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In search of design synthesis by linking ergonomic evaluation and constraint modelling to attain 'Design for All'

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Abstract

To enable designers to 'design for all', a sound understanding of the intended users, their anthropometry and mobility is needed. Information is also required regarding users' abilities and disabilities based on the tasks they are to perform while using the product being designed. Users, each of whom is an individual (and not just a part of the population), have different needs, physical sizes, coping strategies, abilities and disabilities. To use and apply each of these parameters together with the variables of the product and to meet the challenges of 'design for all' criteria, it is imperative for the designers to use effective and efficient tools.

This paper presents an approach for design synthesis with the objective of determining design parameters of a design that would meet the needs of a specified user population or maximise the percentage accommodation.

A new software tool is being developed to assist designers in the product development process. This software is able to suggest design parameters that would maximise user accommodation, after considering all the data sets for individual users. To achieve this, the software utilises capabilities of three very different pieces of software. The first of these is called HADRIAN, which is the prototype software currently under development, by the 'Design for All' project group at Loughborough University. HADRIAN provides an integrated database about individual users and can carry out a task analysis for the tasks that the user has to perform when interacting with the product or the environment that is being developed. Mathematical analysis software is used to fit functions to this data so that the SWORDS Constraint Modelling software can be used to find the optimum parameters of the design that would maximise the user accommodation.

Issues in the design and implementation of this software system are discussed in the context of simple examples from kitchen design and automated teller machines (ATMs).

Introduction

The main ingredients of the design process can be identified as the designer, the concept of a product or a workplace and the user. Of these, the user must be considered as the most important ingredient of the design, for what use would the product be if it couldn't be used? The earlier in the design process the designer considers the user, the better the design from this perspective. Ultimately the users will decide on the suitability of the design by evaluating the product or the workplace on the basis of whether they can perform all the intended tasks.

Contrary to the established method of using anthropometric data of populations and univariate percentiles, it is extremely important to regard each user as an individual. Designers typically use databases that present data for the male and female 5^{th}, 50^{th} and 95^{th} percentile for each variable. The 5^{th} percentile stature means that 5% of the population are shorter than this and 95% are taller. Similarly, 95^{th} percentile means that only 5% of the population are taller than this. When considering percentiles the most important things to remember are, firstly, that percentiles are specific to the populations that they describe, which means that for example the 95^{th} percentile stature for a Vietnamese population could be equivalent to the 5^{th} percentile for a US population. Secondly, percentiles are specific to the dimension they describe. I.e. a person who is 70^{th} (or any other) percentile in stature can be 80^{th} (or any other) percentile in sitting height.

Hence it is obvious that these univariate data refer to only one characteristic at a time and provide little or no information of other body dimensions [1]. Therefore, using multivariate data on individuals is doubly important if the inclusive design concept is to be achieved. These multivariate data refer to the data gathered on real people of various ages, abilities, sizes and shapes and all the data for each individual is presented as a set, enabling the designers to picture the individual rather than just a statistic. To include all the intended users, each individual's anthropometry, mobility, abilities and disabilities need to be identified and addressed. This is especially true in the case of elderly or disabled users.

This is a daunting task for most designers as the multivariate database to accommodate all these parameters would be complex and gigantic in size. The fact that many designers are not trained ergonomists makes matters worse. Added to this, the designer needs to consider the usual aspects of the design with regards to reliability, functionality etc. Many software tools are now available for the designers to develop and visualise the physical aspects of their design three dimensionally. Human modelling systems such as SAMMIE [2], JACK [3] and SAFEWORK [4] can be used to evaluate the designs using three-dimensional human models. Figures 1 and 2 show two screen shots from JACK and SAMMIE showing their three dimensional human models.

Figure 1: A screen shot from JACK

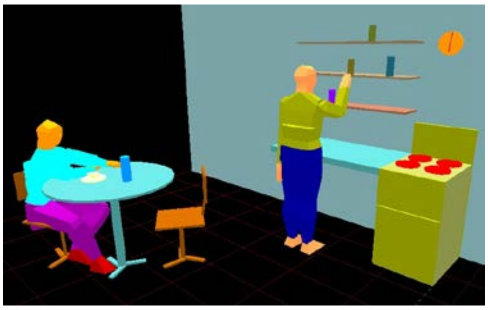

Figure 2: A screen shot from SAMMIE

HADRIAN, a new software tool that has been developed by the Design for All project group at Loughborough University, provides an integrated multivariate database of the individual users together with task analysis functions. HADRIAN can be used to analyse tasks that the user has to perform while interacting with the product or workplace under development.

These software eliminate the need for tedious, and when considering disabled users, sometimes impossible, user trials. However, to find the design parameters that would maximise the user accommodation, the designer will have to check every design parameter against every aspect of each individual user. Even with the fastest computer system, performing this task with existing software is unrealistic and almost impossible because of the very large search space generated by the multivariate nature of the user population and the infinite range of design parameters.

In this paper we describe a new software tool, SHIELDS (System for Human Interaction Evaluation and Design Synthesis), which utilizes the capabilities of three very different pieces of software, namely, HADRIAN, MATHEMATICA (mathematical software) and SWORDS (constraint modelling software) to find a set of design parameters that maximises user accommodation in relation to a design.

Background

When tackling a design problem, a designer has to consider the product or workplace's functionality, its ability to meet manufacturing and economic conditions as well as its geometry and usability. To include all the users, or at least to maximise the user accommodation of a design it is important to consider the physical aspects of a particular design and the multivariate aspects of the whole population. In order to evaluate issues such as access, fit, reach, vision, strength and posture, a good understanding of these users is required. The needs of older and disabled users must be given special attention, whereas young and able-bodied users may have greater ability to adjust to the additional stresses imposed by a poor design.

New design approaches within the concept of inclusive design are used to tackle this problem. For example Universal Design from the USA [5], the User Pyramid method [6] and the Inclusive Cube [7] from Europe and UK. However, these do not provide systematic design assistance for practical implementation of inclusive design practice.

HADRIAN (Human Anthropometric Data Requirements Investigation and Analysis) provides just such a tool [8]. It uses the functionality of SAMMIE, a human modelling system capable of modelling humans considering anthropometry, somatotype (flesh shape) and joint constraints. HADRIAN has the capability to assess fit, reach and vision of users of a particular design. An important feature of HADRIAN is that it contains a multivariate database of individuals, which includes anthropometric and mobility data and video of task behaviours and capabilities for the designer to be more familiar with the user. HADRIAN also provides the designer with a task analysis tool to enable analysis of the product or workplace under development and to apply sound ergonomic principles in evaluating it. It also has the ability to find who has been designed out of a product or an environment and why.

Design Synthesis

The prediction of the percentage of the users physically accommodated in a design is of utmost importance to the inclusive design approach. At the same time, if the parameters of the product or environment that would maximise the user accommodation, can be found without going through tedious user trials and laborious programming to test each individual, it would result in a huge saving financially and with respect to manpower. The software tool SHIELDS will provide this functionality by utilising the capability of HADRIAN in discovering which users have been designed out and why.

SHIELDS provides the designer with the capability to optimise the design parameters. It does this by considering the individual components of the product or the workplace being designed. For example, in an ATM machine, these components are the card slot, the screen, the receipt dispenser etc. In a kitchen work place these could be the cooker, the work surface, shelves etc. In this case if the remodelling of the cooker is allowed, (that is, if the cooker is not a standardised model used in the workplace) its components like the oven, hobs, knobs and the grill are analysed separately. These components can be independent or dependant based on whether remodelling or repositioning it would affect any other component. If there are components that affect others they are all taken together and their positions and/or sizes are fed to the system as dependant constraints that limit each other's movement or size.

Each of these components is first ergonomically tested using the multivariate data of individuals based on predetermined task criteria. If any of the components fail this and could not accommodate the required percentage of users, then that component is taken to the next stage of the optimisation process. In this stage, the size and/or the position of that component which maximises the user accommodation is found by using SWORDS.

SWORDS is a constraint modeller that has the ability to find an optimum solution using iterative techniques, given an objective function and constraints. The principle behind the constraint modeller is that it applies direct search techniques to find states that satisfy a set of chosen objectives [9].

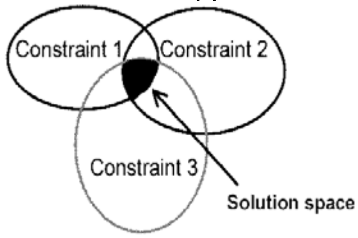

Figure 3: Use of Constraints

Figure 3 shows a solution space where a fully acceptable solution may exist within the given sets of constraints.

SWORDS is essentially a research tool, and uses these constraint modelling ideas for the design synthesis and optimisation of mechanism and machine systems. It allows users to define variables of a problem and then to specify the constraints between them. The software will then automatically search the configurations, which would satisfy these constraints. In the SWORDS macro language, which has features of BASIC and C languages, the constraints are specified within 'functions'. Functions also contain lists of variables, which the system is allowed to modify while searching for a solution.

Then the constraint modeller uses a concept known as 'truth maintenance', where the mathematical function that model each constraint has the value zero when it is fully satisfied (or true) [10]. SWORDS tries to satisfy all the functions that have been set as objective functions and/or constraint functions and will settle for the closest option or options in the case where a perfect answer cannot be found.

We have used SWORDS capability of finding the solution that satisfies a large number of constraint functions, to solve our design optimisation problem. The objective in this case is to find the sizes or positions of the components that would maximise the user accommodation. Constraints are due to the dependency of the components on each other and the limitations of the human individuals.

The computer tool

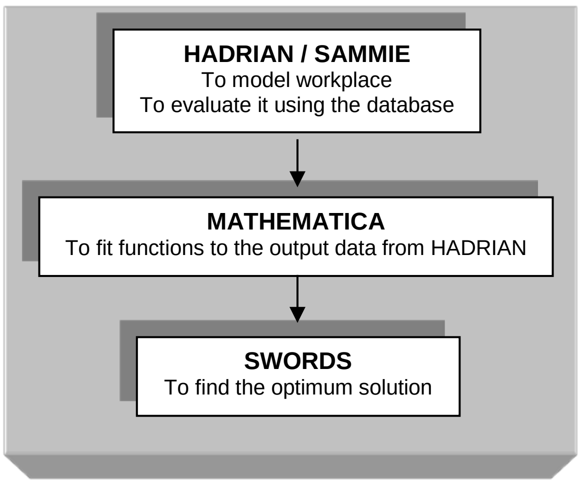

Figure 4: Components of SHIELDS

Figure 4 shows a block diagram of the components of SHIELDS, the new software tool. Basically it consists of three pieces of software bound together by underlying Visual Basic code. The communication between the software is by a series of text files. The output of the system will be the optimised parameters of the design and the users who are able to use it.

To optimise the design, first, the product or workplace model to be evaluated is loaded and is evaluated on the basis of predetermined task criteria. If the system specifies that any of the components has failed on the selected task criteria, the designer executes a program by means of selecting the components and pressing a few keys, to find the 'out of reach' values for every user. Out of reach value is the distance by which a user has failed to reach a specified object when the task criterion is set for reach.

Each component of the workplace may have one or several variables depending on its degrees of freedom of movement. For example, the shelves of a kitchen or a supermarket etc have only one degree of freedom, in the z direction. But a kettle on a work surface has three degrees of freedom in x, y directions and the rotation around z-axis. Since it depends on all these variables, the out of reach value is a function of all these variables. By varying the position of the component, out of reach values for each position are recorded for the desired object.

The initial challenge with this approach was determining how to translate the relevant sets of discrete data into the objective functions that the SWORDS software can understand. Figure 5 shows a sample set of data obtained for a single user (Subject 11) to reach the card slot of an ATM machine. Out of reach values were obtained by varying its position. –1 indicates that it is within reach for that particular position. All the positive figures for Out of Reach indicate varying degrees the respective users have in their inability to reach these positions. Now the objective lies in finding a position (values of x, y and z) such that all the users can reach the Card Slot.

Subject 11
REACH Card Slot

x	y	z	Out of reach by
-33.31	696.52	990.25	-1.00
-33.31	696.52	1115.25	-1.00
-33.31	696.52	1240.25	-1.00
-33.31	697.40	1488.13	4.93
154.30	696.55	990.23	-1.00
154.26	696.55	1115.23	-1.00
153.24	696.55	1240.23	15.96
153.19	696.55	1365.23	-1.00
153.12	697.42	1488.11	27.51

Figure 5: A data sample obtained for the ATM card slot

The solution proposed is to fit functions to these discrete sets of data. Since the 'out of reach' value depends on the position variables (x, y and z in this case), it is possible to write 'out of reach' as a function of these variables. e.g. out of reach for user 1 = f (x, y, z).

Similar functions are then fitted for all the users for that particular object, and for other objects if they fail the task criteria. This function was fitted to the above set of data using MATHEMATICA. It is an established commercial software package, which provides a multitude of technical computing facilities [11]. We used its ability to fit functions to non-linear data for this purpose.

The objective of the optimisation is the minimisation of these functions within the given set of constraints. Designers can provide these constraints through the user interface. Although components of the product or workplace are analysed separately, the composite problem is bound together at the optimisation stage by providing constraints of dependent objects that would influence each other.

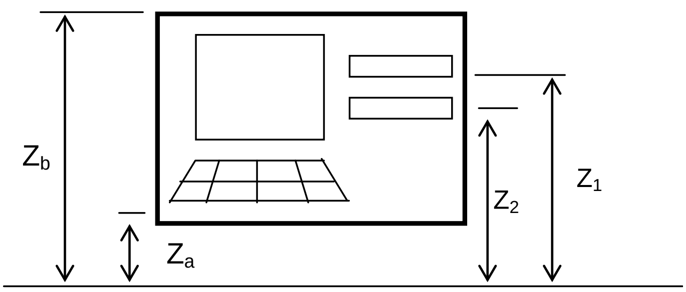

Figure 6: A line diagram to represent the ATM machine

For example, consider the diagram of the ATM machine shown in figure 6.

Z_a and Z_b are the minimum and maximum heights of the ATM casing and the card slot and the receipt dispenser are to be placed within this. The difference between Z_a and Z_b are say, 500mm. Together with this, if the distance between the height of the card slot (Z_1) and the height of the receipt dispenser (Z_2), needs to be set at 60mm, these constraint can be defined as,

$Z_a < Z_1 < Z_b$, $Z_a < Z_2 < Z_b$, $Z_1 – Z_2 = 60$, $Z_b – Z_a = 500$

Any number of these constraints can be specified at this stage. Optimisation can be carried out without the designer’s intervention or if necessary, the designer can specify which of the constraints should be given priority over the others. This may be used to (a) set the parameters of the design within a predetermined range (b) to grant a set of users priority over the others (c) to give everyone an equal opportunity.

Conclusion

The computer tool SHIELDS is being developed as part of PhD research. While recognising the fact that for a good design users’ cognitive ability, strength and other factors must be considered, the scope of this research is limited to their physical dimensions, constraints and vision.

Initial case studies conducted with the ATM machine have shown the ability of SHIELDS to be used as a tool for designers to enable them to optimise design parameters without the difficulties of user trials. SHIELDS is still in the development stage and although it demonstrates many potential capabilities it also has got certain limitations. This is especially true in specifying the number of degrees of freedom a component can have. The problem is due to the limitations of the underlying software and could easily be eliminated with the enhancements and developments anticipated in the newer versions of these software.

Further work on this is still being carried out. These will include SHIELDS’ capability to accommodate more components at a time, which is currently limited to two dependant groups although it can accommodate any number of independent components.

Acknowledgement

HADRIAN is the result of a three-year EPSRC funded project that was part of the EQUAL initiative. This project concluded in October 2002 but the development of HADRIAN is ongoing. The work described in this paper is outside the EPSRC-funded project but makes extensive use of HADRIAN, which is thankfully acknowledged.

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