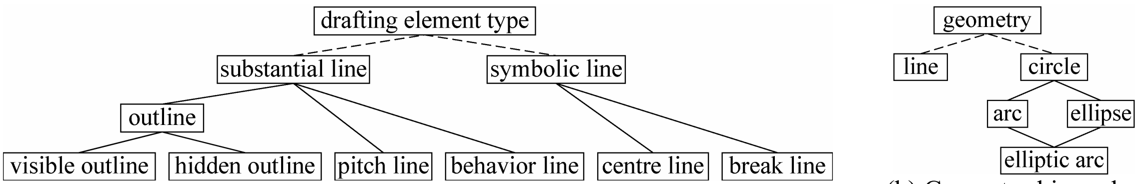
4. Similarity between drafting elements

Two drafting elements score high similarity when their element type, geometry, related physical quantities and direction are similar by the following definition.

4.1 Element type similarity

The element type is either 'outline' ('visible' and 'hidden'), 'centre line', 'pitch line', 'break line' or 'behavior line'. Here, 'behavior line' is not a conventional drawing standard but is introduced in this study to represent physical phenomena, such as applied force, in a sketch. We define element type similarity sim_{etyp} ($0<sim_{etyp}<=1$) between drafting elements a and b, using the distance $dist_{type}$ (number of arcs) between the element types in the conceptual class hierarchy (Figure 3(a)), by equation (3). sim_{etyp} is 1 when two drafting elements are of the same type.

$$sim_{etyp}(a, b) = f_{ds}\left(dist_{type},\ 1.5,\ 3\right) \tag{3}$$



(a) Drafting element type hierarchy.

(b) Geometry hierarchy.

Figure 3. Conceptual class hierarchies of type and geometry of drafting element.

4.2 Geometry similarity

The geometry is presently either a 'line', 'circle', 'ellipse', 'arc' or 'elliptic arc'. Although geometry similarity sim_{egeo} ($0<sim_{egeo}<=1$) is defined by equation (4) in the same manner as element type similarity, projection types are also considered here.

$$sim_{egeo}(a,b) = f_{ds}\left(dist_{geom},\ 1,\ 3\right) \tag{4}$$

Table 1. Projection type, axes parameters and geometric property preservation.

projection type	axes parameters	geometric property preservation			
		linearity	parallelism	perpendicularity	shape of figure
orthographic	two axes directions	yes	yes	yes	yes
axonometric	three axes directions	yes	yes	no	no
oblique	three axes directions and a depth ratio	yes	yes	yes (conditional)	yes (conditional)

For example, an ellipse in an axonometric sketch and a circle in an orthographic sketch should be matched ($dist_{geom}$=0) if the ellipse satisfies specific conditions. In this research, projection type and axes parameters of the sketch and the consequent geometric property preservation in Table 1 are considered with some tolerance when comparing geometries because the sketch may be drawn roughly.

4.3 Physical quantity similarity

When a drafting element represents physical phenomena, the relevant physical quantities are related to the drafting element (whose element type is behavior line). When physical quantity sets $\boldsymbol{Q}_A$ and $\boldsymbol{Q}_B$ are related to drafting elements a and b, respectively, we define physical quantity similarity sim_{eqty} ($0<sim_{eqty}<=1$) by equation (5) [4].

$$
\begin{aligned}
& q_{Ai} \in \boldsymbol{Q}_A \ (i = 1,2,\cdots,N_A) \quad q_{Bj} \in \boldsymbol{Q}_B \ (j = 1,2,\cdots,N_B) \\
& sim_{eqty}(a,b) = \frac{1}{N_A}\sum_{i=1}^{N_A} \max_{j=1,2,\cdots,N_B}\left(sim_q(q_{Ai},q_{Bj})\right)
\end{aligned}
\tag{5}
$$

4.4 Direction similarity

The direction of a drafting element is either 'no direction', 'one direction' or 'two directions', and is specified typically for a behavior line to represent, for example, a force direction or a motion range. We define direction similarity sim_{edir} between two drafting elements as 1 (the two values are the same), 0.5 (one is 'one direction' and the other is 'two directions'), and 0 (otherwise).

4.5 Drafting element similarity

Similarity between drafting elements is defined by combining individual similarities for each attribute above using equation (6). First, each similarity sim_x (x = '*etyp*', '*egeo*', '*eqty*' and '*edir*'), ranging in [0, 1] or (0, 1] depending on the definition, is transformed to a similarity sim'_x ranging in [l_x, 1] or (l_x, 1] by linear transformation. Then we define the total similarity sim_e ($0<=sim_e<=1$) between drafting elements a and b by multiplication. The influence of each sim'_x to the total sim_e is controlled by specifying smaller (more influence) or larger (less influence) values independently for l_{etyp}, l_{egeo}, l_{eqty}, and l_{edir}.

$$
\begin{aligned}
& sim'_x = l_x + (1 - l_x)\cdot sim_x \quad (0 \le l_x \le 1 : \text{lower limit value}) \\
& sim_e(a,b) = sim'_{etyp}(a,b)\cdot sim'_{egeo}(a,b)\cdot sim'_{eqty}(a,b)\cdot sim'_{edir}(a,b)
\end{aligned}
\tag{6}
$$

5. Similarity between sketches

A key sketch S_A representing a design with similar physical quantity causalities, geometry and size to a target sketch S_B scores high similarity by the definition presented below.

5.1 Drafting element set similarity

We define sketch similarity according to drafting elements by equation (7). Suppose two sketches S_A and S_B consist of drafting element sets $\boldsymbol{E}_A$ and $\boldsymbol{E}_B$, respectively. First, we extract all drafting elements related by physical quantities or geometric or causal relations from $\boldsymbol{E}_A$ as valid drafting elements $\boldsymbol{E}_{AV}$. Among valid drafting elements, important ones can be specified as principal drafting elements if necessary (as used in 5.6). Then we select the drafting element b'_k in $\boldsymbol{E}_B$ that corresponds to every valid drafting element a'_k in $\boldsymbol{E}_{AV}$. By multiplying $sim_e(a'_k, b'_k)$ directly for principal drafting elements and the weighted mean by the length for valid (but not principal) drafting elements, we define the similarity sim_{SE} ($0<=sim_{SE}<=1$) of $\boldsymbol{E}_A$ to $\boldsymbol{E}_B$. Since different correspondence of drafting elements between $\boldsymbol{E}_{AV}$ and $\boldsymbol{E}_B$ yields different sim_{SE}, we take the maximum value, as described in 5.5.

$$
\begin{aligned}
& a_i \in \boldsymbol{E}_A \ (i = 1,2,\cdots,N_A) \quad b_j \in \boldsymbol{E}_B \ (j = 1,2,\cdots,N_B) \\
& \boldsymbol{E}_{AQ} = \{a_i \mid \text{"physical quantities related to } a_i\text{"} \neq \phi\} \\
& \boldsymbol{E}_{AR} = \{a_i \mid \exists a_h \in \boldsymbol{E}_{AQ}, \text{"geometric or causal relations between } a_i \text{ and } a_h\text{"} \neq \phi\} \\
& a'_k \in \boldsymbol{E}_{AV} = \boldsymbol{E}_{AQ} \cup \boldsymbol{E}_{AR} \ (k = 1,2,\cdots,N_{AP},\cdots,N_{AV}) \ (N_{AP}: \text{number of principal elements}) \\
& b'_k \in \boldsymbol{E}'_B \subseteq \boldsymbol{E}_B \ (k = 1,2,\cdots,N_{AV}) \quad (\text{when } N_B < N_{AV}, \ b'_k = e_{dummy} \ (k = N_B + 1,\cdots,N_{AV})) \\
& sim_{SE}(\boldsymbol{E}_A, \boldsymbol{E}_B) = \left\{\prod_{k=1}^{N_{AP}} sim_e(a'_k, b'_k)\right\} \cdot \left[\left\{\sum_{k=N_{AP}+1}^{N_{AV}} sim_e(a'_k, b'_k) \cdot len(a'_k)\right\} \Big/ \sum_{k=N_{AP}+1}^{N_{AV}} len(a'_k)\right] \\
& \qquad (sim_e(*, e_{dummy}) = sim_e(e_{dummy}, *) = 0)
\end{aligned}
\tag{7}
$$

5.2 Geometric relation similarity

Presently, the geometric relation type is either 'parallel', 'perpendicular', 'collinear', 'concentric', 'connected', 'in the same direction' or 'in opposite directions'. To exclude unintentionally satisfied geometric relations in a key sketch, we only select geometric relations $\boldsymbol{GR}_A$ intentionally indicated in the data for drafting elements in $\boldsymbol{E}_{AV}$, as in equation (8). Then, such geometric relations in $\boldsymbol{GR}_A$ that are also indicated or satisfied for the corresponding drafting elements in $\boldsymbol{E}'_B$ are collected as $\boldsymbol{GR}_B$. Projection type is considered in the verification of geometric relation satisfaction, as in 4.2. By calculating the achievement rate of $\boldsymbol{GR}_B$ to $\boldsymbol{GR}_A$ as a weighted mean by length, we define similarity sim_{SGR} ($0<=sim_{SGR}<=1$) of S_A to S_B by a geometric relation.

$$
\begin{aligned}
& a'_i, a'_j \in \boldsymbol{E}_{AV} \quad \boldsymbol{GR}_A = \{gr(a'_i, a'_j) \mid gr(a'_i, a'_j) \text{ is indicated.}\} \\
& b'_i, b'_j \in \boldsymbol{E}'_B \quad \boldsymbol{GR}_B = \{gr(a'_i, a'_j) \mid gr \in \boldsymbol{GR}_A \wedge (gr(b'_i, b'_j) \text{ is indicated or satisfied.})\} \\
& sim_{SGR}(S_A, S_B) = \begin{cases} \sum_{\boldsymbol{GR}_B} \{len(a'_i) + len(a'_j)\} \Big/ \sum_{\boldsymbol{GR}_A} \{len(a'_i) + len(a'_j)\} & (\text{when } \boldsymbol{GR}_A \neq \phi) \\ 1 \quad (\text{when } \boldsymbol{GR}_A = \phi) \end{cases}
\end{aligned}
\tag{8}
$$

5.3 Causal relation similarity

We define similarity sim_{SCR} ($0<=sim_{SCR}<=1$) of S_A to S_B by causal relation using equation (9) in the same manner as in 5.2.

$$
\begin{aligned}
& a'_i, a'_j \in \boldsymbol{E}_{AV} \quad \boldsymbol{CR}_A = \{cr(a'_i, a'_j) \mid cr(a'_i, a'_j) \text{ is indicated or satisfied.}\} \\
& b'_i, b'_j \in \boldsymbol{E}'_B \quad \boldsymbol{CR}_B = \{cr(a'_i, a'_j) \mid cr \in \boldsymbol{CR}_A \wedge (cr(b'_i, b'_j) \text{ is indicated or satisfied.})\} \\
& sim_{SCR}(S_A, S_B) = \begin{cases} \sum_{\boldsymbol{CR}_B} \{len(a'_i) + len(a'_j)\} \Big/ \sum_{\boldsymbol{CR}_A} \{len(a'_i) + len(a'_j)\} & (\text{when } \boldsymbol{CR}_A \neq \phi) \\ 1 \quad (\text{when } \boldsymbol{CR}_A = \phi) \end{cases}
\end{aligned}
\tag{9}
$$

A causal relation $cr(e_{cause}, e_{effect})$ indicates causality between two drafting elements e_{cause} and

e_{effect} with physical quantities. Special symbols, 'initial cause' and 'final effect', are used to indicate that a drafting element e represents physical quantities given from or passed to the outside of the sketched design by cr('initial cause', e) or cr(e, 'final effect') . When $cr(a, b)$ and $cr(b, c)$ are indicated, $cr(a, c)$ is judged to be satisfied.

5.4 Size similarity

Sketch data contain the parameters *width* and *height* in the sketch coordinates, and *scale*, indicating unit length in the coordinates, represents 10^{scale} mm. Similarity sim_{SSZ} ($0<sim_{SSZ}<=1$) between sketches according to the depicted object sizes is defined by equation (10).

$$\begin{aligned} size(S) &= scale(S) + \log_{10}\sqrt{width(S)\times height(S)} \\ sim_{SSZ}(S_A, S_B) &= f_{ds}\left(\left|size(S_A) - size(S_B)\right|,\ 0.5,\ 3.0\right) \end{aligned} \tag{10}$$

5.5 Sketch similarity

In the same manner as in 4.5, we define the similarity sim_S ($0<=sim_S<=1$) of sketch S_A to sketch S_B by multiplication as expressed by equation (11). Since different correspondence of drafting elements, as described in 5.1, consequently causes different sim_S, we adopt the maximum sim_S obtained by a search technique.

$$sim_S\left(S_A, S_B\right) = \max_{\substack{\text{drafting element} \\ \text{correspondence}}} \left(sim'_{SE}(\boldsymbol{E}_A, \boldsymbol{E}_B)\cdot sim'_{SGR}(S_A, S_B)\cdot sim'_{SCR}(S_A, S_B)\cdot sim'_{SSZ}(S_A, S_B)\right) \tag{11}$$

5.6 Similarity from different viewpoints

The similarity calculation can be controlled by changing the control parameters described above. We also introduce different viewpoints of physical quantity causality.

- Transformation-oriented: Sketches containing similar causalities (e.g., cause is electricity and effect is force) score high similarity. This viewpoint is effected when no principal drafting elements are selected (N_{AP}=0) in 5.1.
- Cause-oriented: Sketches with similar causes (e.g., linear and rotary motors whose cause is electricity) score high similarity regardless of effects. This viewpoint is effected by selecting drafting elements e with cr('initial cause', e) as principal drafting elements.
- Effect-oriented: Sketches with similar effects (e.g., linear motor and hydraulic cylinder whose effects are force and linear motion) score high similarity regardless of causes. This viewpoint is effected by selecting drafting elements e with cr(e, 'final effect') as principal drafting elements.
- Physical-quantity-set-oriented: Sketches containing similar physical quantities (e.g., gear pump and gear motor) score high similarity regardless of causality directions. This may identify the potential availability of a design concept in a different usage. This viewpoint is effected by using 1 for the lower limit to map sim_{SCR} in 5.3 to sim'_{SCR} in 5.5.

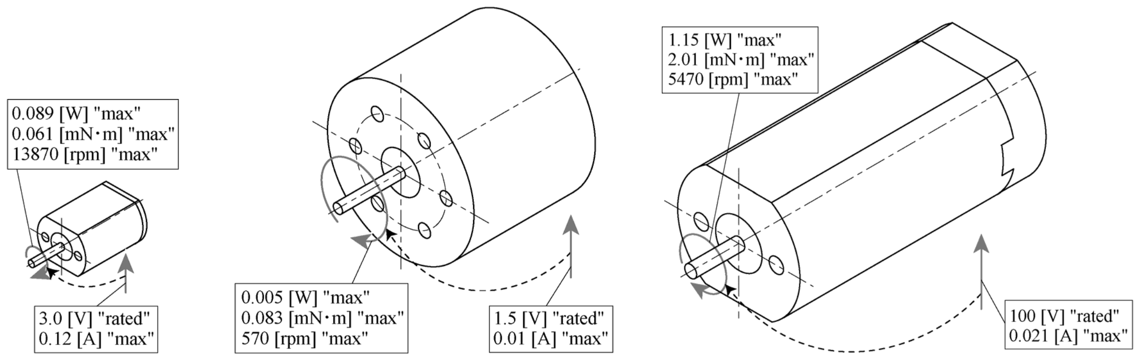
6. Calculation examples

6.1 Implementation

We implemented a similarity calculation program in Common Lisp and a simple sketch editing program in Java. To make sketch data, first we draw a sketch using a commercial drawing tool and make a DXF file. Then we load the file to the Java program, add necessary arrangements and make a Lisp S-expression text file. In the following examples, compiled Lisp programs were executed on Windows XP Pro. PC (CPU: Pentium4 2.4GHz, memory: 1GB). Unless specifically noted, similarity is calculated from a transformation-oriented viewpoint described in 5.6.

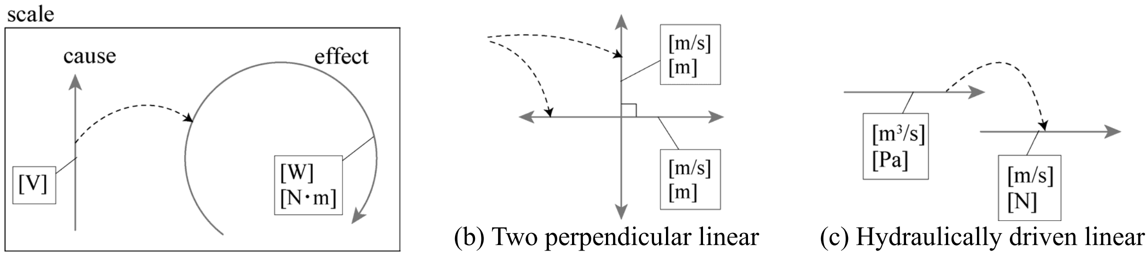
6.2 Retrieving sketches according to conditions of quantity magnitude and object size

First we produced axonometric sketches S_{M1} - S_{M7} of seven different electric motors based on a manufacturer's catalog (Figure 4). Then we drew a key sketch S_K for retrieval (Figure 5(a)) and calculated $sim_S(S_K, S_{Mi})$ (i =1 - 7). When no magnitude is specified for physical quantity and object size consideration is inactive, all seven sketches were scored 1. As Table 2 shows, however, when magnitude is specified for some physical quantities in the key sketch (condition 1) and when the size consideration is active (condition 2), motor sketches quantitatively closer to those conditions got higher scores. Total calculation time was about 7 seconds.



(a) Motor M1 (b) Motor M2 (c) Motor M3

Figure 4. Sketches of electric motors of different specifications (only three are depicted).



(a) Quantity magnitude and size. (b) Two perpendicular linear motions. (c) Hydraulically driven linear actuator.

Figure 5. Key sketches used for retrieval.

Table 2. Similarity calculation using conditions of quantity magnitude and object size.

	cause	effect		size			similarity of motors						
	[V]	[W]	[mN*m]	*scale*	*width*	*height*	M1	M2	M3	M4	M5	M6	M7
condition 1	1.5	-	0.01	-	-	-	0.84	0.88	0.59	0.82	0.60	0.61	0.62
condition 2	-	1.2	-	0.0	60	35	0.87	0.61	0.56	0.82	0.48	0.33	0.83

6.3 Retrieving sketches according to condition of geometric relation

Next, we produced sketches S_1 - S_{10} of ten products based on various manufacturers' catalogs (Figure 1): orthographic sketches of a linear motor, hydraulic cylinder, DC motor, diaphragm pump, gear motor, gear pump, vane motor, and rotary oscillating motor, an axonometric sketch of an XY table, and an oblique sketch of a cooling fan. Then we drew a key sketch S_K representing two perpendicular linear motions as effects (Figure 5(b)) and calculated $sim_S(S_K, S_i)$ (i =1 - 10). As Table 3 shows, the XY table scored highest and sketches with one linear motion followed. Note that the key sketch was orthographic whereas the XY table was an axonometric sketch. Total calculation time was about 1 second.

Table 3. Similarity calculation for two perpendicular linear motions.

XY ta.	hy.cyl.	lin.mo.	cool.fan	vane mo.	DC mo.	dia.pump	ro.oscil.mo.	gear pump	gear mo.
0.850	0.449	0.416	0.246	0.086	0.083	0	0	0	0

6.4 Retrieving sketches with exact and potential availability

Then, we drew an orthographic key sketch S_K representing a hydraulically driven linear actuator (Figure 5(c)) and calculated $sim_S(S_K, S_i)$ (i =1 - 10). Table 4(a) shows the calculated similarity from the transformation-oriented viewpoint. The hydraulic cylinder scored highest and sketches with linear motion or flow followed. On the other hand, Table 4(b) shows the similarity calculated from the physical-quantity-set-oriented viewpoint. Note that the diaphragm pump scored second highest. This result gives the designer the idea that a diaphragm pump can potentially be a hydraulically driven linear actuator if we consider causality in the opposite direction. Total calculation time was about 1 second.

Table 4. Similarity calculation for hydraulically driven linear actuator.

(a) From transformation-oriented viewpoint.

hy.cyl.	lin.mo.	cool.fan	gear pump	gear mo.	XY ta.	DC mo.	dia.pump	ro.oscil.mo.	vane mo.
0.801	0.627	0.548	0.497	0.443	0.429	0.358	0.250	0.090	0.083

(b) From physical-quantity-set-oriented viewpoint.

hy.cyl.	dia.pump	gear pump	cool.fan	lin.mo.	ro.oscil.mo.	vane mo.	gear mo.	DC mo.	XY ta.
0.801	0.709	0.709	0.665	0.627	0.610	0.564	0.564	0.463	0.436

6.5 Classifying sketches from different viewpoints

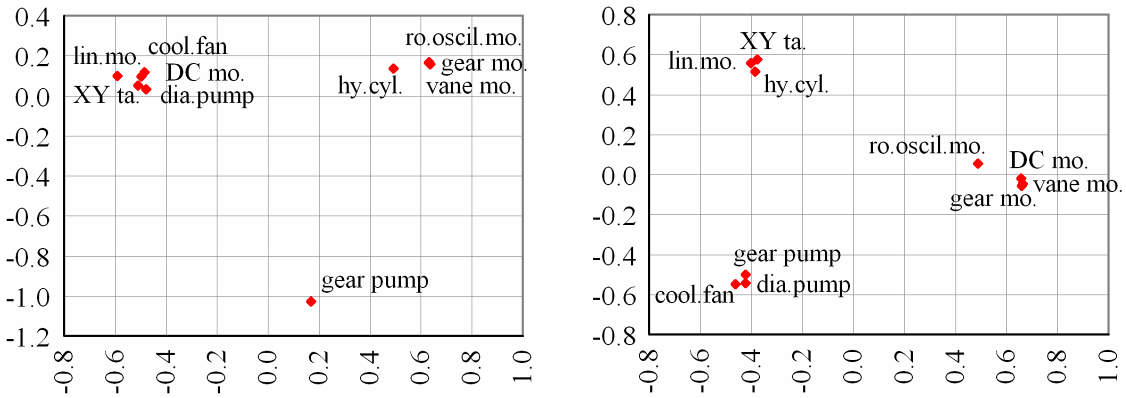
Finally, we calculated a similarity matrix among the ten sketches of the ten products by max($sim_S(S_i, S_j)$, $sim_S(S_j, S_i)$) (i =1 - 10, j = i - 10). The upper right and lower left triangles of Table 5 show the calculated similarities from cause-oriented and effect-oriented viewpoints, respectively. Total calculation time was about 270 seconds. Figure 6 shows scattergrams based on Principals Analysis. Figure 6(a) correctly clusters electrically driven, hydraulically driven and mechanically driven designs, whereas Figure 6(b) correctly clusters linear actuators, rotary actuators and pumps.

7. Conclusions

We proposed a definition of the similarity of design concept sketches based on physical quantities and geometry. By applying the idea to some simple examples, we confirmed that our approach enables objective and quantitative similarity estimation, retrieval and classification of design concept sketches from the viewpoints of behavior and structure. Our future directions include an investigation of a method of representing and extracting design knowledge, as well as the application of our approach to practical design sketches in industry.

Table 5. Similarity matrix of ten sketches from two viewpoints.

	XY ta.	lin. mo.	DC mo.	cool. fan	dia. pump	gear pump	gear mo.	vane mo.	ro.oscil. mo.	hy. cyl.
XY ta.	1	0.855	0.590	0.595	0.625	0.027	0.087	0.086	0.098	0.175
lin.mo.	0.606	1	0.771	0.811	0.715	0.029	0.093	0.095	0.110	0.184
DC mo.	0.040	0.159	1	0.883	0.579	0.042	0.153	0.152	0.139	0.153
cool.fan	0.181	0.333	0.164	1	0.617	0.042	0.177	0.173	0.173	0.202
dia.pump	0.153	0.273	0.127	0.887	1	0.030	0.096	0.097	0.096	0.154
gear pump	0.108	0.250	0.115	0.898	0.634	1	0.074	0.087	0.077	0.070
gear mo.	0.017	0.126	0.862	0.165	0.134	0.142	1	0.811	0.699	0.536
vane mo.	0.024	0.126	0.824	0.164	0.146	0.119	0.809	1	0.716	0.539
ro.oscil.mo.	0.040	0.167	0.526	0.123	0.110	0.089	0.524	0.593	1	0.685
hy.cyl.	0.523	0.917	0.159	0.333	0.297	0.272	0.135	0.142	0.190	1



(a) From cause-oriented viewpoint.   (b) From effect-oriented viewpoint.

Figure 6. Scattergrams of ten design concept sketches from two different viewpoints.

References

[1] Roth K., "Design Catalogue and Their Usage", in Chakrabarti A., ed., "Engineering Design Synthesis", Springer, 2002, pp.121-129.

[2] Lim S., Duffy A.H.B. and Lee B.S., "Shape Matching and Clustering", ICED 01, Design Management - Process and Information Issues, Glasgow, 2001, pp.163-170.

[3] Maher M. and de Silva Garza, A.G., "Developing Case-Based Reasoning for Structural Design", IEEE Expert, Vol.11, No.3, 1996, pp.42-52.

[4] Murakami T., Shimamura J. and Nakajima N., "Design Case Relevance in Quantity Dimension Space for Case-Based Design Aid", ICED 01, Design Management - Process and Information Issues, Glasgow, 2001, pp.51-58.

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