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QUANTITATIVE MEASURES FOR DESIGN BY ANALOGY

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ABSTRACT

In this paper a quantitative measure for design-by-analogy is developed. This measure is based on the functional similarity of products. By using this product similarity measure, designers are able to formalize and quantify design-by-analogy techniques during concept and layout design. The similarity measure and its application is clarified and validated through a case study. The case study is the original design of a pickup winder.

KEYWORDS: Design-by-Analogy, Product Similarity, Functional Analysis, Customer Needs, Novel Product Design

1 Introduction

During the design and development of new products, design engineers use many techniques to generate and define new and "good" concepts. Inherent in this search of solutions is the conscious and unconscious reliance on prior experience and knowledge. Numerous attempts have been made to organize, qualify, and make accessible the critical design experience and knowledge needed to solve particular problems. Some of these techniques take the form of knowledge based design, expert design systems, and design rules or design guidelines. In this paper, quantitative measures are developed that allow designers to identify products which are similar in a manner critical to the success of a design. This focused identification allows these similar products to be reviewed in context of the design problem at hand for configuration, concept, and embodiment information. These measures allow formalized design-by-analogy efforts by identifying products that have design-critical similarity.

The paper is organized in the following way. First, the notion of similarity as used here is clarified. Toward the goal of finding the important product similarities, ground work is developed to make comparisons between products. In the remainder of this paper, these notions of product similarity in the search for analogies are explored. Also, a procedure for applying these techniques to a design problem is presented. Lastly, an example application of the design-by-analogy techniques is applied to an original design case study. The paper concludes with a brief discussion of the contributions of the work presented here.

2 Relevant Analogies

The notions of similarity, and analogies based on similarity, are broad. From Moody charts to the Periodic Table, organizing schemes based on similarities and differences is a critical tool in engineering and science. In the field of fluid mechanics, the comparison of different objects based on similarities in the Reynolds number, the Biot number, or other meaningful metrics for comparison, is not only common place, but critical to the fundamental understanding of the relevant physics that affect the systems. Before developing a design tool based on analogy, the basis for making the comparison is necessary. For example, based on a color comparison, a car and a watch may be similar. In fact, they also may share the similarity of manufacturing country of origin. Reviewing a watch as an exercise to find alternative ways to mix fuel and air in the car is likely a fruitless exercise. Before searching for design information in existing and similar designs, the notion of similarity needs to be understood in the context of design.

A fundamental philosophy of this paper is that customer needs drive the product function. In turn, the resulting required functions have a key impact on the resulting form. Design philosophies such as this have been proven valid and effective in the literature (Pahl and Beitz, 1996; Ullman, 1997; Ulrich and Eppinger, 1995; Hubka and Eder, 1988). Based on this philosophy, the similarity notion of interest here is at a customer influenced level. In other words, if two products have a function in common, such as *store energy*, and this function is related to

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important customer needs, these two products have a design relevant similarity. When comparing between more than two products, the notion of *more* or *less* similar becomes relevant. Thus, the wish is to extend beyond a binary notion of similar to a quantitative numerical measure of product similarity.

2.1 Design-by-Analogy in Engineering Design

The material presented in this paper makes novel and significant contributions to design-by-analogy techniques. The majority of successful design-by-analogy efforts in engineering design have been the the area of circuit design (Huhns and Acosta, 1988). This is largely do to the lack of of quantitative similarity measures available in mechanical design as compared to those available in circuit design. As pointed out by Huhns (Huhns and Acosta, 1988), to develop design-by-analogy systems, an analytical similarity measure is needed. Such measures require a domain metric which is not typically available during conceptual design. In this paper, such a metric and measure are developed.

The approach to design-by-analogy techniques presented here is to develop tools that assist the designer during the design process. This approach is distinct from many design-by-analogy efforts where the goal is to reproduce the actions or tasks generally the responsibility of the designer (Doheny and Monaghan, 1987).

There are some significant successes for mechanical design-by-analogy (Howe et al., 1986). Often, these expert systems or knowledge based design tools are focused on problems that can be solved by a fixed and finite set of design variables (Howe et al., 1986). Other successes have come when developing expert systems for specific problem domains (Mittal et al., 1985). The effort in this paper is a toward a more general tool for design-by-analogy methods.

3 Measures of Similarity: Process and Details

The goal here is the provision of a measure that reveals analogies at a level that is useful for concept, configuration, and embodiment design. As discussed above, there are two key comparison criteria. The first criteria is functional similarity. Do other products "do" the same thing as the one being designed? The second is the significance of this functional similarity. Rather than search for all potential analogies, the search needs to be focused on those that are most likely to affect the quality of the design. In this case, those analogies are the functional similarities of importance to customers. To find this similarity, there are three key needs. The first is to express products in a similar and accurate functional language. The second need is to associate the product functionality with customer relevance. The third is to construct quantitative measures of product similarity. This measure then provides a powerful indicator for products which contain relevant design information.

3.1 Product Functional Models

In this subsection, the steps required to organize the product-function data are detailed. To begin, customer need data and functional models are needed for each product in the group (Pahl and Beitz, 1996; Ullman, 1997; Ulrich and Eppinger, 1995; Hubka and Eder, 1988). The first step is to construct the functional models using a common terminology of *basic* functions and flows. These *basic* functions and flows need to be a basis set; functional models for a large class of products can be generated from this finite set of functions and flows. Shown in Table 1 is a set of these basic functions. Similarly, shown in Table 2 is a corresponding set of basic flows. These functions and flows were originally presented by Little in (Little et al., 1997). The complete formal definitions for these functions and flows is presented in (Stone and Wood, 1999). These functions are used here as the best available set of basis functions.

Class	Basic	Sub-basic	Complement
material	solid		hand, foot, head, etc
	liquid		
	human		
	gas		
energy	human		motion, force
	biological		pressure, volumetric flow
	mechanical	rotational	torque, angular velocity
		translational	force, velocity
		vibrational	amplitude, frequency
	electrical		electromotive force, current
	hydraulic		pressure, volumetric flow
	thermal		temperature, heat flow
	pneumatic		pressure, mass flow
	chemical		affinity, reaction rate
	radioactive		intensity, decay rate
	acoustic		pressure, particle velocity
	magnetic		magnetomotive force, flux rate
	electromagnetic	optical	intensity, velocity
		solar	intensity, velocity
signal	status	auditory	tone, verbal
		olfactory	
		tactile	temperature, roughness, pressure
		taste	
		visual	position, displacement
	control		

Table 2. Basic flows.

3.2 Customer Functional Importance

The goal in this section is to develop a procedure that relates functions to customer needs. By extension, the method is used to determine the importance of a function. For example, a customer has the requirement that a hand sander "remove wood quickly and easily." What product functions are related to this customer need? And, what other customer needs are related to that function? Products with common important functions are those that have the desired function similarity. Thus a tool to identify the critically important functions is crucial to the similarity measures sought for design-by-analogy. In addition, identifying important functions early in the design phase is an important contribution to engineering design in general.

Though not presented in it's entirety, the procedure for relating customer needs to functions is presented here in sufficient detail so that it may be repeated. Customer need weights are used to determine the functional importance. Before relating customer needs to functions, customer need ratings for each product are translated to a scale of 1 ("optional") to 5 ("must have"), using an appropriate method (Otto, 1996). Doing this provides that functional models are represented using a common terminology and all the customer need weights are ranked on a common scale. Next, functions are related to customer needs and assigned a nu-

Function Class	Basic Function	Flow Restricted	Synonyms
channel	import		input, receive, *allow*, form entrance, *capture*
	export		discharge, eject, dispose, remove
	transfer		
		transport	lift, move, channel
		transmit	conduct, transfer, convey
	guide		direct, straighten, steer
		translate	
		rotate	turn, spin
		allow DOF	constrain, unlock
support	stop		insulate, protect, *prevent*, shield, inhibit
	stabilize		steady
	secure		*attach*, mount, lock, fasten, hold
	position		orient, align, locate
connect	couple		join, assemble, *attach*
	mix		combine, blend, add, pack, coalesce
branch	separate		switch, divide, release, detach, disconnect, disassemble, subtract, valve
		remove	cut, polish, sand, drill, lathe
	refine		purify, strain, filter, percolate, clear
	distribute		diverge, scatter, disperse, *diffuse*, empty
	dissipate		absorb, dampen, dispel, *diffuse*, resist
provision	store		contain, collect, reserve, *capture*
	supply		fill, provide, replenish, expose
	extract		
control magnitude	actuate		start, initiate
	regulate		control, *allow*, *prevent*, enable/disable, limit, interrupt
	change		increase, decrease, amplify, reduce, magnify normalize, multiply, scale, rectify, adjust
	form		compact, crush, shape, compress, pierce
convert	convert		transform, liquefy, solidify evaporate, condense, integrate, differentiate, process
signal	sense		perceive, recognize, discern, check, locate, verify
	indicate		mark
	display		
	measure		calculate

Table 1. Function classes, basic functions, and synonyms. Italics indicate a repeated synonym.

merical importance.

To determine the importance of a function, the impact of a function on a customer need is evaluated. If a function affects a specific customer need, then the weight of that customer need is assigned to the importance value of that function. Proceeding through each customer need, the assigned customer need weights are summed to determine function's importance.

It is important that the designer accurately assess the relationship between customer needs and functions so that functions are appropriately weighted. To assure that the function importance value is accurate and repeatable, a two stage process is used. First, the material, energy, and signal flows from the functional model are assigned to the appropriate customer needs. For example, a customer need for "quiet operation" is related to the flow of acoustic energy. After the customer need flow assignment, flows are related to functions by following the path of the flow through the functional model. In this manner, functions are related to flows, and in turn to customer needs.

Customer needs are not always obvious constraints on material, energy, and signal flows through functional models. Nevertheless, simple, repeatable, physical reasoning provides a clear relationship to be determined between customer needs, flows, and sub-functions. A customer need for an electromechanical hand sander is "light weight." The forces input to, and transmitted through, the sander govern the volume, geometry, material makeup, and consequently mass, of components throughout the sander. Thus, the flow *human force* is assigned to "light weight". In the functional model of the sander, the flow is operated on

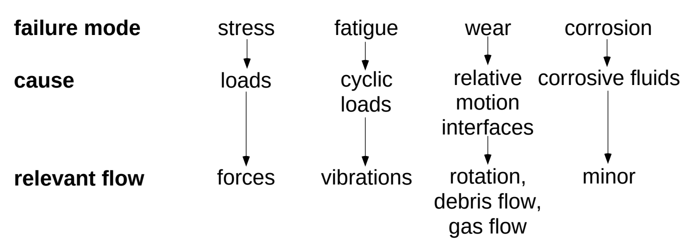


Figure 1. The process of relating the customer need of "low maintenance" to functions for a hand sander.

by the functions *import human force* and *transmit human force* Thus, these functions are assigned to "light weight." This assignment may require some thought, but is based on the type of experience pervasive through much of the engineering discipline. The motor coil windings and magnetic structure of the electric motor are large contributors to the mass of the sander. Thus, any attempt to reduce weight during design or redesign must address the mass added by energy conversion solutions. Following the *electricity* flow, the sub-function *convert electricity to rotation* is assigned to the customer need "light weight."

In an electromechanical hand sander, another customer need the does not relate directly to a flow is "low maintenance." Figure 1 shows common causes of failure in electro-mechanical devices and their relationship to the product flows. These flows are then used to relate the sub-functions to the customer needs.

At this point in the procedure, each product is represented in terms of a set of functions, and importances for those functions, based on customer needs. The entire set of products is easily represented as a group by recognizing the similarity of the current product-function representation with a vector space. Each product is representable in a simple manner as a vector. Each element of this function vector is the importance measure of that function. Similarly, the function vectors naturally assemble into a product-function matrix. This matrix representation provides a clear and compact way of reviewing the data. Also, this approach to data organization facilitates computations on the importance measures. With this representation, the methods of matrix algebra can be applied to the space of products. Numerical computations can now be performed with great ease and elegance.

Before assembling the vectors into a product-function matrix, the value of one (1) is added to each of the function importance values. This shift is performed so that the product vectors may be assembled into a matrix. In the product-function matrix, the functions that a product does not have are represented by a zero. The function importance scale is now a 1 to 6 point scale. Functions with an importance of 1 - those not directly related to a customer need - are supporting functions. A function importance value of 6 or higher indicates an essential, or highly important, function. Often values greater than 6 can occur when one function relates to several customer needs. This product-function matrix, Φ, is a *mxn* (*m* total different functions, *n* products) matrix. Each element ϕ_{ij} is the cumulative customer-need importance of the i^{th} function for the j^{th} product.

Different product complexity and customer enthusiasm (during the customer need acquisition process) affect the magnitude of the ϕ_{ij}'s for each product. To compensate for these differences, Φ is normalized to validate comparisons between products. The philosophy used to normalize the function-product matrix consists of two complimentary aspects:

1. all products are of equal importance (to compare products), and
2. products with more functions are more complex; thus the customer-need rankings must be normalized to compensate for varying complexity.

First, to equalize products, the customer-need value of each function is scaled so that the sum of a given product's importance level is equal to the average sum of the customer need importance for all products. Second, to represent varying levels of product complexity, each product function is scaled by the ratio of the number of functions in a product to the average number of functions per product.

Implementing these steps precisely, the elements of N, the normalized version of Φ, are

$$\nu_{ij} = \phi_{ij}\left(\frac{\overline{\eta}}{\eta_j}\right)\left(\frac{\mu_j}{\overline{\mu}}\right). \quad (1)$$

The average customer rating is

$$\overline{\eta} = \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n}\phi_{ij}. \quad (2)$$

The total customer rating for the j^{th} product is

$$\eta_j = \sum_{i=1}^{m}\phi_{ij}. \quad (3)$$

The number of functions in the j^{th} product is

$$\mu_j = \sum_{i=1}^{m} H(\phi_{ij}). \quad (4)$$

And the average number of functions is

$$\overline{\mu} = \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n} H(\phi_{ij}). \quad (5)$$

H is a Heaviside function defined as

$$H(x) = \begin{cases} 1 & \text{when } x \neq 0 \\ 0 & \text{when } x = 0 \end{cases} \quad (6)$$

In the above equations, n is the number of products, and m is the total number of different functions for all products.

Figure 2 shows the complete normalization process for some hypothetical set of products. The top left matrix in the figure (A) is the original matrix Φ, moving from left to right and then down in the figure, first the matrix is adjusted to equalize product importance (B). Then, using the average number of function per product (in C), the final matrix N is calculated (D). The functions in the N matrix are comparable for importance from product to product.

3.3 Computing Similarity

The elegance and power for the vector product representation is made clear here in the development of a quantified measure of product similarity. Using the matrix representation, N, the entire domain of products can be reviewed for functional similarity. The product vectors generated from Equation 1 are renormalized so that their norm is 1. After scaling, the inner product of the normalized product vectors for each combination of products is calculated. Forming the inner product between a product a and a product b, $a \circ b$, gives the projection of product a on product b. Forming the inner product of a product with itself (the completely similar product) gives a value of 1. Forming the inner product of a product with one that shares no common functions yields a result of zero. If the product vectors had not been renormalized to unity, it would be possible to have a product more similar to another product than itself. This potential result is removed by the renormalization.

Once calculated, this projection is a measure of product similarity. It is based on the number of functions occurring in both products. The result is weighted by the customer importance. In other words, this projection provides the desired measure of product similarity. It is a simultaneous measure of functional

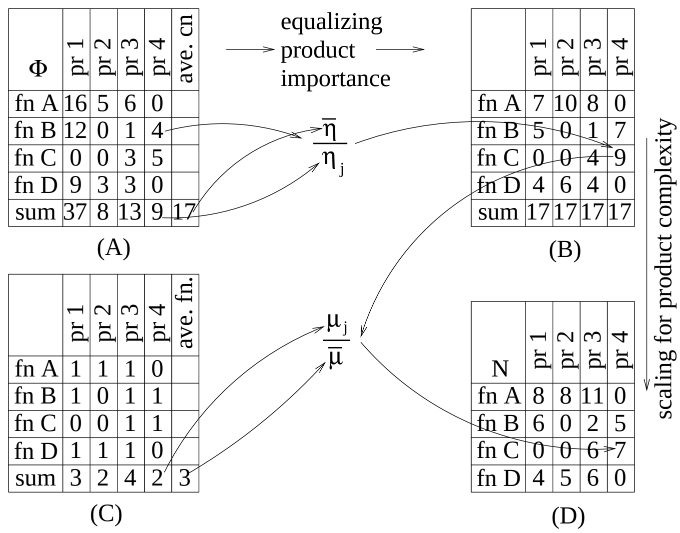


Figure 2. Normalization process: (A) original function-product matrix Φ, (B) equalizing product importance, (C) determine average number of functions per product, and (D) scaling for product complexity to get the final matrix N.

similarity and customer importance. This projection for functional similarity is made clear by referring to Figure 3. In this figure a portion of the function space is shown for the functions *secure solid*, *convert electricity to rotation*, and *position solid*. Product vectors for Product A and Product B and the projection of Product B on Product A are shown. This represents the similarity measure λ_{BA} for these two products.

A matrix of these projections is

$$\Lambda = \mathcal{N}^T \mathcal{N}. \tag{7}$$

$\mathcal{N}$ is the matrix of unity normalized product vectors, similar to N. Each element, λ_{ij}, is the projection of the i^{th} product on the j^{th} product. Λ is the product similarity matrix. Using matrix multiplication to form the product similarity matrix Λ is similar to a technique Taylor (Taylor, 1996) used to determine topics and frequencies of discussion on internet newsgoup communication in student design teams. The product projections with high λ values are candidates for finding meaningful design by analogy information at the functional level.

4 Steps for Using these Metrics for Design-By-Analogy

Briefly reviewing the procedure, it can be succinctly reduced to the following steps.

- Gather customer needs.
- Construct a functional model using a common functional language for all products modeled.
- Determine functional importances.
- Scale functional importances for comparison.
- Compute similarity index λ.

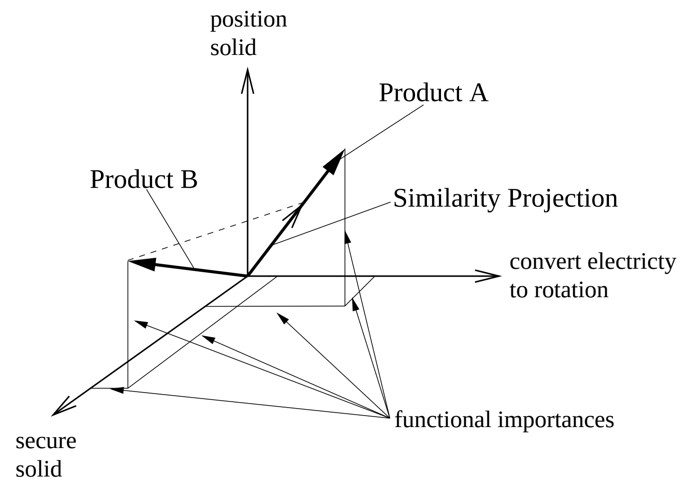


Figure 3. A graphical interpretation of the product functional similarity projection.

- Using high values of λ, select a similar subset
- Review these similar products for analogous solutions, insights, success and failures.
- Review coupled functions for potential adaptations of modules and other adaptable design solutions.

A key strength of this procedure is that it can be implemented during the conceptual design stage immediately after the collection of customer needs and the development of a functional model. In other words, the design-by-analogy method can be applied during the traditional concept generation stage before any commitment to a particular solution variant has been made. The next section shows the usage of this process by application to an example product design.

5 Application to an Original Design Problem

As a usability and validity check for the measures and methods developed here, a design case study is presented. The problem in question is the design of an electric guitar pickup winder. Not only does the design serve as an epitome of the material developed, the problem requires insightful design to meet all the customer and manufacturing requirements. Thus the winder serves as an excellent vehicle for testing the design tools. For brevity, the decisions and specifics of the design are not presented completely: the focus is on the presentation of the techniques developed in this paper. First, the design problem is briefly introduced. Then, the similarity measures are applied and reviewed.

5.1 A Brief Introduction to the Design Example

A guitar “pickup” is an electromechanical transducer that transforms the motion of the guitar string into an electric current. The current is then amplified and transformed into sound. The coil winding consists of 6000 to 12,000 turns of insulated copper wire. This wire is generally 41, 42, or 43 gage.

The target customers for this winder are guitar repair technicians, custom luthiers, and guitar tinkering hobbyists. In general, this winder will be used to repair broken pickups, wind custom designed “one-off” pickups for custom guitars, and wind prototype pickups to test new pickup designs. A brief visualization of a machine or process that winds this wire neatly (the wire diameter is $58\mu m$ to $83\mu m$) without breaking it (the maximum working strength is varies from roughly $0.5N$ to $1N$) indicates a need for thoughtful design.

5.2 Application of the Design-By-Analogy Process

Proceeding with the design-by-analogy process for the pickup winder, customer need data is acquired and a functional model is generated. The functional model for the winder is shown in Figure 4. Briefly reviewing some of the important flows across the system boundary, the material flows into the pickup winder are the human hand, the bobbin, the spool of magnet wire, and winding adhesive. The winding adhesive is usually a shellac or similar bonding agent that creates a “solid” coil. The material that flows out of the winder are the human hand and the completed pickup. The rest of the functional operation of the winder should be clear by review of this model.

The next step in the design by analogy process is to determine the function importances. This is done using the approach presented in a prior section. Table 3 summarizes this procedure for the pickup winder. The resulting function importances for the winder are listed in Table 4. A review of Table 4 reveals that the critical functions are *secure solid*, *allow a DOF solid*, *import solid*, *position solid*, *guide solid*, *regulate solid*, and *convert electricity to rotation*.

Now, the winder is added to an existing Φ matrix. The N matrix is formed using Equation 1 so that the products may be properly compared. Although the two most similar products in the entire data set could be determined by reviewing each λ_{ij} in Λ, the goal is to find products similar to the pickup winder. Thus, only the projections of products with the pickup winder, or $\lambda_{i,pickupwinder}$, are computed. The resulting products which have the highest values following this computation are shown in Table 5. These are the five products most similar to the pickup winder when compared to the entire set of 68 products reviewed here.

The products ranked and shown in Table 5 are now reviewed for solution concept, embodiment, module, and layout architecture possibilities for the winder. To assist in the review of the common functions, Table 6 shows the importance of functions in each of the similar products that have been included for review.

The review begins with the winder’s most important function. The most important winder function is *secure solid*. This function’s importance is a result of its relation to customer needs combined with its recurrence several times in the functional model. The other product with the highest importance for *secure solid* is the Dazey fruit and vegetable peeler. The solid of interest for the peeler is various food objects such as potatoes, apples, etc. The peeler uses a forked prong to penetrate the vegetable thus holding it firmly in place. The question here is, can this solution be adapted to the pickup winder? Using a pin or prong to secure the bobbin is a viable solution. Most bobbins have a number of voids in the interior between the pole pieces. A material (generally vulcanized fiber) that holds the pole pieces in place can be pierced thus providing for a securing of the bobbin. The implementation of this concept as adapted for the winder is shown in Table 7. The basic concept of piercing the pickup has been modified to include small nuts on the end of the piercing bolts instead of using a piercing axis (at the “top” of the fruit) as implemented in the vegetable peeler. In the example pictured, the

Customer Need	Weight	Assigned Flow	Function
prevent wire breakage	5	wire	secure solid, remove solid guide solid
		tension in wire	regulate force
		rotation	change rotation
even distribution of wire	5	bobbin	secure solid, position solid allow DOF solid
		wire	guide solid
graduated distribution of wire	5	bobbin	secure solid, position solid allow DOF solid
		wire	guide solid
various bobbin sizes	5	bobbin	export solid, separate solid secure solid, position solid import solid, allow DOF solid
various wire sizes	5	wire	secure solid, remove solid regulate force guide solid
allow application of winding adhesive	5	adhesive	import liquid
count coils	4	# turns	sense status, indicate status store signal, sense control signal
wind pickup in both directions	4	rotation	regulate rotation
		direction	sense control signal
unwind pickup	4	direction	sense control signal
		rotation	convert electricity to rotation
		bobbin	allow DOF solid
interrupt process	4	wire tension	regulate force
		stop bobbin	sense control signal transmit control signal
		on-off	import signal
		electricity	regulate electricity
		bobbin	allow DOF solid
easy to operate	4	bobbin	export solid, separate solid secure solid, import solid
		wire	secure solid
		hand	import human hand
		adhesive	import liquid
		spool	import solid position solid
regulate tension	3	wire tension	regulate force
		wire	guide solid
produce randomly wound bobbin	3	bobbin	secure solid, position solid allow DOF solid
		wire	guide solid
various wire spool sizes	3	spool	import solid secure solid position solid
reliable	3	wire tension	regulate force
		rotation	convert electricity to rotation change rotation
		wire	guide solid
		bobbin	allow DOF solid
stable	3	human hand	import human hand
		electricity-rotation	convert electricity to rotation
simple setup	3	bobbin	secure solid secure solid import solid
		adhesive	import liquid
		human hand	import human hand
		wire	secure solid
		spool	import solid position solid
safe operation	3	human hand	import human hand
small storage size	3	bobbin	import bobbin
		spool	import solid allow DOF solid
		rotation	convert electricity to rotation
adjustable wire tension	2	human hand	import human hand
		wire tension	regulate force
		rotation	convert electricity to rotation
easy to clean	2	human hand	import human hand
		adhesive	import liquid
desktop size	2	bobbin	import solid
		human hand	import human hand
		adhesive	import liquid
		spool	import solid
		electricity-rotation	convert electricity to rotation
		wire	guide wire
		bobbin	allow DOF solid
weight $<$ 15 lbs.	2	bobbin	secure solid
		spool	secure solid
		wire tension	regulate force
		electricity-rotation	convert electricity to rotation
		bobbin	allow DOF solid

Table 3. Relating customer needs to sub-functions for the pickup winder.

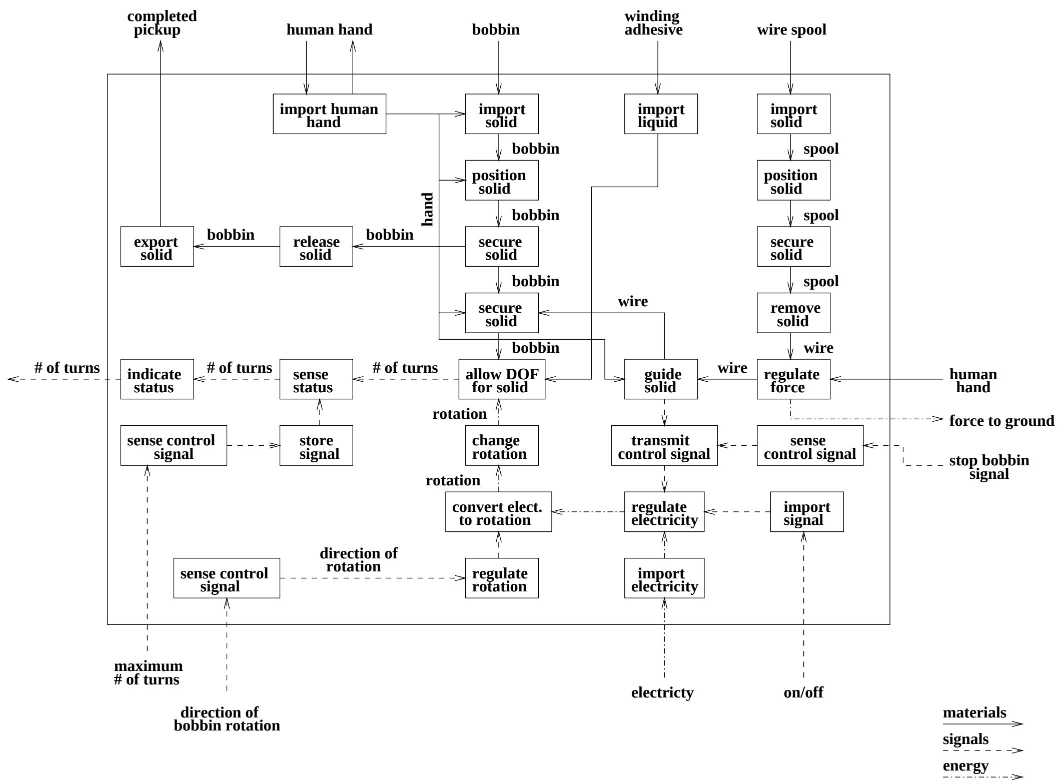


Figure 4. The functional model of the pickup winder.

Function	Customer Weights	Sum
allow DOF solid (bobbin)	5,5,5,4,4,3,3,3,2,2 1,	37
change rotation (adjust speed)	5,3,1	9
convert electricity to rotation	4,3,3,3,2,2,2	20
export solid (bobbin)	5,4,1	10
guide solid (wire)	5,5,5,3,3,3,2,1	32
import electricity	1	1
import human hand	4,3,3,3,2,2,2,1	20
import liquid (adhesive)	5,4,2,2,1	14
import control signal (on-off)	4,1	5
import solid (bobbin)	5,4,3,3,2,1	18
import solid (spool)	4,3,3,3,2,1	16
indicate status (# turns)	4,1	5
position solid (bobbin)	5,5,3,3,1	22
position solid (spool)	4,3,3,1	11
regulate electricity	4,1	5
regulate force (wire tension)	5,5,4,3,3,2,2,1	25
regulate rotation	4,1	5
separate solid (bobbin)	5,4,1	10
remove solid (wire)	5,5,1	11
secure solid (bobbin)	5,5,5,4,3,3,2,1	28
secure solid (spool)	3,2,1	6
secure solid (wire)	5,4,3,1	18
sense control signal (# turns)	4,1	5
sense control signal (direction)	4,4,1	9
sense control signal (stop bobbin)	4,1	5
sense status (# turns)	4,1	5
store signal (# turns)	4,1	5
transmit control signal (stop bobbin)	4,1	5

Table 4. Determining the function importance for the pickup winder.

Product	λ
pickup winder	1.0
Dazey fruit & vegetable peeler	0.78
electric can opener	0.74
De Walt sander	0.73
fishing reel	0.72
Krups cheese grater	0.69

Table 5. Results of the similarity calculation for the pickup winder.

function	pickup winder	fruit & vegetable peeler	electric can opener	palm sander	fishing reel	cheese grater
secure solid	22.43	24.31	19.82	17.56	1.83	8.55
allow DOF of solid	15.96	0	0	0	0	0
import solid	14.67	8.11	12.20	1.35	25.67	1.43
position solid	14.23	8.11	0	10.81	11	8.55
guide solid	13.80	2.03	6.10	0	11	14.30
regulate force	10.78	0	0	0	11	0
convert elect. to rot	8.62	8.11	13.72	12.16	0	19.96
import human hand	8.62	12.16	7.62	20.26	9.16	8.55
sense control	8.19	0	0	0	0	0
import liquid	6.04	0	0	0	0	0
remove solid	4.74	22.30	21.34	8.10	0	19.96
export solid	4.31	2.03	1.52	1.35	9.17	9.98
separate solid	4.31	0	0	8.10	0	0
change rotation	3.88	8.1	18.29	0	6.41	5.70
import signal	2.16	0	0	0	0	0
indicate status	2.16	0	0	1.35	0	0
regulate electricity	2.16	2.02	0	1.35	0	0
sense status	2.16	8.10	0	0	0	0
store signal	2.16	0	0	0	0	0
transmit control signal	2.16	0	0	0	0	0
import electricity	0.43	8.1	1.5	1.35	0	0

Table 6. The normalized function importances for each of the similar products.

bobbin is a semi-transparent plastic instead of vulcanized fiber.

The *import solid* function refers to two flows: the solid flows are the bobbin and the the magnet wire supply spool. Though these function are critical to the success of the winder, they are

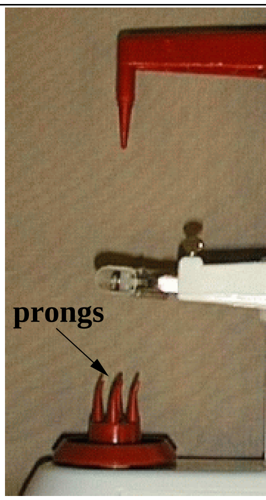
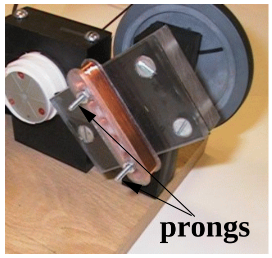
secure solid	
vegetable peeler	pickup winder
	

Table 7. Solution concept for *secure solid* as adapted from the vegetable peeler.

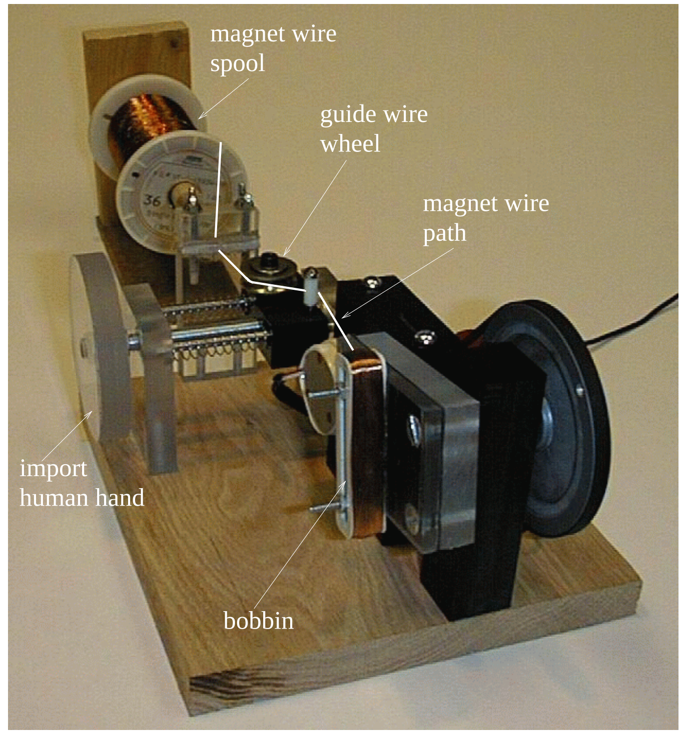


Figure 5. An alpha prototype of the pickup winder.

simply solved. As in the case of the vegetable peeler, the solids are imported by providing access space for the importation of the solid. The comparison of this embodied solution for the vegetable peeler and the winder is shown in Table 8.

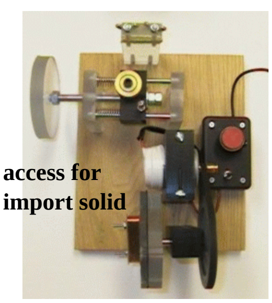
import solid	
vegetable peeler	pickup winder
	

Table 8. Solution concept for *import solid* as adapted from the vegetable peeler.

Similar to the *import solid* function, the flows related to the *position solid* function are the magnet wire supply spool and the bobbin. In the case of the magnet wire supply spool, a simple stand is determined sufficient for positioning the spool. No analogous solutions from the similar products were adapted for the winder. The wire spool stand is visible in Figure 5 which also shows the general layout of the pickup winder prototype.

In addition to referring to the position of the wire spool, the *position solid* function involves the position of the bobbin relative to the wire such that the wire coil builds evenly on the bobbin. The required wire position changes in time as the coil builds on the bobbin. As a solution to *position solid*, the vegetable peeler provides an insightful and successful concept which is easily adapted to the winder. In the case of peeler, the problem is very much the same. As the blade removes peelings from a vegetable, the relative position of the blade and the vegetable change. The peeler uses a lead screw, or power screw, for its *position solid* solution. Adapting such a solution to the winder allows the user to have precise control over the location of the wire. This solution is embodied in the winder as shown comparatively in Table 9. An input wheel is attached to a threaded rod. On the other end, the rod is attached to the shuttle, or pillow block, that carries components from the *guide solid* function discussed next.

The function *guide solid* is a not only important to the target customers, but because of the precision required to meet the customer need metrics, it is a challenging aspect of the winder design. Reviewing Table 6 shows that the the fishing reel has a high importance for *guide solid*. The fishing reel uses a small circular pin to guide the fishing line as in winds onto the reel. This solution is easily adapted to the pickup winder as shown in Table 10. On the pickup winder, the circular pin guide has been modified to allow rotation. The rotating pin guide, or wheel, prevents the additional tension added to the wire as a result of the drag friction as the magnet wire as it moves by a non-rotating guide.

The next function for comparison is *regulate force*, referring

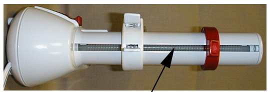
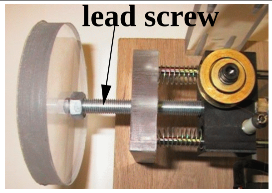
position solid	
vegetable peeler	pickup winder
	

Table 9. Solution concept for *position solid* as adapted from the vegetable peeler.

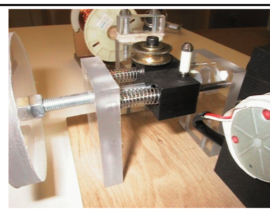
guide solid	
fishing reel	pickup winder
	

Table 10. Solution concept for *guide solid* as adapted from the fishing reel.

here to the tension control required for the magnet wire. The only other reviewed product that shared this function is the fishing reel. Though the adaptation of this solution is not direct, one key feature of the *regulate force* function in the reel is adapted to the winder. As in the fishing line reel, a continuous adjustment of wire (or line) tension is allowed. This continuous adjustment allows for different sizes of wire to be used without dependence on precise settings and small component tolerances. The continuous tension adjustments for the winder and the fishing reel are shown in Table 11

For the function of *converting electricity to rotational motion* the winder adapts a solution from the vegetable peeler. In this case, a DC electric motor. Though this solution would likely have been selected without use of the design-by-analogy efforts, the analogous connection in this case shows that the design-by-analogy methods are consistent with standardized solutions when they exist and are prevalent. This result contributes to the validity of these design-by-analogy methods.

A very rich understanding of the power of computing these similarity metrics and using the identified products is had by viewing the vegetable peeler in its entirety as a similar product with the winder. A side-by-side comparison of the fruit and vegetable peeler reveals a interesting and powerful result of these similarity measures and the design by analogy procedure. If rotated on its side, the vegetable peeler implies a layout structure that can be used by the winder.

This layout adaptation can be seen by substituting the pickup bobbin for a piece of fruit and the wire guide wheel for the peeling blade. Using this approach, the peeler architecture is adapted to the winder. The relative location of the controlling lead screw in both these systems is essentially the same. Shown in Figure 6 are photographs and sketches emphasizing the layout of the primary components of the peeler and the winder. As implemented, product layouts are similar. Key layout concepts taken from the peeler and adapted to the winder include the same relative position of components and assemblies. Also, the concept of moving the blade or wire rather than the potato or bobbin is adapted to the winder.

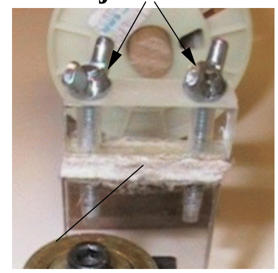
regulate force	
vegetable peeler	pickup winder
	

Table 11. Solution concept for *regulate force* as adapted from the fishing reel.

On the pickup winder, the wire position is controlled manually whereas in the fruit and vegetable peeler it is synchronized to the rotation motor. Such an adaptation could easily be made to the winder. Fully automated control, however, was not a customer need for the pickup winder. Thus, a synchronized position control for the wire was not included in the winder prototype.

6 Conclusions And Future Work

In this paper, a measure of product similarity is developed. This measure is combined with a simple process to provide a novel and powerful design-by-analogy procedure. The practical usefulness of these design tools is validated through application to an original and innovative design. The problem is the design of a machine that winds guitar pickups. Through the simple application of the design-by-analogy techniques, elegant solutions were found for the *guide wire*, *position bobbin*, and *secure bobbin* functions. These solutions, as integrated into a final alpha level prototype, are shown in Figure 5.

To find these results without the analysis and methods presented in this paper is practically impossible. There are 68 products reviewed in the database with over 1400 functions. Reviewing this many products and functions for similarity is infeasible. The methods, as applied here, allow a designer with limited experience to develop sophisticated solutions that enhance the overall design of the winder. Using these measures, existing products, that may have not been identified as similar based on unstructured inspection, can be reviewed for important design-

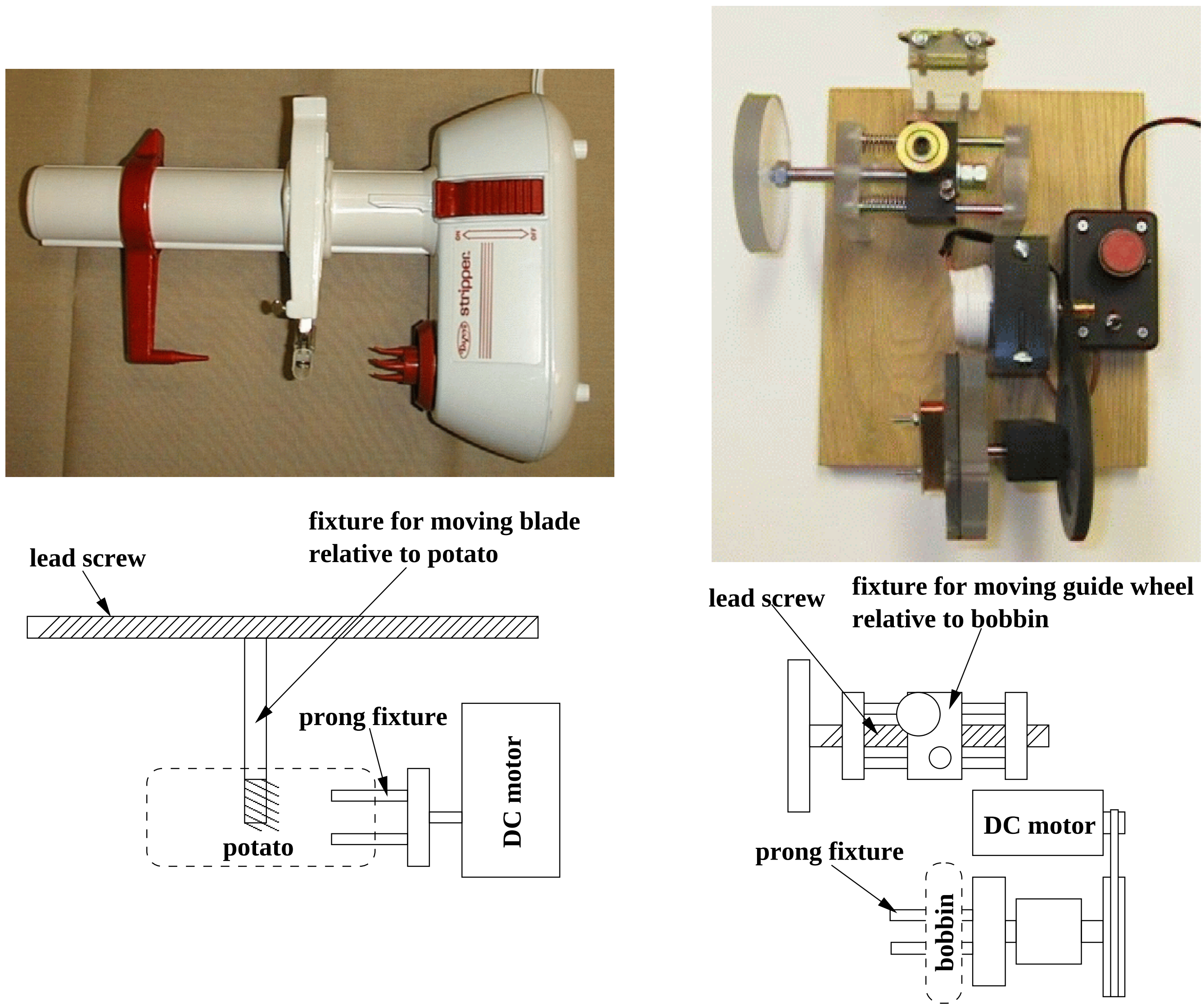


Figure 6. The vegetable peeler layout architecture as adapted to the winder.

by-analogy information. Also, a designer's current design-by-analogy vocabulary can be extended beyond their immediate experience, providing access and contributions to new domains by discovering different products with common functions.

A key result of the winder example is the identification of the fishing reel as similar to the pickup winder. Though, the fishing reel similarity may be obvious to some, the fact that the method quantified this similarity validates the accuracy of the design-by-analogy approach. Also, because this similarity comparison is made without any experience required in either fishing or pickup winding, the identification shows how the measure extends an engineer's experience base. In the final evaluation of the design, the adaptation of the fishing reel's wheel to guide the wire is an elegant solution to a difficult portion of the winder design. Also, during design concept review and selection, a review of the fishing reel validates the manufacturing and durability potential of the *guide solid* solution.

The more powerful result of the design by analogy techniques is the identification of products that do not initially appear similar. The fruit and vegetable peeler has a completely different customer base than the pickup winder - home makers and cooks as opposed to guitar technicians and hobbyist - and produces a completely different end product - peeled fruits and vegetables as opposed to guitar pickups. Yet, they contain a great deal of functional similarity. Using analogous concept solution from the stripper provided solution guidance for specific functions as well as important layout and architecture information used in the winder design.

These results are based on customer need focused functional similarity between products contained in the measure λ. A component, manufacturer, or structural comparison is unlikely to identify products as candidates for analogous design information for several significant reasons. To make a structural comparison, a solution for the winder must already exist. Thus, such a search would be fruitless in an effort to find suitable structural solutions for a given design problem. A component level comparison suffers the same inadequacy.

In addition, the methods presented here make contributions to product redesign and benchmarking efforts. The methods developed here present a quantitative measure of product similarity. This measure allows a designer to locate products for benchmarking whose similarity, or comparability, is not initially clear.

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