A Quantitative Similarity Metric for Design-by-Analogy

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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 for solutions is the conscious and unconscious reliance on prior experience and knowledge, or design-by-analogy. In this paper, a quantitative metric for design-by-analogy is developed. This metric is based on the functional similarity of products. By using this product-similarity metric, designers are able to formalize and quantify design-by-analogy techniques during concept and layout design. The methods, as developed in this paper, allow a designer with limited experience to develop sophisticated solutions that enhance the overall design of a new product. Also, a designer's current design-by-analogy vocabulary can be extended beyond his or her immediate experience, providing access and contributions to new domains by discovering different products with common functions. The similarity metric and its application are clarified and validated through a case study. The case study is the original design of a pickup winder. [DOI: 10.1115/1.1475317]

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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 for 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 metrics are developed that allow designers to identify products that are similar in a manner critical to the success of a design. This focused identification allows these similar products to be reviewed within the context of the design problem at hand for configuration, concept, and embodiment information. These metrics 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, groundwork 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 are critical tools in engineering and science. In 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. Such design philosophies have been proven valid and effective in the literature [1–4]. 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 important customer needs, these two products have a design-relevant similarity. When comparing more than two products, the notion of *more* or *less* similar becomes relevant. Thus, the goal is to extend beyond a binary notion of similar to a continuous and quantitative 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 in circuit design, due to the lack of quantitative similarity metrics available in mechanical design as compared to those available in circuit design [5]. As pointed out by Huhns [5], 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 is 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 in which the goal is to reproduce actions or tasks that are generally the responsibility of the designer [6].

There are some significant successes for mechanical design-by-analogy [7]. Often, these expert systems or knowledge-based design tools focus on problems that can be solved by a fixed and finite set of design variables [7]. Other successes have come dur-

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ing the development of expert systems for specific problem domains [8]. The effort in this paper is a toward a more general tool for design-by-analogy methods.

Bhatta and Goel develop an elegant model-based design-by-analogy method that is based on functional similarity [9,10]. Using functional similarity for locating relevant concept solutions is the basis for the approach presented here. Thus, the work presented in this paper and that of Bhatta and Goel have common goals and philosophies. A key contribution and distinction of the product similarity comparison method presented here is that it is not based on overall product function, but on sub-functions that are combined to provide overall product function.

An analogy-based problem-solving and concept-generating method which has been applied to mechanical and product design is the *Theory of Inventive Problem Solving* (TIPS or TRIZ) [11]. The basis of this theory is the discovery of patterns based on working principles in patents (largely from the former U.S.S.R.). In TIPS, recurring engineering conflicts and solutions have been identified and categorized. By making an analogy between an observed challenge in a new product and a TIPS conflict, design principles which have proven successful in the past can be applied to pursue possible means of solution. Though TIPS presents no quantified indicator of analogy, the work presented here shares the observation and reuse of existing solutions as a conceptual design aid in common with TIPS.

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

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
	stablize		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

3 Metrics for Similarity: Process and Details

The goal here is the provision of a metric that reveals analogies at a level that is useful for concept, configuration, and embodiment design. As discussed above, there are two key comparison criterion. 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 is to associate product functionality with customer relevance. The third is to construct quantitative metrics of product similarity. This metric 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 required for each product in the group [1–4]. 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 [12]. The complete formal definitions for these functions and flows is presented in [13]. These functions are used here as the best available set of basis functions.

From here forward, the *basic functions* are used. A more coarse representation can be achieved by using the *function classes* rather than the *basic functions*. Regardless of the expressiveness of the functional representation used, the procedure presented below is valid. Determining the different analogies discovered by using different levels of expression in the functional model is beyond the scope of this paper.

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 requires that a hand sander ''remove wood quickly and easily.'' What product functions are related to this customer need? What other customer needs are related to that function?

Functions that are important to customers are those that are central and critical to the overall success or failure of a product. The effort, innovation, and insight of design engineers is displayed in these functions. Thus, the importance of a function is central to a design-relevant similarity comparison. By extension, a tool to identify the critically important functions is crucial to the similarity metrics sought for design-by-analogy.

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 [14]. This first step ensures 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 numerical 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

Table 2 Basic flows.

Class	Basic	Sub-basic	Complement
	solid		hand, foot, head, etc
material	liquid		
	human		
	gas		
	human		motion, force
	biological		pressure, volumetric flow
		rotational	torque, angular velocity
	mechanical	translational	force, velocity
		vibrational	amplitude, frequency
	electrical		electromotive force, current
	hydraulic		pressure, volumetric flow
	thermal		temperature, heat flow
energy	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
		auditory	tone, verbal
		olfactory	
signal	status	tactile	temperature, roughness, pressure
		taste	
		visual	position, displacement
	control		

through each customer need, the assigned customer need weights are summed to determine a 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 subfunctions. 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 the 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 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. Any attempt to reduce sander 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 that 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 the importance of 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

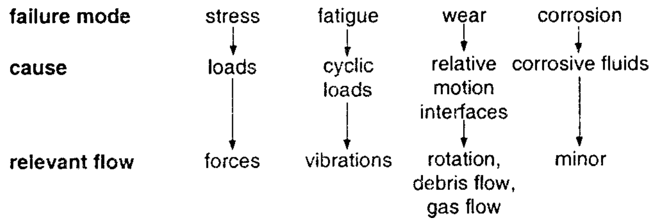


Fig. 1 The process of relating the customer need of "low maintenance" to functions for a hand sander

is simply represented 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 which provides a clear and compact way of reviewing the data. This approach to data organization facilitates computations on the importance measure. With this representation, the methods of matrix algebra can be applied to the space of products. Numerical computations can now be performed with 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 scale from 1 to 6. 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 occur when one function relates to several customer needs. This product-function matrix, Φ, is an mxn (m total different functions, n products) matrix. Each element ϕ_{ij} is the cumulative customer-need importance of the ith function for the jth product.

Differences in 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 the matrix N, the normalized version of Φ, are

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

The average customer rating is

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

The total customer rating for the jth product is

$$\eta_j=\sum_{i=1}^{m}\phi_{ij}. \tag{3}$$

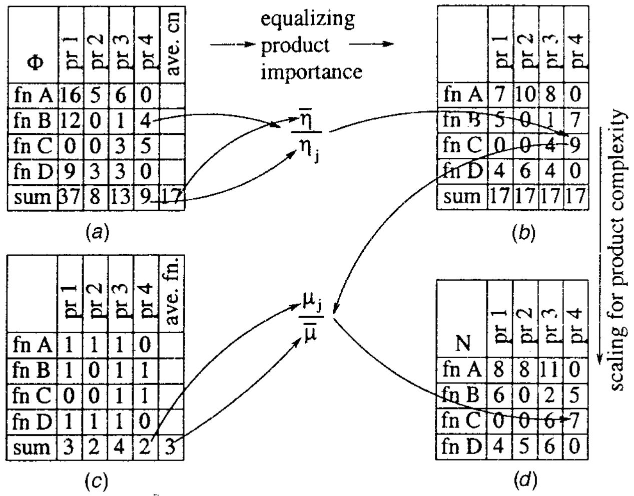


Fig. 2 Normalization process: (*a*) original function-product matrix Φ, (*b*) equalizing product importance, (*c*) determining average number of functions per product, and (*d*) scaling for product complexity to get the final matrix *N*

The number of functions in the jth product is

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

The average number of functions is

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

H is a Heaviside function defined as

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

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). This is done be multiplying ϕ_{ij} by the scaling coefficient ($\overline{\eta}/\eta_j$) as computed from Φ. Then this term is multiplied by the scaling coefficient ($\mu_j/\overline{\mu}$) as determined from the matrix shown in (c). The result is the final matrix N shown in (d). The functions in the N matrix are comparable for importance from product to product.

3.3 Computing Similarity. The elegance and power of this vector representation are made clear in the development of the quantified product similarity metric. Using the matrix representation, N, the entire domain of products can be reviewed for functional similarity. The product vectors generated from Eq. (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. Such a potential result is removed by the renormalization.

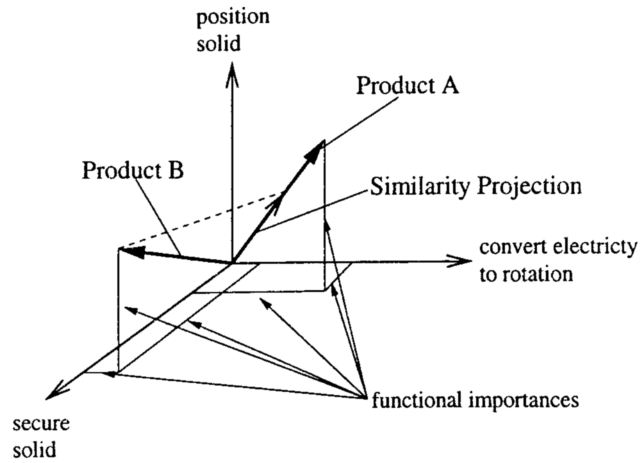


Fig. 3 A graphical interpretation of the product functional similarity projection

Once calculated, this projection is a product similarity metric. This projection is denoted with a λ_{ab} and is defined as the inner product between the product vectors for products a and b. The measure λ is based on the number of common functions in both products and the customer importance of those functions. In other words, this projection provides the desired measure of product similarity. It is a simultaneous measure of functional similarity and customer importance. A graphical representation of this projection is shown in Fig. 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 metric λ_{BA} for these two products.

For clarification of the formulation of λ consider the following representative numerical example. Shown in Table 3 are the product vectors for Product A and Product B. Forming λ_{BA} gives $(0.22,0.44,0.87)\circ(0.54,0.71,0.54) = 0.22\times0.54 + 0.44\times0.71 + 0.87\times0.54 = 0.55$

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 ith product on the jth product. Λ is the product similarity matrix. Using matrix multiplication to form the product similarity matrix Λ is similar to a technique Taylor [15] used to determine topics and frequencies of discussion on internet newsgroup 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.

As this similarity metric is computed in real time, the only data that need to be stored and accessed to allow for broad application of this method are customer need weighted functional models. This approach greatly reduces the overhead in data storage needed for locating similar products. The fundamental work needed to allow the generation of data to be performed by any designer is currently in progress [16].

Table 3 Product vectors for Products A and B.

	Product A	Product B
convert electricity to rotation	0.54	0.22
position solid	0.71	0.44
secure solid	0.45	0.87

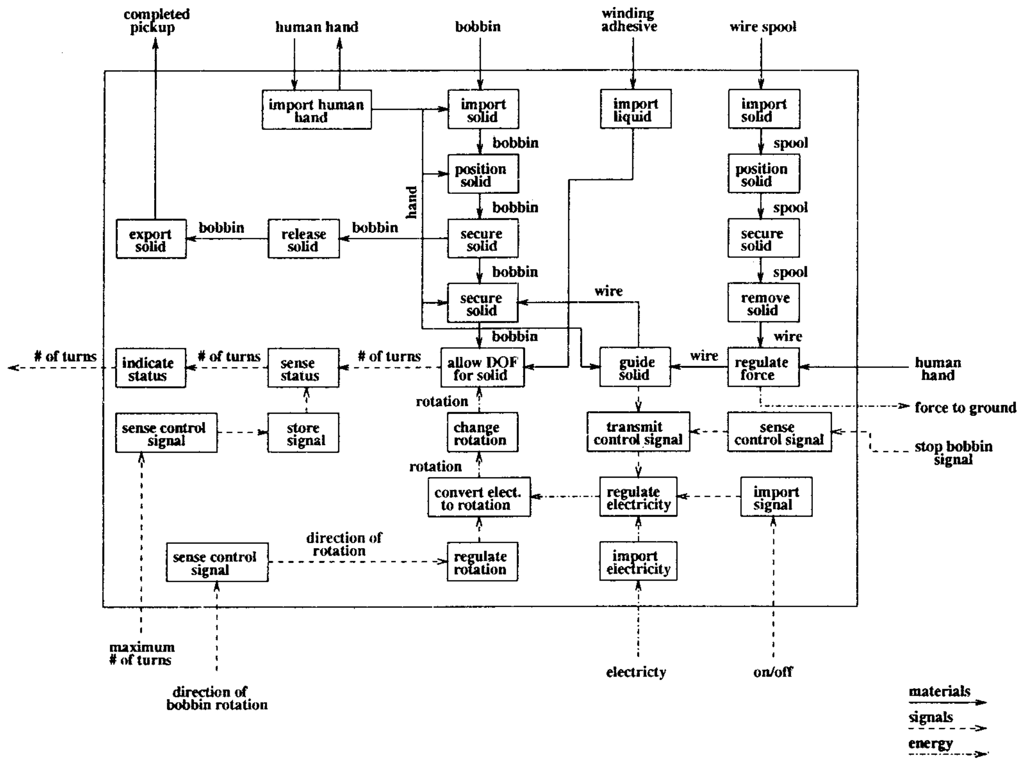


Fig. 4 The functional model of the pickup winder

4 Steps for Using Metrics for Design-By-Analogy

Using the product similarity metric λ, a design-by-analogy process consists of the following steps.

- Gather customer needs.
- Construct a functional model using a common functional language for all products modeled.
- Determine functional importance.
- Scale functional importance for comparison among products.
- Compute similarity metric λ.
- Using high values of λ, select a similar product subset
- Review these similar products for analogous solutions, insights, success and failures.
- Adapt solutions from these similar products into the design problem of interest.

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 metrics and methods developed here, a design case study electric guitar pickup winder is presented. Not only does the design serve as an epitome of the material developed, but 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 design-by-analogy process based on the similarity metric λ is applied.

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 58μm to 83μm) without breaking it (the maximum working strength 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 are acquired and a functional model is generated. The functional model for the winder is shown in Fig. 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 materials 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 using the approach presented in Section 3. Table 4 summarizes this procedure for the pickup winder. The resulting function importances for the winder are listed in Table 5. A review of Table 5 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*. Summarizing

Table 4 Relating customer needs to sub-functions for the pickup winder.

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	2	human hand	import human hand
wire tension		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

the approach in Section 3, these functions are important because they are the functions that operate on the flows that are critical to customer needs.

Now, the winder is added to an existing Φ matrix. The N matrix is formed using Eq. (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 6. These are the five products most similar to the pickup winder compared to the entire set of 68 products reviewed here. The products in this database cover a wide range of consumer applications, customer needs, and overall product function. They are mainly consumer-oriented, mechanical or electro-mechanical devices including toys, small kitchen appliances, small construction tools, and other small household appliances. The data from this set of products come from reverse engineering and redesign case studies performed at The University of Texas at Austin and The University of Missouri-Rolla, as well as product development in industry.

Table 5 Determining the function importance for the pickup winder.
The products ranked and shown in Table 6 are now reviewed

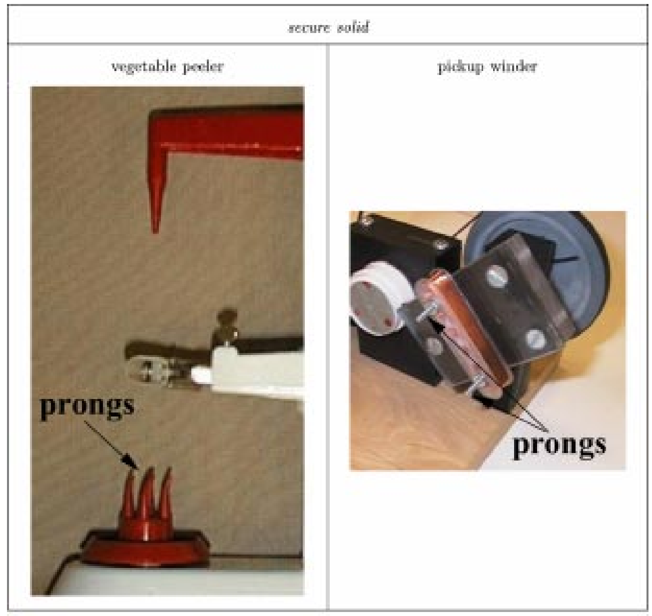
Function	Customer Weights	Sum
allow DOF solid; (bobbin)	5,5,5,4,4,3,3,3,2,2,1,	37
change rotation (adjust speed)	5,3,1	9
convert electricity to rotation	4,3,3,3,2,2,2	20
export solid (bobbin)	5,4,1	10
guide solid (wire)	5,5,5,3,3,3,2,1	32
import electrticity	1	1
import human hand	4,3,3,3,2,2,2,1	20
import 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 6 Results of the similarity calculation 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

The products ranked and shown in Table 6 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 7 shows the importance of functions in each of the similar products that have been included for review.

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



The review begins with the winder's most important function: *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 solids of interest for the peeler are various food objects such as potatoes and apples. The peeler uses a forked prong to penetrate the vegetable, thus holding it firmly in place. The question here is whether this can 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 interior voids in between the pole pieces. The material (generally vulcanized fiber) that holds the pole pieces in place can be pierced thus, allowing the bobbin to be secured. The implementation of this concept as adapted for the winder is shown in Table 8. The basic concept of piercing the

Table 7 The normalized function importances for each of the similar products.

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 9 Solution concept for *import solid* as adapted from the vegetable peeler

import solid	
vegetable peeler	pickup winder
	

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

The *import solid* function refers to two flows of solid: the solid flows are the bobbin and the magnet wire supply spool. These function are critical to the success of the winder and are simply solved. As in the case of the vegetable peeler, access space is provided for the importation of the solid. The comparison of this embodied solution for the vegetable peeler and the winder is shown in Table 9.

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 sufficient for positioning the spool. No analogous solutions from the similar products were adapted for the winder. The wire spool stand is visible in Fig. 5 which also shows the general layout of the pickup winder prototype.

Besides 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 10. 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 below.

The *guide solid* function is important to the target customers and, because of the precision required to meet the customer need metrics, is a challenging aspect of the winder design. Reviewing Table 7 shows that the fishing reel has a high importance for *guide solid*. The fishing reel uses a small circular pin to guide the fishing line as it winds onto the reel. This solution is easily adapted to the pickup winder as shown in Table 11. On the pickup winder, the circular pin guide is 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 of the magnet wire as it moves by a non-rotating guide.

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

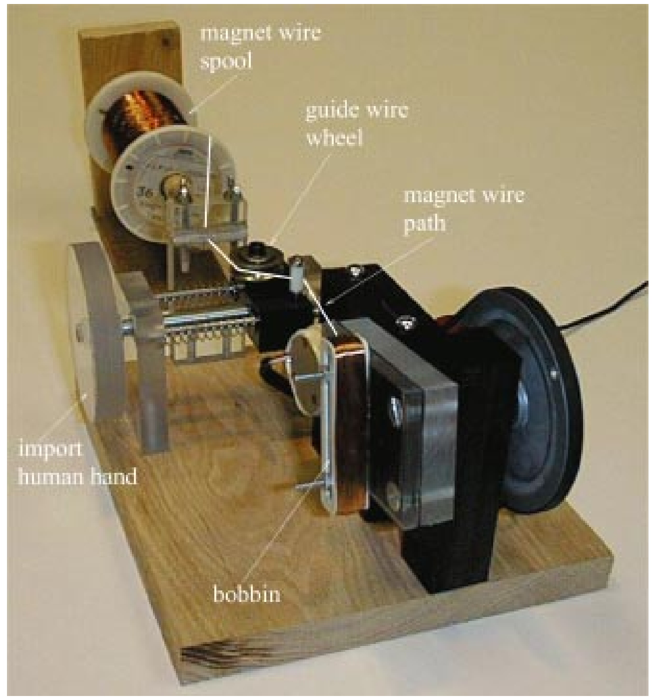


Fig. 5 An alpha prototype of the pickup winder

here to the tension control required for the magnet wire. The only other reviewed product that shares 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 12

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 using formal design-by-analogy methods, 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 can be obtained by viewing the vegetable peeler in its entirety as a product similar to the winder. A side-by-side comparison of the fruit and vegetable peeler reveals a interesting and powerful result of these

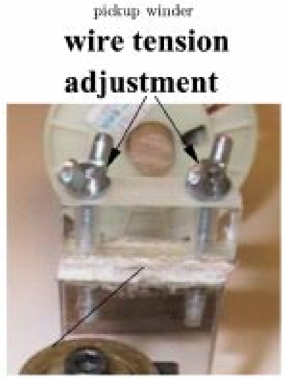
Table 10 Solution concept for *guide solid* as adapted from the vegetable peeler

position solid	
vegetable peeler	pickup winder
	

Table 11 **Solution concept for *guide solid* as adapted from the fishing reel**

guide solid	
fishing reel	pickup winder
	

Table 12 Solution concept for *regulate force* as adapted from the fishing reel

regulate force	
vegetable peeler	pickup winder
	

similarity metrics 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.

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

In this paper, a metric of product similarity is developed and 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 the original and innovative 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 Fig. 5.

To find these results without the analysis and methods presented in this paper is practically impossible. There are 68 products with over 1400 functions reviewed in the database. Reviewing this many products and functions for similarity is infeasible. The design-by-analogy method, as applied here, allows 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-by-analogy information. Also, a designer's current design-by-analogy vocabulary can be extended beyond his or her immediate experience, providing access and contributions to new domains through the discovery of 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 - homemakers and cooks as opposed to guitar technicians and hobbyists - and produces a completely different end product-peeled fruits and vegetables as opposed to guitar pickups. Yet, both devices contain a great deal of functional similarity. Using analogous concept solutions 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 among products contained in the metric λ. A component, manufacturer, or structural comparison is unlikely to identify

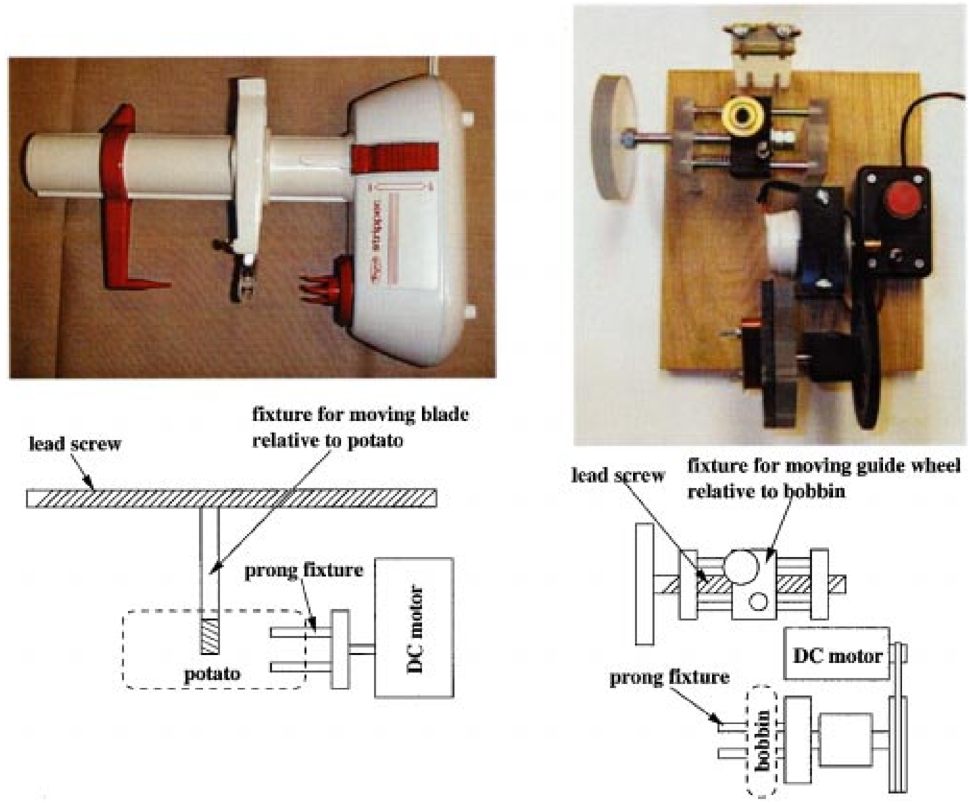


Fig. 6 The vegetable peeler layout architecture as adapted to the winder

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 contribute to product redesign and benchmarking efforts. A quantitative metric of product similarity is developed here. This metric allows a designer to locate products for benchmarking in cases where product similarity, or comparability, is not initially clear.

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