The implementation of a direct search approach for the resolution of complex and changing rule-based problems

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Abstract

During the evolution of constraint modelling approaches, they have increased in their ability to resolve more and more complex problems. They all rely upon their ability to define the design problem by a set of constraint rules, which are true when the problem is solved, by the manipulation of selected free variables. However as they have advanced differing techniques have been applied to address problems of increasing complexity. This study has been directed towards addressing those that are not only complex but also ill structured and evolving. In order to address such problems an approach has been developed that employs sensitivity analysis and problem strategies to form an evolving direct search technique. Whilst this is generic approach that has been applied to a range of engineering problems it is illustrated here through its use in a study into the posture modelling of humans. In this it was recognized that such a new approach was required due to the complex description, limits and postures possible in the human body.

Keywords: design complexity, sensitivity, constraint resolution, human modelling

1 Introduction

Constraint modelling approaches have evolved over the last thirty years, they have increased in there ability to resolve more and more complex problems [1]. Core to the modelling approach is their ability to define the design/engineering problem by a set of constraint rules, which are true when the problem is solved, by the manipulation of selected free variables [2]. However, as they have advanced differing techniques have needed to be applied to address problems of increasing complexity [3]. One such complex problem is that of computer-based models of human, commonly known as manikins. Such manikins are currently being employed to investigate the interactions of man and machines [4] to meet new legislations and in the investigation of *inclusive design* [5] (Keates and Clarkson, 2003). The resolution of human posture presents a very complex problem.

Previous research by the authors has found that the number of variables can only sensibly be limited to 144 [6], in order to be able to cover all the possible movements in the major joints. However, most normal actions (i.e. motions by able humans) can be covered by a reduced set of 57 freedoms [6]. Not all of them will be required in every solution. In some cases very few will be required, such as pointing at an object in front of the human. However in others most variables may be required, such as when taking up a complex posture whilst balancing on one foot. In moving from one posture to another almost all freedoms may be required. As with other design problems the selection of different variables is thus, compounded by the inclusion or elimination of the rules associated with different tasks. The ability to change both variables and task rules, during the resolution process (in order to determine an acceptable state) creates a dynamic problem solving condition, in which no preconceived approach can be established at the start and no solution can be guaranteed.

In order to address such problems an approach has been developed that employs sensitivity analysis to select and rank (by normalizing) the variables that have the greatest influence on the solution, and uses problem strategies to form an evolving direct search technique. Whilst this is a generic approach that has been applied to a range of engineering problems it is illustrated here through its use in a study into the posture of humans. In this it was recognized that such a new approach was required due to the complex description, limits and postures possible in the human body. This paper is structured as follows: section 2 gives a background in the research area of resolutions techniques, section 3 gives an overview of the human modelling problem, Section 4 describes the approach, section 5 presents the approach demonstrated on three examples and conclusions are drawn in section 6.

2. Background

Constraint and rule-based resolution processes have evolved to address engineering problems [1,2,7,8]. These were based upon the approach of defining all aspects that needed to be resolved as *design/ constraint rules* that were deemed to be true when the problem was resolved. These rules could be used to express a state of geometry, a mathematical expression or a logical relationship. All of these were constructed so as to equate to a value of zero when true and could thus be contained within a rule-function that when true itself equated to zero. Selected design variables, within these expressions, could be manipulated by a direct search routine [9] to seek a true (zero state) for all the rules.

This process has been incorporated within a computer modelling environment [10] that allowed the model spaces of the problem to be manipulated as well as the parameters of the equations and geometric components of the defined problem. In this manner components could be sought that fitted to others or the spaces manipulated to form simple assemblies [11]. An increase in complexity was provided to allow the individual rules of a problem to be clustered within a single function in order to provide solutions to complex assemblies and the operation of complete mechanism chains [12]. This technique is illustrated in Figure 1a where a film grip mechanism, employed in a toffee-wrapping machine, has been resolved by this approach. Figure 1b shows the mechanism in solid, it uses two cams to drive a blade that both lifts and pulls the wrapper into the correct position (shown as a trail of points in the upper left sector). Each element of the mechanism train is assembled by rules describing the connectivity that exists between the various components and their pivot points. The resolution variables are declared as the necessary rotations and translations of the component spaces in order to complete a correct (true) assembly of the complete system, in a chosen orientation of the driving cams [11]. By rotating the cams to a new position and resolving again the mechanism can be investigated throughout its operating cycle [12].

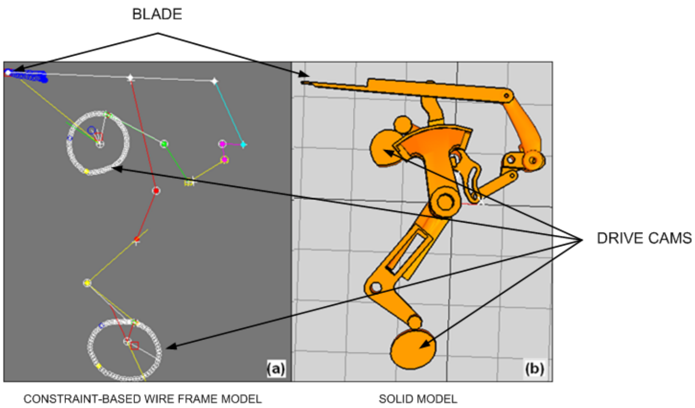

Figure 1. Mechanism chain

With an increase in the ability to handle more rules and design variables, came the need to form internal structures to represent the problem. Multiple rule sets were developed that could be assembled into a sequence of resolution activities (to represent complete mechanism trains) or nested to allow not only the internal rules to be true but to be optimized according to the rules of the external function [13]. The mechanism in Figure 1 was required to meet a new profile of lift and stroke. Rules were written to define the range of movement and selected value in the mechanism freed in order to allow a search to be conducted, and its respective capability to achieve a variant function

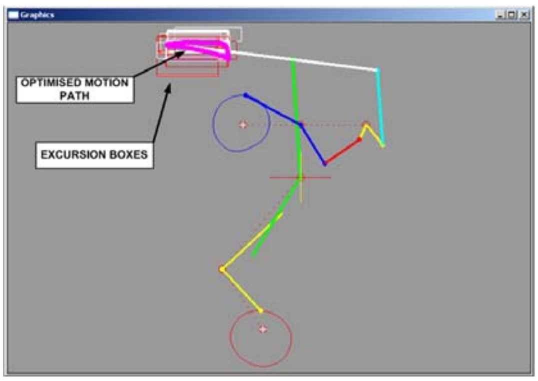

Figure 2. Optimized mechanism

Figure 2 shows the excursion boxes produced at each search together with both the final optimized motion and the modified geometry necessary to achieve it. This approach has been expanded further to find the performance limits and capability envelopes of machinery to handle variations in products [14], where constraint rules are employed to construct a given mechanism and further rules are employed to investigate the machines performance. An applied industrial case study of this approach is presented in Neale *et al.* [15].

The previously described approach can address complex design problems as long as they are well structured and ordered. Here the rules used in the resolution and design variables to be used need to be previously defined [13]. Such problems can then be broken down into a number of sub-problems in order to seek an overall solution, as in the toffee wrapping mechanism. Once complex interrelationships exist between the rules (or requirements) and partial problem rebuilding is allowed during the solution stage, then simple structuring cannot be maintained. This together with a potential large increase in the number of constraint rules and design variables to be used makes this class of problem very difficult to resolve. Such complexities arise when alternative topologies and mechanisms types are to be investigated and merged to create an entirely new solution [13]. Similar complexities arise when a large number of variables are chosen and the search is conducted across a wide and complex domain.

To address the above issues, research has moved progressively into the resolution of more and more complex problems [14]. One stream of research has further developed a range of heuristics and algorithms to investigate the design space [16-18. Another approach has been the formation of networks in which the problems could be reformed and the variables automatically selected for the different sub-clusters of the problem [1, 19-22]. Here the resolution structures were expanded to allow rules and variables to be selected from a predefined set of lists that defined the problem. These could then be restructured as the problem advanced or reformed if conflicts were found between either the individual rules or the derived rule functions.

In this paper a constraint-based network approach has been evolved to allow the problem structure to be derived automatically by the selection of rules from a large list that together defined the complete problem. All possible variables are initially considered and the dominating ones selected for the direct search of the solution. This technique has been further developed in this new direct search approach and been extensively used in the creation of human postures to meet given tasks.

3 Human modelling

Whilst the above approaches have been used in the design of complex engineering devices and machines, it was initially created to allow the complexities of human posture to be studied [4,6]. The simulation of these postures is being used to investigation how humans interact with machines. This is necessary if designers are to meet the new directives and regulations affecting the use of industrial processing machines. The human representation was based upon the ADAPS (Anthropometric Design Assessment Program System) [23] approach created by the group at the Technical University of Delft that had since been adapted for use in the constraint modelling environment at the University of Bath [24-26].

The spatial assembly of the human models (manikins), maintain their connectivity through the embedding of one space within another and the addition of a pivoting constraint, in order to define an articulated skeletal structure. This cannot however define the hierarchical order of the solution approach as this will change depending on the problem being addressed and the starting conditions of the search. When stood on the floor, the obvious order of the hierarchy is to move up from the feet to the highest action point (such as the eyes when looking is required or the hand if pointing). When sitting however the chain of relationships will originate at the buttocks with the legs unmoved. The most appropriate form of the hierarchical chain of limb/body part spaces has thus been found to move in from each extremity towards the torso [27].

Whilst this hierarchy represents no real physical condition, it does have the practical benefit of bringing the centre of the fundamental space (that of the torso) close to the resulting centre of mass when calculated [6]. The complete manikin thus rotates about a point close to that centre of mass requiring only minor translational corrections. Rotating about one foot may be inappropriate in some circumstances and in others results in the rotation of many limbs and an overall correction to reposition the model that could end up generating complex and unrealistic postures.

3.1 Body size data

Whilst the hierarchy of the kinematic assembly can remain fixed the geometric lengths cannot. Although during an individual investigation the skeletal geometry is fix in terms of limb and body sizes, it needs to be changeable to allow different sizes of humans to be represented (either to represent individuals or classes from babies to the elderly). Additionally, for the study of the elderly and disabled it may be necessary to restrict, truncate or remove limbs [28]. Each limb or body part is restricted in its number of degrees of freedom due to the pivoting command linking them. Further restrictions are imposed by the natural limitations of the body (such as the eye being unable to rotate in the plane of the vision). Additionally all actual freedoms are restricted in their total range of movement, both positive and negative. Also the analysis can become even more complex as the normally used range of movement is further restricted by natural or social limits, which may be abandoned or modified if conditions demand.

The range and connectivity of the skeletal geometry is thus seen to create a complex, interactive structure that has over 100 degrees of freedom that can be used to provide a potential posture. However many such postures fail to provide realistic solutions depending upon the tasks that the manikin is being asked to perform. This arises due to the starting condition of the manikin, the position of interacting objects in the world space and the number of constraint rules being imposed. For example if the manikin is initially standing and required to point at an object directly in front of it, then only the freedoms in a single arm may be required to achieve the task. If the manikin must also look as it points then the freedoms associated with the neck, head and eyes may additionally be involved. This relatively simple task can thus require many more freedoms if the focus point is behind and above the starting position of the manikin. The number of freedoms can be very difficult to determine in the general case as the number of rules becomes large and very interactive.

In a general task the approach may require the selection of many rules, the manipulation of a large number of limb freedoms and the determination of the acceptable limits of the movements involved. To find a solution to such a complex problem a new approach was investigated and applied within the constraint resolution environment.

4 The new resolution approach

This approach presented in this paper is based upon that of sensitivity analysis [29]. Here the influence of each variable upon the solution is sought and those having the greatest effects are preferentially applied. The sensitivity of each variable is found by disturbing them in turn. The sensitivity value is then defined as the change in the truth of the overall constraint rules divided by that unit change in the selected variable (When this unit value is small the change divided by the original truth approaches the true sensitivity value). By investigating the sensitivity of each parameter, about its current starting value, the number of freedoms can be systematically reduced. Firstly those having no effect at all upon the truth of the resolution can obviously be eliminated from the search at this stage of the investigation (but may need to be re-included later as the search moves into another part of the search domain).The next task is to normalize the remaining freedoms against the maximum sensitivity found. This allows further freedoms to be eliminated by setting a minimum normalized threshold, at say a hundredth of the maximum.

Beyond this point the selection of the influential variables is based upon the resolution strategy to be adopted. Here if the number remaining is large they must be reduced to a number appropriate for the direct search method being employed. This is initially achieved by raising the threshold for the minimum value, until that number is reached. At the commencement of the resolution search, the number of freedoms is further reduced to include only the most dominant set. At successive searches the number of freedoms is increased until either a solution is found or the lower threshold limit is reached. Such an approach thus commences through the simplification of the problem by applying only the dominant variables in the initial stage. This moves the solution search into the primary area of the solution domain. The gradual inclusion of the other parameters, in rank order, gradually moves the solution into sub-domains that satisfy the less significant rule states.

4.1 Resolution structure

The approach is based upon the above derived strategies and has been implemented, within a constraint modelling environment 'SWORDS' [10]. Here the constraints can be imposed by the user between the design parameters, these are essentially created by forming algebraic expressions which are deemed to be true when they evaluate to zero. The constraint modeller solves an optimization problem to resolve design constraints. The sum of the squares of the constraint expressions are used to generate the corresponding objective function. Mathematically, this problem is written in equation 1:

$$\textit{minimize} \quad f(\mathbf{x}) = \Sigma\, f_i(\mathbf{x})^2 \qquad (1)$$

where $\mathbf{x}$ is the vector of the n design parameters and $f_i(\mathbf{x})$ corresponds to the i-th constraint rule.

For practical problems the "best compromise" solution may be unacceptable because the corresponding design violates one or more essential constraints or physical laws. In this case additional weighting terms can be added to high priority constraint expressions and the resulting objective function is then defined equation 2:

$$f(\mathbf{x}) = \Sigma\, [W_i\, f_i(\mathbf{x})\,]^2 \qquad (2)$$

where W_i is the weighting term corresponding to the *i*-th constraint rule. Large relative weighting terms act as penalty factors against the violation of the corresponding constraint rule and help to ensure these more important constraints are satisfied. All algorithms for optimization problems require at least one set of design parameters to use as a starting point denoted by $\mathbf{x}_0$. From $\mathbf{x}_0$ a sequence is generated $\mathbf{x}_k$ that terminates when a solution has been found to the required accuracy or when no further progress can be made. Methods differ by how they move from one iterate to the next with a lower value of the objective function. The simplest numerical algorithms for the solution of optimization problems are direct-search methods [9]. These methods do not require any derivative information to locate a solution. Since only function evaluations are required, direct-search methods are robust and easy to implement.

The two direct-search methods that have been implemented in the constraint modeller are the Hooke and Jeeves method [30] and Powell's method [31]. These are established iterative methods for the solution of unconstrained optimization problems. Given a suitable starting point these approaches search the solution space by varying the design parameters and moving to regions where the objective function decreases in value. This means that optimization techniques can be used to try to seek design configurations in which all the imposed constraints are as true as possible, that is have a minimum combined falseness. During the search process, design parameters selected by the user are allowed to vary. Although design parameters and their constraints are ultimately specified in the interface language, it is possible to tailor the environment to handle specific types of design problem. This is done via a system of menus. This allows the user to interact with the environment without explicitly having to deal with the language itself. The new approach is carried out in six stages, as show in Figure 3. These stages establish:

- The rules of the defined problem
- The possible variables that may be used in the solution
- The sensitivity of these against the identified problem
- The selection of the key variables
- The problem resolution using the key variables
- The redefinition of the problem variables for the next iteration

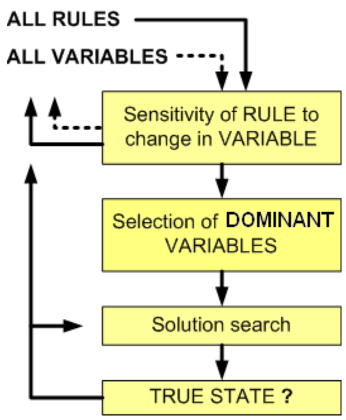

Figure 3. Resolution structure

4.2 Rules

Table 1 Sequence for climbing up a step.

ACTIVITIES	RULES	Stand to step	Balance	Lift foot	Foot over step	Foot to step	CofG over front foot	Raise back foot	Back foot to stand line	Stand on both feet
Left foot contact	1	1		0		1				
Right foot contact	2	1						0	1	
Left buttock on chair	3									
Right buttock on chair	4									
Lower back on chair back	5									
Higher back on chair back	6									
Left heal on chair line	7									
Right heal on chair line	8									
Balance box > x_min	9		10							
Balance box < x_max	10		10							
Balance box > y_min	11		10							
Balance box < y_max	12		10							
Trunk to rising height	13	1								
c of g into lap	14									
Left eye look	15									
Right eye look	16									
Pointing on line	17									
Pointing on end point	18									
Marker on point	19									
c of g onto traj. Point	20									
Left heal on 1st step line	21	1		0						
Right heal on 1st step line	22	1						0		
Left heal on 2nd step line	23					1				
Right heal on 2nd step line	24								1	
Left foot raised (toe)	25			1		0				
Left foot raised (heal)	26			1		0				
Left foot max height	27			1		0				
Right foot raised (toe)	28							1	0	
Right foot raised (heal)	29							1	0	
Right foot max height	30							1	0	
Heal over step	31				1					
Left eye on ball	32		10							
Right eye on ball	33		10							
Right hand on box	34									
Left hand on box	35									
Hold box away from body	36									
Left thigh on seat	37									
Right thigh on seat	38									
Spine points in right order	39									
Hand to handrail point	40									
Left foot point box (right)	41									
Left foot point box (left)	42									
Left foot point box (back)	43									
Left foot point box (fwd)	44									
Right foot point box (right)	45		1							
Right foot point box (left)	46		1							
Right foot point box (back)	47		1							
Right foot point box (fwd)	48		1							
Right arm out of body	49	1								
Left arm out of body	50	1								

	Rule switched on
	Rule kept on
	Rule switched off
n	Weight of rule

All the rules are initially assembled into a single function (termed ‘qqqqq2’, with ‘qqqqq1’ fixing all rules and ‘qqqqq3’ freeing them all). These functions are automatically created, by a parametric program that reads the rule data from a spreadsheet. Each rule in this resolution function is preceded by a weighting value, held in an array ‘rr[n]’, where ‘n’ is the rule number in the list. Each rule can thus be switched off by setting the appropriate weighting value to zero, by setting to 1 or its dominance in the search increased by applying larger values.

Whilst it is useful to increase the dominance of some rules to ensure that they are true in preference to others (such as standing may be far more important than the fine direction of the eyes) care must be taken to not over-weight some rules as this can force the solution into a domain in which the un-weighted rules may effectively be ignored. Ranges of weighting should only be imposed after careful consideration of the logic of the problem being addressed and not as a simple means of speeding up the conclusion of the search procedure.

In the current approach the individual rules can be selected and clustered together to form tasks or 'event elements' to be undertaken in sequence to complete a complicated action. Table 1 shows all activities and their constituent rules that potentially take place during the process of climbing stairs. These rules need to be set and removed as the manikin moves through the following sequence:

- Standing before the bottom step, in an erect posture.
- Obtaining a balanced posture and looking forwards
- Balanced with left foot raised
- Place left foot over step
- Place left foot on step
- Centre of mass over front foot
- Raise back foot (right)
- Back foot to standing position on step
- Standing on both feet

Within the approach, sequences as above are manually derived from practical studies of humans 23,27].

4.3 Variables

The first phase in the evaluation of the problem sets up a list of variables that are to be used in the broad sensitivity investigation and the resolution procedure. The rule list in Table 1 is realized by 57 variables that have been chosen to describe the manikin (and the interactions with a carried box). This list is a shortened version derived from the 144 freedoms possible in the articulated skeleton with the natural restrictions imposed by certain being joints removed. For specialized modelling, such as that of paraplegics, addition freedoms would be further removed. The variables used can be seen in Figure 4. The variable name is given and points to it respective space. The number in bracket below each variable relates to the specific number of freedoms available within that space. This list of variables thus contains all the possible freedoms that can be used to address the problem and includes both the six degrees of freedom that allow the complete manikin to be positioned within the world space (these are the 'man_space' parameters) and those of a box that can be carried. The importance of each freedom will change depending upon the problem described by the rules that have been activated. This is made more complex as in some tasks rules may need to be turned on and off at different stages of the problem [24].

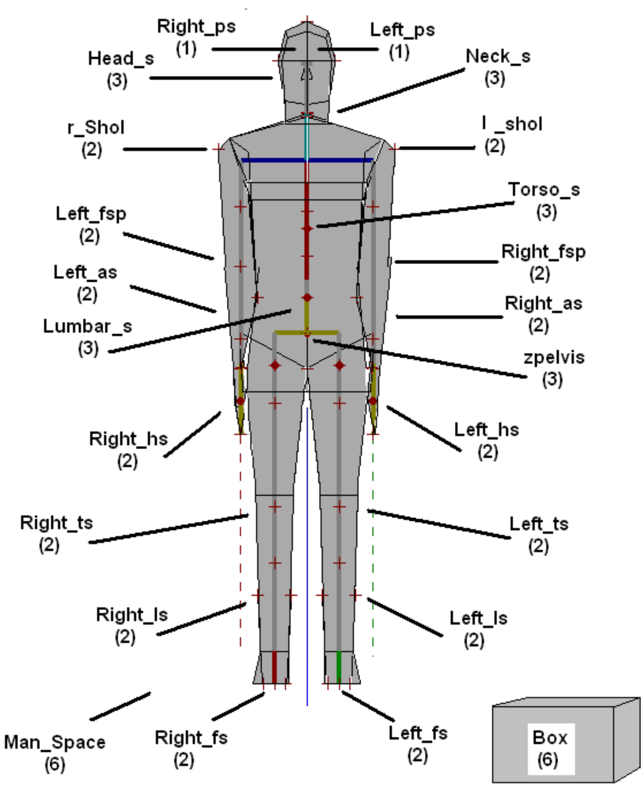

Figure 4. Variables selected for human model study

4.4 Sensitivity investigation

Once the rules and possible variables are established then a sensitivity investigation is undertaken. To achieve this all freedoms are fixed and then selected in turn and individually freed. Their influence on the overall solution is then determined through a 'sensitivity' function built into the constraint modeller. This determines the sensitivity of the overall solution to each freedom, with reference to the starting conditions of the variables. With different starting conditions, and if the search is restarted during the study, the influence of each variable will change. These sensitivity values of each are recorded in an array and the ones that have no effect upon the solution of the rules are then automatically turned off, by employing the 'fix'-function available within the modelling environment.

4.5 Normalizing the freedoms

The list of values are then ranked in descending order and normalized against the maximum value. The list is then scaled against the largest (set as 100). This gives a clear indication of those that dominate the solution and those that have little to no effect.

4.6 Selection of key variables

At this point various strategies can be applied in order to select the key or dominant variables that are to be applied in the initial solution search. This requires:

- *The setting of a minimum number of variables to be used in the solution*

  In most problems there is a distribution of normalized values stretching from a cluster of dominant ones down to those with a minor influence. If the problem is influenced by very few then they should be used but normally the distribution is not so clearly defined. In the general case the practical approach is to start with a very small number (usually 4), in the hope that the problem can be simply solved, and to rapidly increase the number if the search fails to establish the desired level of truth.

- *The setting of a maximum number of variables*

  The maximum number of variables that can be applied will depend upon the search algorithm being applied. Within a general direct search approach it is normally advisable to limit the search to twelve variables. Within this approach, where the number of variables is progressively increased, the solution is progressively moved within the solution domain towards a global true state. It is thus less likely to move randomly about in the domain, as many of the variables will have reached their optimum values before the new freedoms are applied. Thus the maximum number of variables can be sensibly doubled beyond the normal limit.

- *The selection of a threshold below which any variable with a lower normalized sensitivity can be ignored*

  As the constraint approach is based upon reducing the total error in the truth of the problem to a valued below a set termination value (usually set at 10^{-6}) then freedoms with normalized values less that twice that will have no significant effect in a large variable problem and can safely be eliminated.

- *A rate of change at which the threshold is increased as the search progresses*

  As indicated above, the approach converges most rapidly when the search commences with a small number of freedoms, which is progressively increased in repeated searches. If however the rate of increase is too great then the search can be moved widely about in the search domain. Various rates of increase have been used but for normal searches doubling the number of variables at each stage operates successfully.

- *And finally the conditions for the termination of the search*

  The search should be terminated for two main reasons. This can be as soon as the error in the total truth falls below a chosen limit irrespective of the number of freedoms that have been applied. Alternatively, if progressive searches fail to reduce the overall truth any further, indicating that a minimum state has been reached. In complex problems the truth may have been reduced to a low but acceptable state. On the other hand a high untrue state may indicate some conflict exists between some of the rules, which should be investigated and resolved before a true solution can be established.

When the variables have been ranked in order of their normalized sensitivities the dominant ones are readily seen. In cases of simple translations of the manikin only three or four variables may dominate with all others having normalized sensitivities well below 10%. On the other hand, complex actions requiring many rules and interactions can have as many as twelve, or more, variables with similarly high normalized sensitivities. It is for this reason that both high and low values are set to control the number of variable selected for the search routine.

4.7 Commencement of the search

At the commencement of the approach a high threshold is set to eliminate as many as possible of the variables but as the iterations continue, without a satisfactory solution being found, this threshold is decreased. Variables of 'lower and lower' normalized sensitivities are systematically included. There are many ways that can be used to reduce this threshold value but currently a rate of change value is employed that divides the original value repeatedly on each cycle of the search. Normally this is set as 2. The search is thus controlled by both setting the range of allowable variables selected from a progressively widening group of the most dominant. The search hence expands, including more variables until an acceptable level of truth is reached or a point is reached at which no improvement in the truth can be achieved. An ultimate termination of the search is provided when a set number of iterations are exceeded (irrespective of the state of the truth). The approach commences with the simplest form of the reduced problem and progressively expands the complexity, through the 'cascade' procedure until either the problem is resolved or it is established that no solution can be found.

5 Resolution examples

Whilst this direct search approach has been developed as a generic technique for use in complex evolving design problems (and been successfully used on the improvement of processing machinery) it is here demonstrated in the human posture problem, as the successful solutions are self-evident to the reader.

The use of this approach is aimed at providing solutions that seems to take on natural poses, rather than being simply the true state of the rules. This arises through the combination of the reduced variable set, the use of bounded values and the selection of rules. In all instances, whilst the full fifty-seven variables are available, as few as four may be used in the problem solution. In the following examples the approach is used to determine different solutions for a manikin standing upon the floor or step.

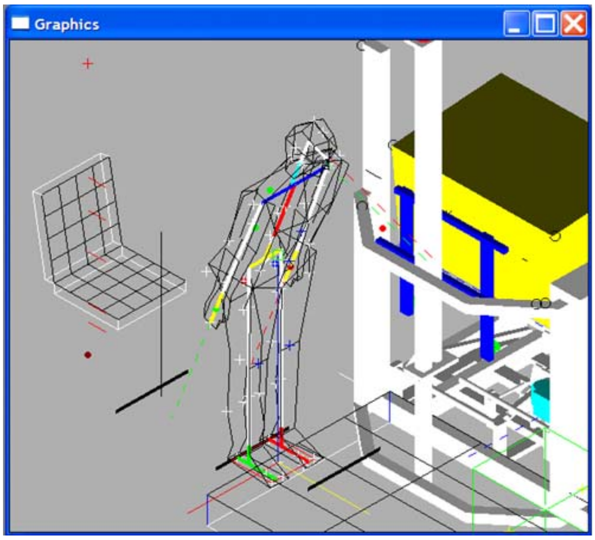

Figure 5. Posture found resulting from a straight starting condition

In the first case, shown in Figure 5, the manikin is initially standing in a straight posture at a point back from and above its final position. The constraint rules imposed upon this solution are those of standing to the step and looking at a forward point. Once in position the manikin is required to balance by moving the centre of mass within the base of support. This posture is found with only three iteration of the sensitivity evaluation. On the first iteration the solution is dominated by the single variable 'man_space:r' (that of moving the man directly down on to the ground). The second attempt is dominated by the four variables 'man_space:ax', 'zpelvis:ax','right_ ts:ax' and left_ts:ax' (those being all the variables contributing to the forward or backward lean of the manikin) together with 'man_space:q' (the variable that moves the manikin forward to the step). In the final iteration the same values are again used to provide minor corrections in the overall truth.

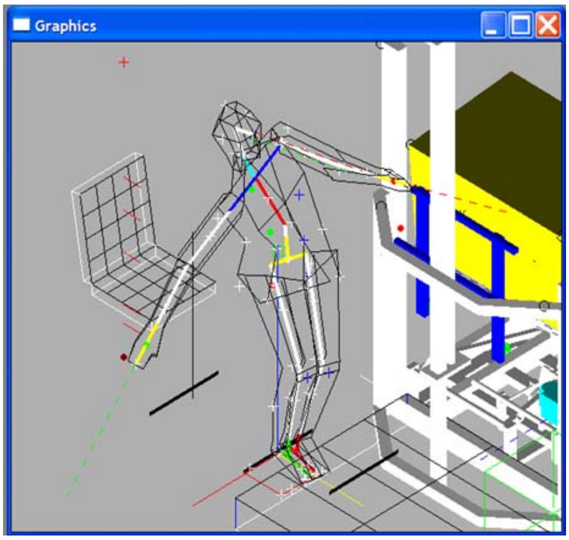

Figure 6. Second case starting with a random posture

Figure 6 shows a second case where the final state reached results from the same starting position as in the same as previously case but the original posture adopted was one of standing on one foot with the other raised and arms outstretched. This took five iterations to reach a standing position at the step and a further three to achieve a balanced state. Whilst the main variables are the same as in the previous case four of them dominate in the first iteration, three in the second, increasing to eight in the third, nine in the fourth and finally eighteen in the fifth. This large increase in variables arises from the need to correct the attitude and positions of the limbs, as well as the body and can extend down to movements of the head and neck in order to achieve an acceptable final posture. Such a large increase in numbers of variables throughout the complete solution greatly increases the computation time. However recognizable and acceptable postures and balance are still achieved.

In the third case the manikin problem has been greatly increased. This results from the additional rules requiring a box to be carried. The image reproduced in Figure 7 shows the state achieved after the manikin has passed through the various intermediate actions required to climb up and stand with both feet upon the step. The result of these complexities has required the search technique to undertake sixteen iterations and manipulate, at various stages, 28 variables.

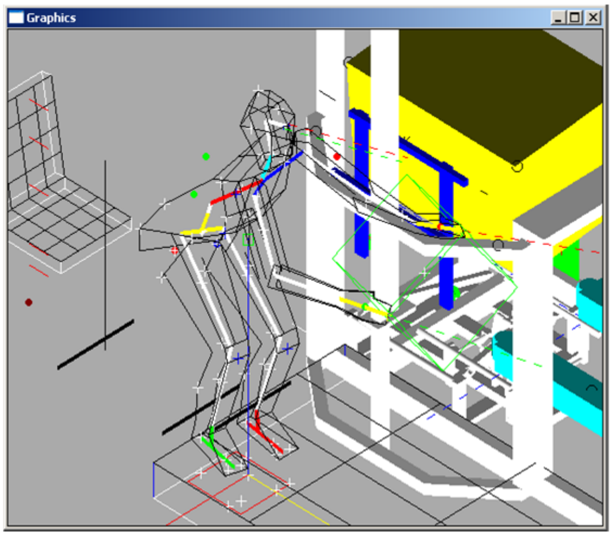

Figure 7. Posture found for manikin having climbed onto step whilst carrying a box

In the complete study of stair climbing all events required to move the manikin from a given starting position and posture to its final position were resolved in order to provide a complete sequence of events.

6 Conclusions

The objective of this study was to create and evaluate a direct search procedure for complex problems in which problems or 'events' could be created by the selection of constraint rules and resolved by the automatic selection of a set of search variables. This selection approach was based on sensitivity analysis followed by problem limiting strategies that selects the number of variables employed a various stages of the resolution. This has been successfully applied to various engineering problems but illustrated here with its application to a human posture investigation.

The need to obtain a solution to complex posture problems, in which rules can change, bounding conditions are imposed and the solution variables can change, necessitates the implementation of a complex solution approach. The one illustrated here is based upon the use of sensitivity analysis to select and rank (by normalizing) the variables that have the greatest influence on the solution. To simplify the problem only the most dominant variables are employed in the initial search. These are then systematically increased in subsequent iterations until an acceptable truth is found, the limiting number of variables is reached or no improvement is found in subsequent iterations. This approach has been developed as a generic constraint resolution approach and been used mainly in the resolution of a range of human posture studies.

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