UNDERSTANDING DESIGN COMPLEXITY THROUGH THE MODELLING OF HUMANS

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Abstract: *Constraint modelling at the University of Bath has in the main focused on issues of machine design and optimisation. Within such systems the mechanical elements can often be defined and resolved as a set of simple constraint rules and variables that sequentially support the overall operation of the machine. When uncertainty and errors are included the solution becomes more complex. In order to determine the possible levels of complexity that could be handled by the constraint approach, an investigation was commenced into the modelling of humans. The successful modelling of human interactions required the existing approach to be extended in three major areas: variability in geometric form, complexity and number of constraint rules applied and in the selection of potential solution variables. The interactions of these three aspects of constraint modelling were key to being able to find potential solutions to such problems. In many problems involving the geometry of a human manikin, constraint rules and solution variables all need to be manipulated in the search for a solution with little preplanning, as problem changes only became apparent as the solution space was searched. Whilst this study addressed the issues of modelling and resolving human interaction problems, the lessons learnt about advanced constraint resolution processes relevant to a wide range of engineering and processing problems. From this work new insights have been gained that will aid in the creation of advanced design approaches to handle problems of greater complexity.*

1. INTRODUCTION

Many methods employed for the design of machines and manufacturing processes rely upon the inherent simplicity of machine elements and their sequential assembly to be able to provide a representation of the complete system. A simulation of the machine can then be performed if timing information or sequential dependency is determined for the complete mechanism chain.

Once the system is less certain in its operation (as can be seen in figure 1) the output from even a relatively simple mechanism is difficult to determine. In this diagram a pusher mechanism is shown (with its pusher output shown at the top left of the figure) is driven by two separate cams. Whilst they were designed to principally provide separate motions (the upper providing the lifting motion and the lower the stroke) they interact to provide a wide range of complex motions if phasing errors are included between the cams. Some changes are highly detrimental to the desired motion of the mechanism and are unlikely to have been considered by the designer, but become all too apparent to the engineer during the assembly and setting of the machine.

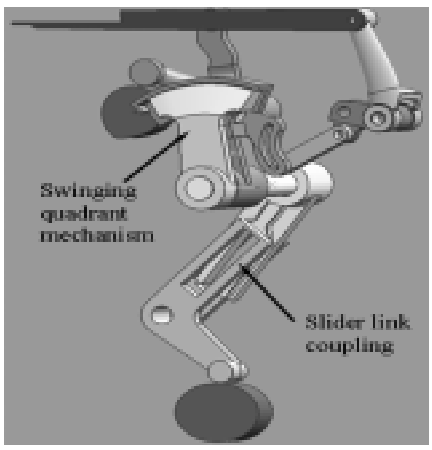

Fig 1. *Pusher mechanism driven by two cams*

Within this example other areas of motion complexity exists. Firstly the swinging quadrant mechanism contains a damped spring system to link the output linkages to the input. This is included to provide a safety device to prevent machine failure if the pusher collides with other parts of the machine or the product. Additionally the design contains mechanisms that, due to their geometric configurations, result in a degree of uncertainty in their output motion. The major, and most apparent, of these is the slider link coupling the lower cam follower to the rest of the mechanism chain. Here small errors in the slotted slider, due to manufacturing tolerances and wear can create large errors in motion down the chain as the movements are magnified.

The inclusion of such uncertainties into the system makes it difficult to solve by conventional approaches. However rules can be written to ensure the topology is maintained and that the additional actions, caused by the slider and safety mechanisms are included at the appropriate time. Through the use of constraint processes [1] such problems can be described and solved by a generic approach built upon a solution network [2]. In order to show the extent and complexity that can be handled (as opposed to the limited degrees-of-freedom in available for mechanism solutions) the approach has been pursued through research into the highly complex problem of human motion and posture.

2. CONSTRAINT RESOLUTION

The constraint based approach to design is based upon a generic problem solving approach [3]. Here the design objectives are specified as a set of testable goals that must be true when the problem is solved. To allow for a solution to be found a number of variables need to be specified that can be manipulated in a direct search for a true state [4].

Within the constraint modelling environment a wide range of rules can be specified that include mathematical, geometric and logical. These interact and manipulate the parametric values of the built-in geometric modeller (including ACIS solids [5]). Additionally the rules and variables can be clustered into sub-problems that can be solved sequentially or nested [6].

A wide range of design problems has been resolved by this approach which extends from medical devices, through machine design, to manufacturing processes [7, 8, 9].

3. HUMAN REPRESENTATION

The complexity of the resolution of human modelling problems arises from three main issues that interact in determining a solution. These are:

1. The variability of the model geometry
2. The number and intricacy of the individual task rules, and
3. The number of potential resolution variables

Additional complexity then arises through the interactions and dependencies.

3.1. Variations in geometry

In most design problems the geometric values are either known (and the performance of the mechanism is sought) or an optimised geometric form is sought to meet a given set of performance criteria. In human modelling both of these can apply, together with the need to select and test a range of known human types. If this is to be used in the investigation of subjects with disabilities this may also have to include deformities or loss of limbs.

In the investigations the skeletal geometry may be fixed to represent a single person. Skeletal types may need to be chosen to determine the class of person who can use a proposed device or the geometry may need to be varied to determine the range of human capabilities necessary to carry out a task (this may be complex in itself due to the possible interactions occurring between the limbs and tasks to be undertaken).

Within the modelling approach the limits to the angular relationships between the component geometry also needs to be taken into consideration in order to find acceptable postures. Some degrees-of-freedom at joints may be fixed whilst others have a limited range. Such ranges may change with age (or with the severity of a disability) or within social context. In public our gestures may be highly restrained whilst in critical situation they may extend over the full range of human capability.

A large and varied number of different geometric parameters and geometry limits may be imposed upon a human modelling problem. These may be restricted to only represent those elements impinging on a well-defined problem or may extend to 80 or more in complex tasks that necessitate full body movements and posture. The connectivity of the body segments results in a theoretical total of 144 degrees-of-freedom that can be reduced to 86 by observation of the restrictions placed upon some of the body joints. As all joint freedoms only operate over a limited angular range a technique was created to allow all to be bounded against a measured list. The model thus has 172 bounded constraints that can be continuously monitored and the limits adhered to throughout the search.

3.2. Task rules

The constraint approach requires that the problem being addressed is defined in terms of a set of rules that need to be simultaneously true if the problem is to be declared as solved. These rules may be explicit in form, such as a point in one piece of geometry coincident with another.

In machine design the rules for the topology ensure that the components assemble to form a valid kinematic mechanism with rules of motion ensuring that the mechanism cycles as required. The nesting of the assembly within the motion rules allows the machine to be run. In addition a set of rules may be defined for the performance and the machine optimised to meet those goals.

Although the levels of nesting may create a complex problem, all of the rules are known to apply throughout the problem. This is however not the case with human analysis.

Whilst most of the rules for human investigations may be simple, such as a point on the manikin's foot must be on the floor to ensure standing, there may, in a real problem, be a very large number of rules that can apply. Which of these is most appropriate for the actual problem may not be clear until a solution is being approached. Similarly the rule may influence other rules that need to be solved. For example the 'contact-with-the-floor' rule may influence the ability to balance and to satisfy the manikin posture rules, and as a consequence may even move the manikin to another position on the floor.

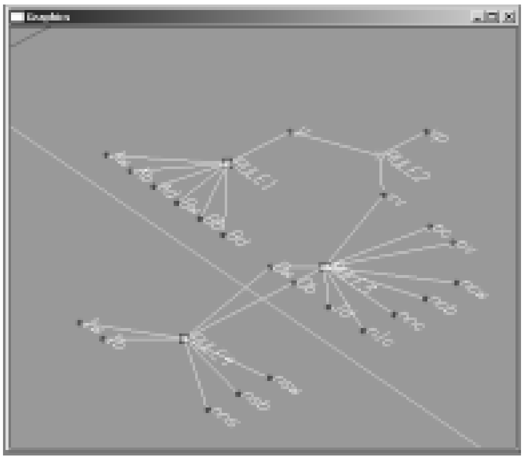

Fig 2. *Constraint rules network*

The number of rules can thus be relatively large (standing in the current research at about 40) which may or may not continuously apply in the final solution. Figure 2 shows the constraint rules network and the associated variables. With large numbers of rules being employed the network is useful in highlighting which rules are in operation.

3.2. Resolution variables

A similar complexity also exists with the variables to be used in the search. Whilst, as in the current model, 86 degrees-of-freedom influence the posture of the manikin not all apply all of the time. Those that influence the solution often are greatly dependent on the current or previous posture state. For example if the manikin is standing and required to point at an object it may be as easy as to simply point a finger. However in the extreme it may, due to the relative positioning, require a complete repositioning of the manikin and forming of a new posture for the body. Moving into a sitting position can conversely, restrict the allowable movement and can eliminate the effect of some variables (such the lower limb angles) which have a great influence whilst standing.

A new approach was thus sought to provide an automatic selection approach for the variables based upon sensitivity analysis (Figure 3).

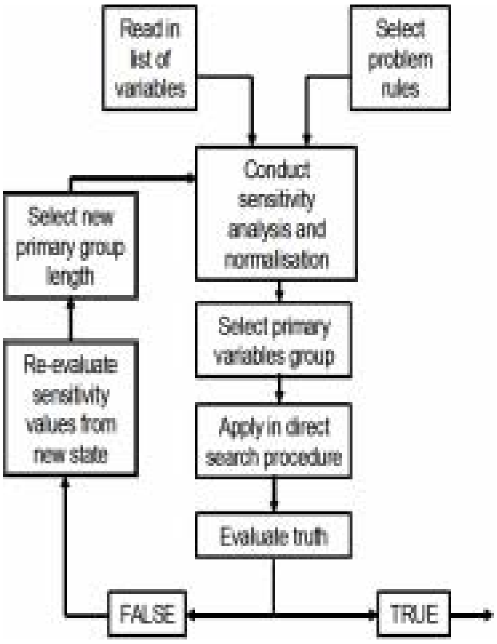

Fig 3. *Search approach based upon sensitivity analysis*

The approach seeks to determine the effect of each variable upon the final truth of the problem, determined from the current stage of the search. The sensitivity analysis is conducted at the starting state and then periodically repeated and modified as the search continues. This allows the variables with the greatest influence to be selected and applied. Additionally the number of variables to be used in the search is increased periodically as the search continues.

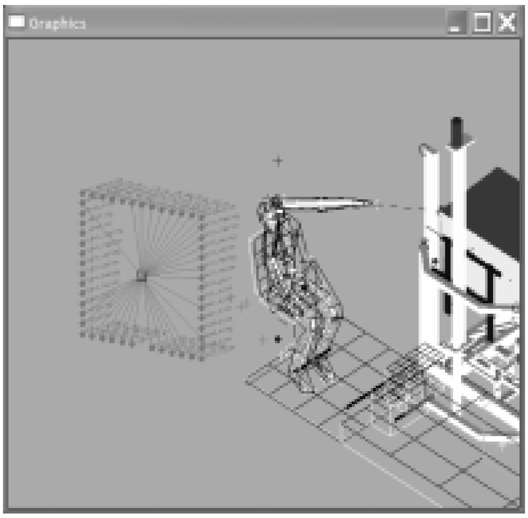

Fig 4. *Variables network*

With this approach the variables used to address the solution change as the search moves within the search space. As the search approaches the region in which the solution is to be found the number of variables increases allowing it to better define the problem space. In figure 4 the variable network is shown. This highlights which variable are being employed through the search process.

3.4. Solution environment

The solution of human modelling problems thus takes place within a complex environment in which the physical space, human rules and solution variables can all be manipulated and, even, redefined as the solution advances. Such a computer modelling environment has been constructed within the constraint modeller SWORDS at the University of Bath [10]. This has evolved over many years of research to allow the full human modelling capability to be achieved.

The approach now includes human data provided by the ADAPS group at the Technical University of Delft [11] who have measured and collected data on ergonomics issues and the human physique for many years. This allows a range of human types, extending from babies at birth through to the elderly, to be imported (figure 5).

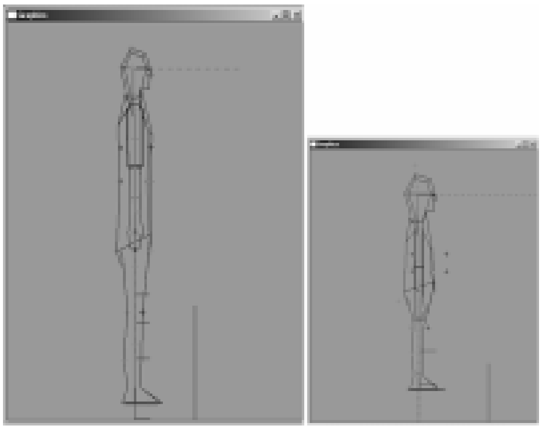

Fig 5. *A tall Dutchman and a 4-year old boy imported from ADAPS*

Whilst the human representation is in wireframe mode, solid elements can be applied for clash detection. Additionally a realistic surface representation is being investigated in the Visual Components environment (figure 6) [12].

Fig 6. *Realistic surface rendering in Visual Components*

4. HUMAN CASE STUDY EXAMPLES

The rules to be included within the constraint modeller have been determined through undertaking a range of research projects and case studies. Two of these initial studies are now presented, with a combination of rules in order to achieve desired tasks.

4.1. Standing

In this study the manikin is required to stand at the bottom of a flight of steps whilst touching a point on a handrail. This must be achieved whilst the model is in balance.

To achieve balance a routine is invoked that calculates the instantaneous positions of twelve body points (distributed throughout the main body parts and on the hands, to allow loads to be carried) and from them generates the current position of the centre of mass of the manikin. For balance, the vertical projection of the point must pass through the convex hull enveloping the points of contact with the floor. If a change of posture is required to achieve this, it may result in a new centre of mass and a new convex hull.

This situation can be further complicated by the fact that the manikin may require to lean upon a handrail reducing the load through the feet, but more importantly forcing the convex hull to change by including a projection of the contact point with the handrail.

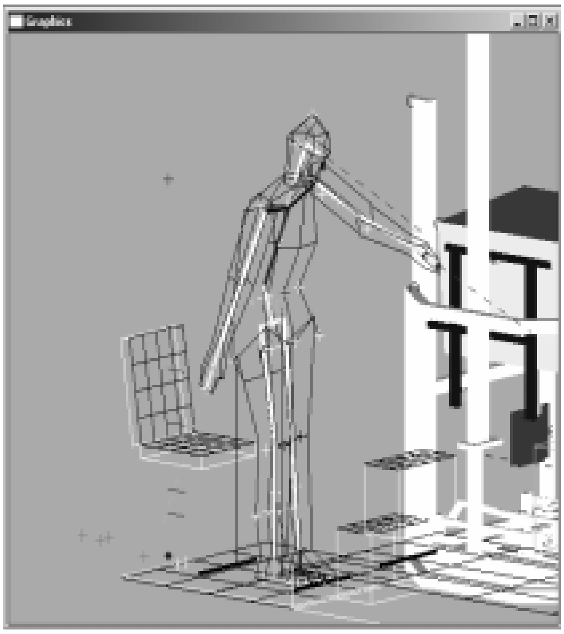

Fig 7. *Standing balanced at the base of steps whilst touching a hand point*

In the example shown in figure 7, the problem is complicated further by the requirement that the manikin needs to be prepared to climb the stair in front of him. It is thus necessary to focus the eyes to a point over the top step and to place the feet close to the bottom step (determined by the dark line ruled on the floor in front of the lower step base

The complexity of this problem arises out of the fact that there are eleven rules that need to be true for a successful solution (as well as all of the bounding conditions for joints being satisfied). These are:

1. *left inside toe on ground*
2. *left outside toe on ground*
3. *left heel on ground*
4. *right inside toe on ground*
5. *right outside toe on ground*
6. *left inside toe to line*
7. *right inside toe to line*
8. *left hand on handrail point*
9. *left eye looking at focusing point above steps*
10. *right eye looking at focusing point above steps*
11. *manikin balance over convex hull around feet*

In order to resolve this posture the potential exists for all of the 86 variables to have an influence upon the form of the solution. However in trials the sensitivity based approach started with only four key variables and then moved around the design space eventually using 34 values in its most complex search before shutting down after 14 iterations having achieved an error less than the chosen minimum (this being a total absolute error of 5 in all of the rules).

The problem commenced with the system having positioned the manikin standing to attention at a position well behind the line, which gave an initial error value of 3473 between all the rules.

The resulting posture is seen to be realistic but is not unique. By modifying the start point of the search, other regions of the search domain can be explored leading to slightly different final configurations (these variations are however greater when less rules and variable are applied to the problem).

The success of this initial study has led onto an investigation into stair climbing in collaboration with the Technical University of Delft. Stair climbing has been shown to constitute one of the most common forms of accident in both the home and the factory. Delft has great experience in such problems with the elderly whilst Bath has been investigating machine loading problems in the manufacturing and packaging areas. These activities have been brought together with Bath providing the modelling and Delft the ergonomic interpretation. An initial (simplistic) model of climbing stairs is being constructed (figure 8) where the transition of balance from one foot to the other is modelled.

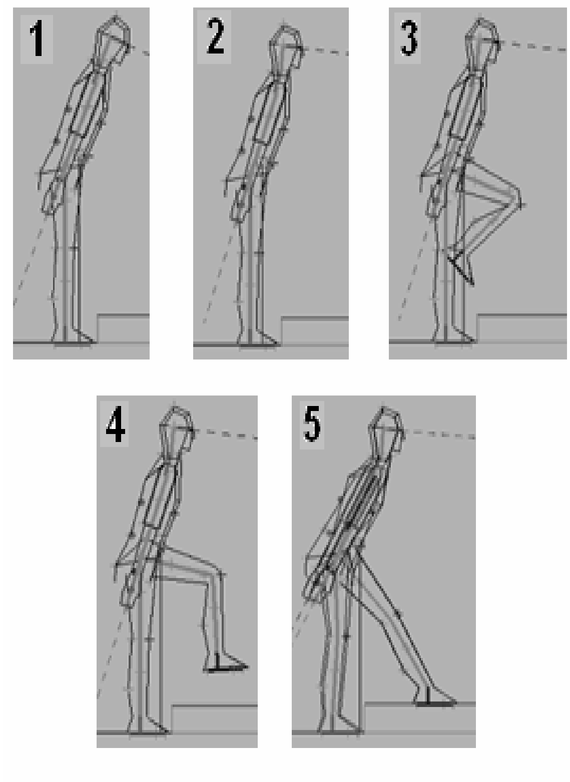

Fig 8. *Initial modelling of stair climbing*

Here the complexity of the problem will be increased still further with the requirement to carry objects up the stairs, for example boxes in the factory and a breakfast tray in the home. This is projected to take the rule count to over 25 and even more (and of greater complexity) when walking down stairs is undertaken.

4.2. Sitting

Sitting was included in the original set of studies in the form of moving from sit to stand. This was investigated under a separate grant studying human posture [13]. Generic processes of moving from sit to stand were investigated through the inclusion of rule sets that allowed transition states to be identified in maintaining balance between the initial sit condition and the end standing posture. This needed to cope with the variation in human stature, different starting postures and end objectives.

The sitting posture shown in figure 9 is one achieved with the objective of being able to look and point at an object on the lower, far end, of the machine. The ‘relaxed’ posture of sitting is one in which the manikin sits squarely upon his buttock and leans against the backrest (requiring 12 rules). His feet are also place together on the floor in front and his arms to the sides.

The requirements of pointing and looking at the far object results in an additional three rules. All of these are shown as follows:

1. *left inside toe on ground*
2. *left outside toe on ground*

3. *left heel on ground*
4. *right inside toe on ground*
5. *right outside toe on ground*
6. *right heel on ground*
7. *left buttock to seat*
8. *right buttock to seat*
9. *left thigh on seat*
10. *right thigh on seat*
11. *lower back point on backrest*
12. *higher back point on backrest*
13. *left eye looking at object*
14. *right eye looking at object*
15. *left hand pointing at object*

In searching for a solution (figure 7) in which the rules governing the ability to look and point, the manikin has had to turn in trunk whilst allowing the buttocks to remain on the seat. This arises because of the restrictions in eye, head and neck rotations. The solution has thus been found with the rule ‘leaning against the backrest’ abandoned and the natural posture of leaning forward used instead.

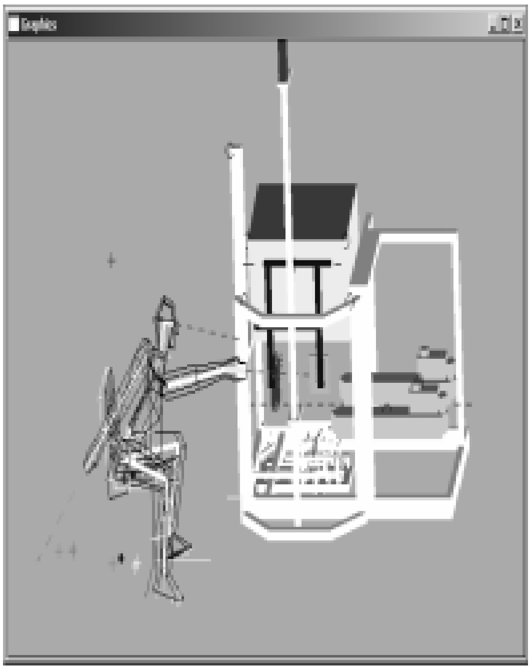

Fig 9. *Leaning forward to point whilst sitting.*

In a similar sitting study, shown in figure 10, a child is required to sit on the same seat (but looking and pointing at another point on the machine). Here there is no way that his feet can reach the floor while he remains on the seat. The complete rule set for floor contact (rules 1 to 6) has thus had to be abandoned showing the complexity that can occur within such a simple study as the postures of sitting

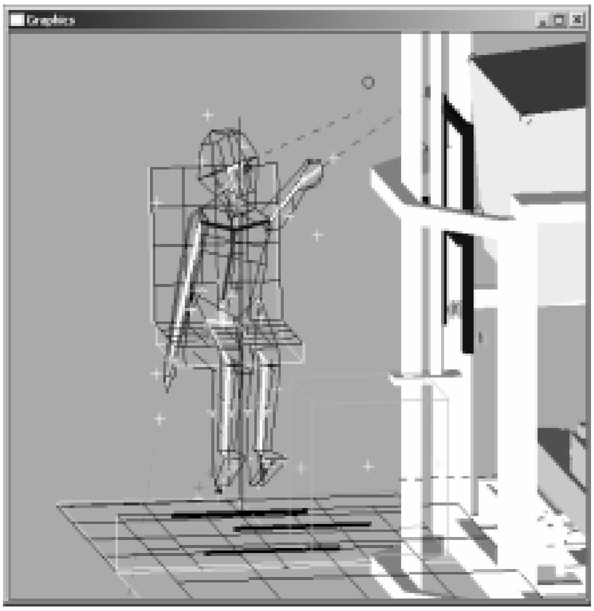

Fig 10. *Child sitting in chair with feet well clear of the ground*

4.3. General studies

The examples drawn from the standing and sitting studies have shown the complexity of rules and variables that exist in even such simple posture studies. Further studies are planned of increasing complexibility to address issues relating to industrial and domestic issues.

The capability of the approach to handle the interaction of the human operator and the machine whilst it is running will be explored. This is to enable the dangers and safety issues of such human/machine interactions to be investigated.

Through the ability to ‘age’ the manikin (by use of the capability data provided by the Delft group) and to restrict or deform the manikin form, studies are to be undertaken to investigate the ability of different people to perform tasks. This is intended to allow products and equipment to be modified to make them usable by a greater range of people. Initial work is curreently being undertaken into the strength and stability of paraplegics and tetraplegics.

5. CONCLUSIONS

The research undertaken into human modelling has provided an insight into the capability of the constraint modelling approach to handle issues of extreme complexity. The work has extended the existing approach in three major areas: variability in geometric form; complexity and number of constraint rules applied; and the selection of potential solution variables.

The interactions of these three aspects of constraint modelling are key to being able to find potential solutions to human based problems. In many cases the geometry may need to be changed to represent humans of different stature, abilities and disabilities.

Whilst it may be desirable to set many potential (and preferred) rules at the commencement of a search some may have to be later abandoned or modified in order to provide a realistic solution. Similarly the number and significance of individual variables may not be easy to determine at the commencement of the problem and may only become apparent as the solution advances through the problem space.

Whilst this study has addressed the issues of modelling and resolving human interaction problems, the lessons learnt about advanced constraint resolution processes are generic and can thus be applied to a wide range of engineering and processing problems. New design approaches to handle problems of greater complexity are now being investigated.

Acknowledgements

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