Multicriteria Design Optimisation of Accessible Products for the Ageing Population

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Abstract— **A conceptual scheme is described for specifying utility objective functions within both multi-objective and multidisciplinary numerical optimisation frameworks, for application to the design of transgenerational accessible products, i.e., those which address optimally the functional and aspirational requirements of older people. A combinatorial, multicriteria objective function, comprising a weighted linear sum of single-effector objective functions (biomechanical, sensory, and cognitive), is formulated within a model framework of activities of daily living (ADL) performance scales and age-indexed anthropometric constraints. The aggregate objective function for accessibility must be parameterised in terms of physical design variables to render it amenable to computational optimisation. Candidate optimised solutions of the aggregate objective function in design variable space can then be found through a synthesis of analytical and stochastic techniques.**

I. INTRODUCTION

Computational multicriteria (or multi-objective) design optimisation (MDO) techniques have been employed productively in the aerospace, automotive, and process industries since the mid 1980s and, more recently, also applied to the design of consumer electrical appliances [1].

There is considerable potential for MDO to facilitate the design of mainstream durable consumer products which are matched optimally to the physical, sensory and cognitive capabilities of older people [2]. However, application of MDO in the gerontechnological domain is not reported in the scientific literature. This paper describes a conceptual framework for how such applications might be implemented.

The goal of computational design optimisation is to minimise (or maximise) the numerical value of an "objective function" - a particular formulation of the system (product) design variables, subject to various design constraints and fixed parameters [3]. The objective function therefore represents a measure of the desired utility or performance attributes of the system.

Design optimisation problems typically involve several, usually conflicting, design criteria that must be satisfied simultaneously (multi-objective). Moreover, design objectives in the same problem may be grounded in several different engineering and other disciplines, requiring the harmonisation of noncommensurate units (multidisciplinary).

MDO furnishes designers and product planners with a set of optimal alternatives based on quantifiable objectives. The designer will select a particular alternative based on additional, possibly non quantifiable, objectives not included in the MDO formulation [4].

The purpose of this paper is to introduce MDO concepts, explain why they are relevant to optimising accessibly design systems, and propose a conceptual framework within which MDO may be applied to accessible design problems.

II. MOTIVATION

Design of accessible products and built environments begins usually from the premise that it is feasible to design a product that adequately serves the needs of a specified range of user ages and abilities, given external constraints of manufacturing, economics, etc. The approach first is to carefully study the target users and the use environment, gather information about their anthropometric characteristics, and catalogue the various actual and potential barriers presented to usability of a particular class of mainstream product. This process involves A) a task analysis of subjects observed while using the products in question, B) identifying through experiment and questionnaires the design features that result in usability problems, then C) attempting to optimise those design attributes iteratively with the guide of user tests. Finally, a design solution is obtained that satisfies the user's needs according to specified performance criteria, such as ADL/IADL functionality [5], while complying with the external (non-user-related) engineering and manufacturing constraints. Additional, non-quantitative, factors may be considered, such as the affective (emotional) response of the user.

The iterative 'test-and-prototype' design approach just described usually is adequate for most situations where a small number of independent design parameters are involved. However, design through the process of user observation and prototype iteration is likely to run into difficulty as the number of design variables and associated constraints multiply, generating multifarious configurations that require physically prototyping and user testing.

Moreover, a design problem for improved accessibility involving multiple design variables may have more than one optimal solution; the challenge posed to the designer then is to select the most appropriate solution taking into consideration additional (possibly non-quantitative) factors. The extent of design freedom and solution complexity introduced by multiple design variables and constraints suggests the need for a formal analytical framework within which to identify potential solutions for optimal design.

Multi-objective design optimisation techniques provide the procedural means and mathematical framework for systematically identifying viable optimal design alternatives. However, in the field of accessible design for older users, and those with disability, the applicability of

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MDO techniques have not to date been investigated; and this is the motivation for the present study.

III. THEORETICAL FOUNDATIONS

Numerical design optimisation is the process of finding values of design variables that minimise one or several objective functions. The objective function is a measure of performance, according to specified functional requirements, based upon a formulation of design variables, fixed design parameters and design constraints. In the application to accessible design, the objective function will be an index of user accessibility, where the minimum value of the objective function corresponds to optimal accessibility.

Keeping within the context of accessible design, an optimisation problem is formulated as a function of decision (design) variables, each of which influences the level of accessibility in a particular respect; essentially the objective function is a model of the system of the system. Minimum values of the objective function represent candidate optimal solutions in design solution space, the dimensions of which equal the number of free variables introduced into the problem. Symbolically the accessibility optimisation problem is expressed as:

$$\text{Min } A(\vec{x}, \vec{p})$$
$$\text{such that } g(\vec{x}, \vec{p}) \le 0 \text{ and}$$
$$h(\vec{x}, \vec{p}) = 0,$$

where $A(\vec{x}, \vec{p})$ is the objective function for user accessibility, $\vec{x}=[x_1, x_2,....x_i,...x_N]^T$ is a column vector of N design variables, $\vec{p}=[p_1, p_2,....p_j,...p_M]^T$ is a column vector of M fixed design parameters of the system, and $g(\vec{x}, \vec{p})$ and $h(\vec{x}, \vec{p})$ are the design inequality and equality constraints respectively. Usually, lower and upper limits of the allowed values of the design variables will be specified: $x_{LB} \le x_i \le x_{LU}$ (where x_i is the i$^{\text{th}}$ element of the vector of design variables $\vec{x}$). The goal is to identify the values of the element of the design variables vector $\vec{x}$ which results in the minimum value for $A(\vec{x}, \vec{p})$.

The solution of Min $A(\vec{x}, \vec{p})$ is rarely trivial and often is not achievable using analytic function methods such as Steepest Decent, Simplex or Lagrange Multipliers. In practice, various evolutionary and stochastic search algorithms are required to find values of the design variable vector $\vec{x}$ components which result in minimum values for the objective function $A(\vec{x}, \vec{p})$ for given design constraints and boundary conditions [6,7]. Genetic algorithms, particle swarm [8], and simulated annealing [9] also are used extensively to plot possible optimum solutions in design space.

IV. MULTI-OBJECTIVE OPTIMISATION

In real-world design problems, even concerning relatively simple products, usually there will be two or more conflicting design objectives of the kind just described; Non user-related manufacturing-related objectives constraints will exist too, which further compounds the problem. As the number and dimensionality of the design objectives increases, the complexity in computing the solution for optimal values of interdependent variables increases geometrically.

The goal of multi-objective optimisation is to find the single solution that gives the best compromise between multiple objectives. A generic multi-objective optimisation problem can be expressed as finding the values of an N-variable vector $\vec{x}$ such that all sub-objectives $U_i(\vec{x})$ (i = 1 to K) are simultaneously optimised; i.e.,

$$\min_x [U_1(\vec{x}), U_2(\vec{x}), ..., U_K(\vec{x})]^T,$$

where the vector $\vec{x}$ contains the design variables of the product and each of $U_i(\vec{x})$ represent a functional design objective that is to be individually minimised to achieve optimal accessibility in some particular respect. The fixed design parameters $\vec{p}$ and, the inequality and equality constraint conditions $g(\vec{x}, \vec{p})$ and $h(\vec{x}, \vec{p})$, and the lower and upper bounds for $\vec{x}$ are included in the problem, as for the single objective paradigm described earlier.

V. PARETO OPTIMALITY

A multi-objective optimisation problem normally will contain several objective functions based on the same design variable vectors $\vec{x}$, or a least one or more members of $\vec{x}$. This will mean that the minimum values of one or more of the objective functions cannot be found simultaneously without causing non-minimum values for other objective functions; a trade-off therefore is required.

Whilst in single-objective optimisation a unique solution is sought, in multi-objective optimisation a set of non-dominated optimal solutions is required; this is known as the *Pareto optimal set*, and the corresponding values in objective function space constitute the Pareto front. The optimal situation is where there is no single dominant solution of the dependent variables. If this non-dominance optimality condition is satisfied, the solutions of the objective functions will then lie on the *Pareto Frontier*, in which further improvement in one objective can only occur at the expense of at least one other objective [10,11].

A multi-objective optimisation problem generally has a set of Pareto-optimal solutions rather than a single global solution. The choice of solution algorithm to compute values on the Pareto frontier is dictated by how well the solutions converge to the actual optimal solutions and the degree of diversity among these solutions [12].

To place the concept of Pareto optimality into the context of accessible design, multiple conflicting objectives may be specified in terms of particular sets of requirements by various demographically diverse user groups (old ,young, with disability, etc.). The locus of the Pareto frontier will be traced in N-dimensional user requirements objective space, where no single objective is dominant. This condition then would formally specify the possible design configurations for a universally-designed product.

A multi-objective optimisation problem will result normally with a set of solutions which line up on the locus of the Pareto optimal set. The design task is then to select the most appropriate solution from the set. This selection process is essentially a trade-off between the conflicting objectives among as set of non-dominating solutions of the objective function [13].

VI. Aggregate Objective Function (AOF)

An approach which results automatically in Pareto optimal solutions is the scalarised aggregate objective function, (AOF), which combines all the objectives as a weighted linear sum. Scalar weights are assigned for each component objective to be optimised. The AOF is expressed symbolically as:

$$\min J\{A(\vec{x},\vec{p})\}$$

where $J = \sum_{1}^{N} \alpha_i \frac{A_i}{k_i}$

in which α is a weighting factor , $\sum_{1}^{N} \alpha_i = 1$,

and k is an appropriate normalization scaling factor for each accessibility objective function A .

Solutions obtained using the linear weighted sum will be Pareto optimal; however specifying appropriate weights is left open to the designer's discretion. In the case of accessibility, clearly higher weights will be given to objective functions which are believed to most strongly influence accessibility. When conflicting objectives, each of which pertains to some aspect of accessibility are encountered, the designer needs to decide which accessibility attribute is the most important for the product or application in question.

VII. Multidisciplinary Design Optimisation

Product accessibility is a function primarily of the following effectors on the user:

- Biomechanical stress
- Sensory discrimination
- Cognitive Load

In other words, user interaction with the product should impose minimum biomechanical stresses (such as lifting and turning forces); it should confer maximum perceptibility by visual, auditory, and tactile senses; and it should present minimum cognitive load through simplicity of operation.

Owing to the multidisciplinary nature of the design optimisation problem to meet accessibility requirements with respect to distinct factors as biophysical stress, sensory discrimination, and cognitive load, the overall accessibility objective function necessarily will be a composite of individual objective functions for the three user effectors just described. For each sub-objective, a vector of variables is defined whose values influence accessibility with respect to each effector. The three variable vectors respectively for biomechanical stress, sensory perception, and cognitive load, shall be defined as: $\vec{b}$, $\vec{s}$, and $\vec{c}$. The corresponding objective functions for the effectors are $f(\vec{b},\vec{p}_b)$, $f(\vec{s},\vec{p}_s)$, and $f(\vec{c},\vec{p}_c)$, where $\vec{p}$ is the fixed parameter vector for each effector, as for the single objective problem, inequality and equality constraints $g(\vec{x},\vec{p})$, $h(\vec{x},\vec{p})$, and upper/lower boundary conditions for variable values will be specified. The global accessibility objective function can now be written as:

$$U(\vec{x}) = f(\vec{b}) + f(\vec{s}) + f(\vec{c}) ,$$

where $\vec{p}$, the vector of fixed parameters for each effector objective function, is implicit.

In the generalized formulation, each of the component objectives comprising the multidisciplinary objective function $U(\vec{x})$ is itself a function of multiple subobjectives (e.g., $f(\vec{b},\vec{p}_b)$ may be composed of several - possibly conflicting - biomechanical design objectives).

In the form which we have posed the accessibility optimisation problem, the operational function for each accessibility effector (biomechanical, sensory, and cognitive) is determined by empirical anthropometric data and theoretical models relating effectors to ADL/IADL performance measures and corresponding product design variables.

To optimise the biomechanical objective function $f(\vec{b})$ the desired solutions should, for instance, satisfy minimum values of required actuation force or applied loads for flexion/extension, pronation/supination, and radioulnar deviation of the arm. Corresponding minimum values typically are specified also for other musculoskeletal structures in the spine, pelvis, and lower limbs. Fixed design-related parameters will include anthropometric data and ADL/IADL scales.

The sensory discrimination objective function $f(\vec{s})$ is likewise decomposed into auditory, visual, and tactile sub-objectives. It may be necessary in certain design optimisation problems to further decompose tactile discriminatory variables into somatosensory (pressure, temperature) and proprioceptory attributes. Similar effector variables decomposition may be necessary also for visual acuity.

To specify quantitatively the variables and parameters comprising the cognitive load objective function $f(\vec{c})$ presents a more substantial challenge. Various cognitive functional scales (e.g., Folstein MMSE [14]) could be adapted for the purpose; but from a straightforward functional perspective for product accessibility, cognitive load can be assumed to be proportional to the number of user decisions and sequence of instructions required to operate or use the product [15].

VIII. AN ACCESSIBILITY OBJECTIVE FUNCTION

In seeking the appropriate variables with which to formulate the objective function, it is necessary to define the key parametric relationships between dependent variables and the performance measures which we wish to optimise.

The primary goal is to maximise user accessibility among the widest population of users subject to the inequality constraint that all individuals with ADL/IADL functionality greater than ADL_{min} are included. Secondary ranked (and possibly conflicting) objectives will include market and cost factors, etc.

The form of the objective function may be parameterised in terms of constraints specifying the proportion of the user population (say 65+) which is matched to the product with respect to anthropometric factors such as visual acuity, range of motion in joints, maximum forces and load required to use the product, etc. These factors in turn should be in correspondence to the relevant system attributes of the product to be optimised.

We must, therefore, operationalise 'accessibility' in quantitative terms in order to achieve our goal of formulating an objective function based on physical design parameters. The most direct approach is to map anthropometric capabilities to the design variables (size, weight, topology, etc) because anthropometric parameters values such as strength and range of motion are a function of age [16,17].

IX. CONCLUSION

This paper had sketched the essential aspects of multi-objective and multidisciplinary design optimisation methods and discussed how they might usefully be applied to the efficient design of accessible products and environments. More detailed analysis is required to elaborate practical application of MDO techniques to accessible design and demonstrate feasibility of the approach though case studies.

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