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UNDERSTANDING THE PERFORMANCE LIMITS OF HIGH-SPEED MACHINERY

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1 Background

A significant amount of high-speed machinery used within the packaging and process industry has evolved incrementally over time as the result of direct working experience of the individual designers. As customers have increased their demands for higher performance and greater variations in product handled, the designers have continued to adapt or modify their machines to achieve them. Many of these designs, and the principles upon which they are based, are reaching their fundamental performance limits. Any further increase in their performance envelopes can make them highly sensitive to slight changes in component geometry, set up, and variations in the product form and material properties.

Many such designs have evolved by a process of experimental adaptation, which has not been supported by any form of detailed analysis. The designs have thus migrated away from their original concepts without any means of verifying their current performance and with no way of predicting their capability of meeting new performance goals in the future. As this has been carried out in a haphazard manner, in order to simply meet customer requirement, often very little record is kept of what has taken place and all design knowledge is lost, except for the anecdotal stories of some long-term employees.

In order to overcome these limitations there is a need to create a full understanding of the existing machines and their limitations, together with means of recording and modifying the underpinning knowledge and principles of the design. From this it is possible to identify the true performance limits, the bounds on the performance capabilities and to ascertain the most appropriate approaches to be adopted in seeking new ways to develop machines of greater capabilities.

The engineering design team, within the Innovative Manufacturing Research Centre at the University of Bath, draws upon many years of experience of working with the packaging and food processing industries, which has led to the creation of design techniques that have been used to address the above problems. These are, in the main, centred on the team's expertise in constraint resolution techniques [1, 2].

2 Constraint resolution approach

The constraint modelling approach used for the resolution of engineering problems is based upon direct search strategies to problem solving [3]. The objectives of the design problem are formed as a set of constraint rules, which are all formed so as to be true when the problem is solved. A solution is then sought, by a direct search manipulation of the variables that are declared as 'free' within the problem. The approach thus seeks to find a set of values for these variables that result in all the rules being simultaneously true.

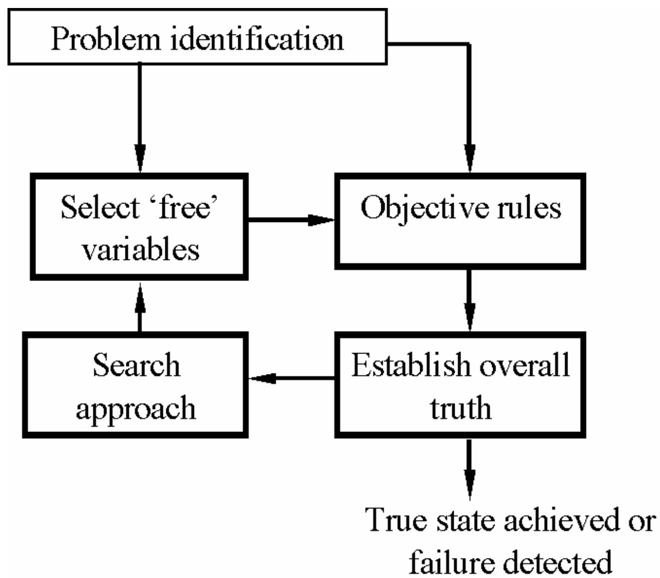

Figure 1. Structure of constraint resolution approach

The strategies set out to describe the rules of what must be achieved within the design, rather than to specify how it is to be accomplished (through a set of procedures). The search techniques allow new solutions to be found through differing combinations of design variables or new approaches to be found to meet an extended or modified set of requirements (through the change of rules).

As each rule is formed such that it is true when the relationship being sought equates to zero (thus containing no error in the equation or relationship) a 'true state' is declared when the square root of the sum of the squares of all the rules is zero (or within a chosen tolerance of zero).

Such an approach allows the problem to be formulated and solved in various forms extending from a sequential evaluation of all individual rules, a clustering of them or through the formation of nets. The internal structures can thus be created to allow a wide range of design and modelling problems to be considered that include machine/product interaction [4] through to the representation of human posture [5].

In the study of machines the kinematic analysis is performed not through the application of classical geometric solutions but through the creation of the rules of assembly [3]. These define the assembly by the use of 'point-on-point' commands to assemble the linkages, whilst a 'point-on-curve' command allows the follower to sit on the cam. The solution is then found through the manipulation of the model spaces, containing the components, until the direct search technique establishes that a 'true' solution has been found (that is one in which the errors in assembly are below a specified minimum). Such an approach allows all variables of the problem to be manipulated in a search for an optimised solution, including the component lengths, ground point positions and the types of assembly. The constraint resolution approach thus allows complex interactions between mechanisms and systems to be explored in a single environment.

3 Design methodology

The approach taken to the determination of the performance limits of machinery design is based upon an initial fundamental evaluation of the machine requirements and performance. As has previously been stated this is often not available at the outset of the investigation. It is usually evident that the machine works, as it can be seen to run and produce product. What is often unknown is how well it performs, whether it really does achieve the stated performance and whether it has the capability to cope with a set of desired performance changes [6]. In order to provide the basis for such studies it is necessary to build and validate a model of the current state that is known to work.

To illustrate this methodology a sweet/confectionary wrapping machine was investigated. This was chosen as it was not provided under any commercial confidentiality agreement and has a long history of improvements and changes, with very little available design history. For this study the pull-off mechanism was selected as it was seen to be a complex two cam system, contained many adjustments and was known to be very sensitive to changes in set up (Figure 2).

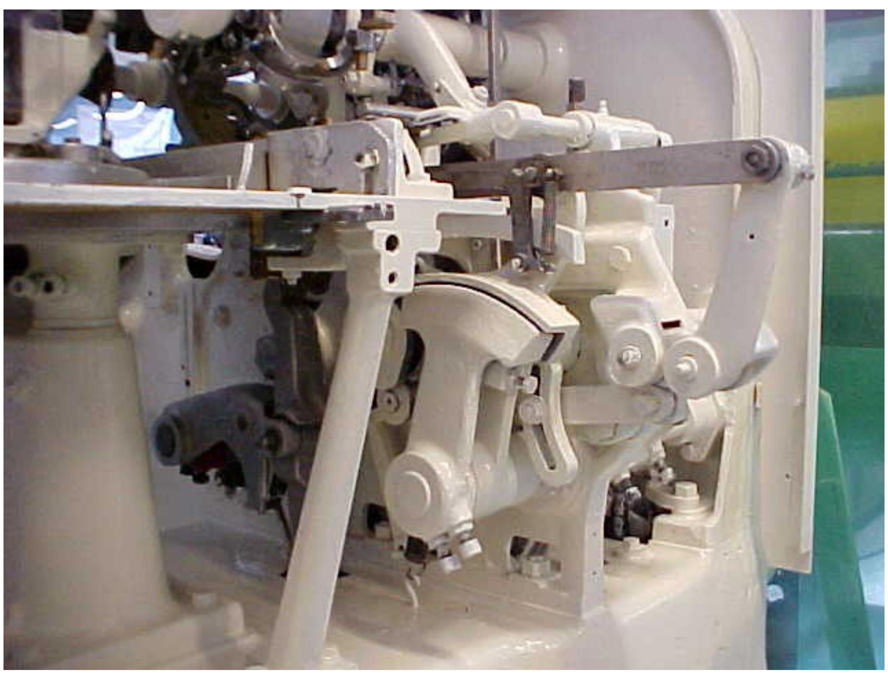

Figure 2 Pull-off mechanism in machine

This pull-off mechanism was measured and then modelled within the constraint modelling environment RASOR (Figure 3) that has been created by the research group at Bath. Many of the parts had to be measured whilst upon the machine and their setting values estimated. Additionally the cam profiles had to be estimated and attempts were made to take into account slop and wear that were present in the machine after over thirty years of use. These were then represented in the CAD environment as spline curves. These cams, together with all of the linkages, were entered into separate model spaces within the constraint modelling environment. The relationships between all components were then specified by either implicit or explicit rules to allow the mechanism to be positioned, pivoted and assembled (figure 3).

Within this assembly the mechanism can be seen to be reaching its functional limits is at the extremes of motion the transmission angles between some of the linkages are well beyond those normally accepted in practice. These have not as yet been extended to the point at which failure occurs but do result in the motions becoming uncertain. As two links in the pusher mechanism, for example, become aligned their angular positions becomes less certain and with slight tolerance errors can snap through into an alternative configuration.

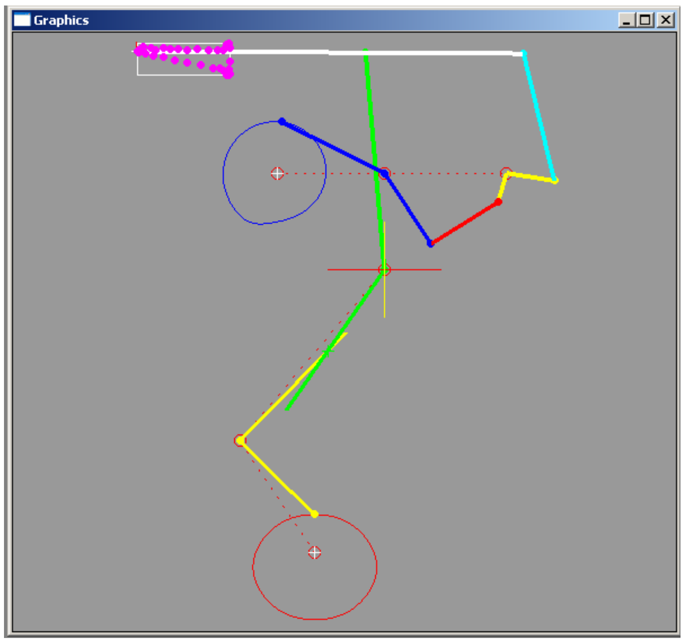

Figure 3. Constraint model of pull-off mechanism for toffee wrapping machine

Rules aligning the cam followers to cams were also included so that the mechanism motion could be simulated and the output motion of the pull-off end linkage obtained (figure 4). This was then compared directly with high-speed video images taken of the actual machine in operation (figure 5).

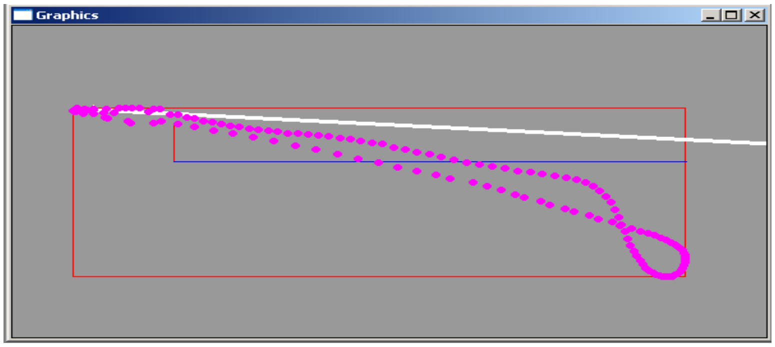

Figure 4. Motion of output pusher

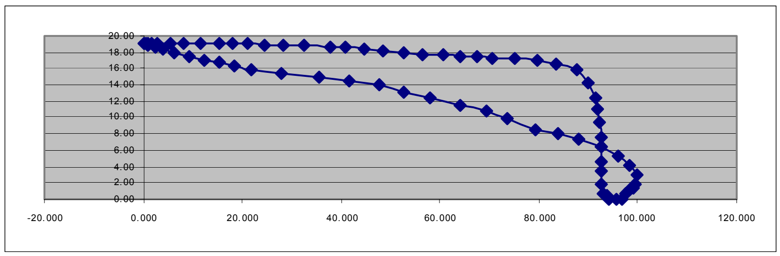

Figure 5. Motion obtained from high-speed video

Whilst both the absolute range of the stroke motion and the general form of the curves showed good comparison the forward motion of the machine appears to be flatter than in the results generated by the model. An investigation of this error showed it arose due to the inability of the splines to follow closely the small wear variations in the cam sets. This further demonstrated the sensitivity of this mechanism arrangement and the need for its improvement.

4 Limits to performance

In order to gather more design knowledge on this mechanism's capability, a study needed to be undertaken into the theoretical and practical limits of its performance. The understanding from the initial modelling provided the basis for this further study.

Each linkage assembly within the mechanism was considered in terms of the geometric values that enabled it to perform the desired motion and how they interacted with all of the others to provide a working mechanism. Each of these link lengths, ground points and component orientations has some influence upon the correct operation. In particular changes in the configurations of these may not be significant but in others they may cause major changes that can lead to non-assembly of the mechanism or major changes to the output motion.

So for each linkage element it was necessary to determine the different types of limitations that existed and their significance in the performance (or modification) of the overall mechanism. In normal practice a working envelope would be set will within these limits, by restricting transmission angles for example but in this case the machine performance has already been extended close to the limits where non-assembly occurs. For example in the pull-off mechanism a four-bar chain is employed within the arm lifting linkage (as shown in Figure 6 and annotated from Figure 3). This has various failure limits depending upon the geometry that is allowed to change in the redesign.

4.1 Minimum and maximum geometric limits

These limits define the conditions in which the mechanism fails to assemble as the result of the combination of linkages being either too small or too large to bridge between to ground point A and D and is well beyond limits that should be imposed to ensure reliable machine operation. If the mechanism is driven through a complete revolution, then these limits can be expressed as the sum and difference of a combination of the link lengths. If however there are set angular limits to the driver or driven members (AB and DC) then the failure occurs when the coupler fails to complete the bridged assembly. This can be seen in Figure 6 where the links BC and CD almost form a straight line so that if link AB is rotated slightly anti-clockwise the assembly cannot be maintained.

When an assembly is only just achievable the mechanism become very sensitive to slight variations in geometry and configuration. This is readily detectable using the constraint resolution approach as the number of iterations (or tries) required to achieve assembly increases considerably.

4.2 Limits to operating conditions

In normal operation the mechanism is required to transmit a combination of forces and angular outputs throughout its operating cycle or range. It is thus necessary to limit the lengths of the component parts and to ensure that the angles between the links remain as close to ninety degrees as possible. For example in Figure 6 the angle between driver and coupler (angle ABC) provides a good transmission relationship, whilst that of angle BCD is very poor with most of the force component acting along link CD with only a small component acting normally to rotate this bell crank component.

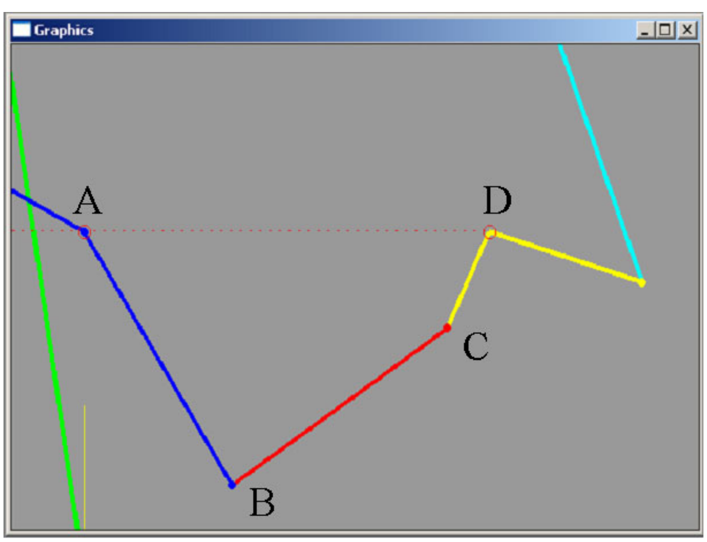

Figure 6. Four-bar mechanism A-B-C-D with ground points at A and D.

For these reasons the length of the component link CD cannot be shortened, whilst any significant increase in it must be accompanied by corresponding reductions in a combination of AB and BC if the mechanism is not going to change the acceptable angle of the pull-off arm.

4.3 Output limitations

Whilst internal limitations occur that influence the assembly and operation of the linkages are present other, often more significant, limitations are imposed by demands of the desired outputs. These may arise due to the requirement that the desired movement or action should take place within a given space in order to meet with other mechanisms or products passing through the machine. Whilst there is often the opportunity to move some configurations, the more that is changed the more uncertain the machine becomes and so the risk (and costs) rise.

It is these practical limits that in the majority of cases constrain (or bound) the available design space. Often ideal solutions require major changes in size to be accommodated but these may not be achievable within the allowable footprint of the machine.

5 Performance evaluation

The RASOR constraint modelling environment has been constructed to allow optimisation and search procedures to be performed [ ]. Here a range of free variables can be selected and the model of the mechanism disturbed by their manipulation whilst the mechanism created on each occasion is tested against a goal function. This goal function must be constructed to ensure the correctness of the mechanism's assembly throughout its operating cycle (satisfying the geometric and operating conditions) whilst an additional set of constraint rules is also applied to control and bound the output conditions.

If the mechanism fails to assemble for any reason or the bounding conditions are not met, a failure error is imposed upon that computational solution that shows that the derived configuration as unacceptable (or untrue). Regions of strong and weakly performing solutions can then be mapped for selected groups of variables in order to find areas providing new and successful forms that meet changes in the performance requirements.

5.1 Performance envelopes

Sets of parameters were investigated for this pull-off mechanism to determine the range of values that provide workable solutions. Here the effects of changes in the link lengths of components BC and CD (shown in Figure 6) are presented in tabular form in Figure 7. This shows the truth of the assembly of the complete four-bar mechanism (including also the alignment of its follower and cam) as the values of the two links are increased from their minimum acceptable values to their maximum practical sizes. The largest degree of untruth occurring during a complete cycle of the mechanism is calculated for each set of these two variables incremented over their accepted ranges.

flag_l	0	1	2	3	4	5	6	7	8	9	10
0	19.9	17.7	15.5	13.2	11	8.8	6.6	4.3	2.1	0.2	0.2
1	17	14.7	12.5	10.3	8.1	5.8	3.6	1.4	0.2	0.2	0.1
2	14	11.8	9.6	7.3	5.1	2.9	0.7	0.2	0.2	0.1	0.1
3	11.1	8.9	6.6	4.4	2.2	0.2	0.2	0.1	0.1	0.1	0.2
4	8.1	5.9	3.7	1.4	0.2	0.2	0.1	0.1	0.1	0.1	0.1
5	5.2	3	0.7	0.2	0.5	0.1	0.1	0.1	0.1	0	0
6	2.2	0.1	0.2	0.3	0	0	0	0.1	0	0.1	0.2
7	0.2	0.3	0	0	0	0	0.1	0.1	0.1	0.2	0.2
8	0.1	0	0	0	0.1	0.1	0.1	0.2	0.2	0.2	0.2
9	0	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
10	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1

Figure 7. Variation in true values calculated for the selected range of components BC and CD (60mm to 120mm for BC horizontally and 20mm to 60mm for CD vertically)

This shows that large errors occur when the combination of links is too short (in the top left-hand section) due to non-assembly of the mechanism as discussed in Section 4.1. Within the lower right-hand section good assembly is achieved with low maximum errors, indicating good mechanical operation. The combination of these values allows lower bounds to be set upon this combination if changes are to be made.

Whilst many other combinations need to be considered, this one is selected to illustrate the point that the machine design has already migrated into an uncertain region. The current component dimensions for the BC and CD place the truth of the mechanism on this mapping at the intersection of column 4 and row 3 to give an untruth value of 2.2. This is well outside of the design bound set by the preferred values of maximum untruth and explains to some degree the uncertainty of the current design and the random variations that are seen to occur in its motion. A bounce of the follower from the cam of just over 1mm, when magnified down the mechanism chain can move the potential untruth to a value greater than 5 which could result in a straight-lining of the components BC and CD and flip it into an unstable operating state.

Within the complete assembly three separate interacting mechanisms are incorporated: the lifting mechanism (described above and shown as 'flag_l' in Figure 7), stroke control arrangement (swinging the vertical arm as the result of the lower cam motion) and finally the pull-off arm itself which together with its rear linkage couples the two previous devices together to provide the desired output motion (and shown as the assembly in Figure 3).

When the stroke motion is analysed for the effect of variations in the components BC and CD it shows, as expected, very low values of untruths at 0.3. The reason for this is that this disturbance influences a different mechanism chain (Figure 8). This mechanism is thus seen to be insensitive to variations in components in other parallel chains. However due to the interacting nature of the pusher mechanism it is sensitive to changes occurring in the lower lift mechanism chain, as can be seen in Figure 9.

flag_s	0	1	2	3	4	5	6	7	8	9	10
0	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
6	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
7	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
8	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
9	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
10	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Figure 8. Untruth matrix of stroke mechanism, showing its insensitivity to variations in components BC and CD.

flag_p	0	1	2	3	4	5	6	7	8	9	10
0	0.1	1.7	1.5	1.2	0.9	0.9	0.9	0.9	1	12.2	1.1
1	4.3	1.4	1.1	0.9	0.9	1.3	0.9	1.1	1.1	1	1
2	1	1	1.8	10.9	1.2	0.9	1.1	1	1	0.9	6.6
3	9	0.9	1.5	0.9	0.9	12.4	1	1	6.6	5.5	4.6
4	10.2	0.9	0.9	4.7	1.2	1	6.8	5.4	0.9	0.9	0.8
5	11.4	3.2	1	1.1	1.9	5.6	0.9	0.9	0.8	0.8	0.8
6	1	1.5	1.3	6	0.9	0.9	0.8	0.8	0.8	0.8	0.8
7	1.4	1	0.9	0.9	0.8	0.8	0.8	0.7	0.7	0.7	0.7
8	1	0.9	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7
9	0.8	0.8	0.7	0.7	0.7	1	0.6	0.6	1.1	0.6	0.7
10	1.1	0.7	0.6	0.6	0.6	1.1	1.1	1.1	1.1	1.1	1.1

Figure 9. Untruth matrix of pull-off mechanism, showing the sensitivity to components BC and CD.

The influence of changes in the pull-off mechanism, as the result of these component changes, is seen to be complex. The matrix (in Figure 9) contains a number of large untruths in a top left-hand section of mostly at 1 or above, whilst a region of mostly less than 1 exists below and to the right (except for a group of just over 1 along the bottom right). The extreme of values are seen to change with cam timing, suggesting that the mechanism and cams interact differently as their phase changes to result in sudden large errors in the truth of the assembly of the pull-off arm.

Again the current design is seen to sit in the higher left-hand region with an untruth of 0.9 but adjacent to regions of greater than 10. This also shows that the mechanism in its current form is very sensitive and on the boundary of the design envelope.

6 Exploration of alternative designs

The completion of the activity of identifying the influence and interaction effects, through the construction of the bounded relationships of combinations of design variables, provides an understanding of both the limits to change and their sensitivity in the creation of alternative solutions. This does not however provide an understanding of the ability of the existing design to be modifiable to meet new design requirements. It is here that knowledge of these effects needs to be investigated by the disturbance of the design parameters to determine whether new goals can be achieved.

Within the constraint modelling environment the capability exists to construct rules to allow the design to be optimised to meet new goals. These are set within a looping function that internally checks the overall untruth of a chosen mechanism (as presented in the previous section) whilst the new constraint rules and a selected set of free variables are placed externally. The function is formed to ensure that the mechanism design operates correctly and the new objectives are achieved where possible.

In an extension to the mechanism study undertaken in the previous section, a new design was proposed that sought to create a form of output motion that approached a horizontal straight line. This was proposed as the current design had the unfortunate tendency to perform complex motions in the vertical direction. In use the preferred motion should be as long and as linear a motion as can be achieved. To achieve this goals were set to seek a motion in which the envelope was represented by a bounding box around the extremes of the output motion was as long as possible in the horizontal and as short as possible in the vertical. The results of this study appear in the motion diagram shown in Figure 10.

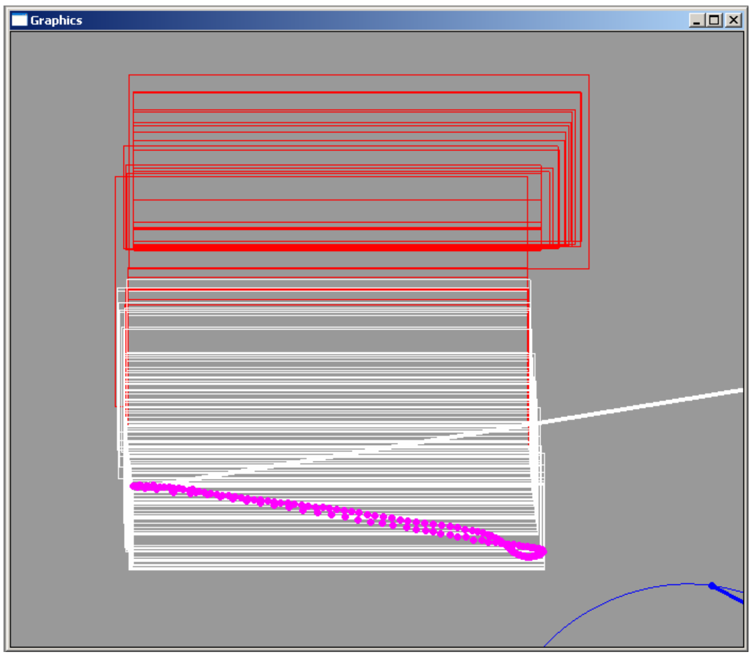

Figure 10. Optimisation study to reduce the height of the bounding box of output motion

These results show principally that good mechanism assembly takes place in the lower portion of the diagram (shown as white when true). These bounding boxes do have greater heights than the group above that have poor mechanism assembly. This led to a further study in which the four-bar mechanism (considered above) was deliberately allowed to fail. This effectively removed this mechanism chain from the solution and fixed the output from the lifting mechanism (as is shown in Figure 11). Here the components BC and CD are shown to be too short to meet and the cam follower is permanently depressed below the profile of the cam effectively locking the mechanism in position.

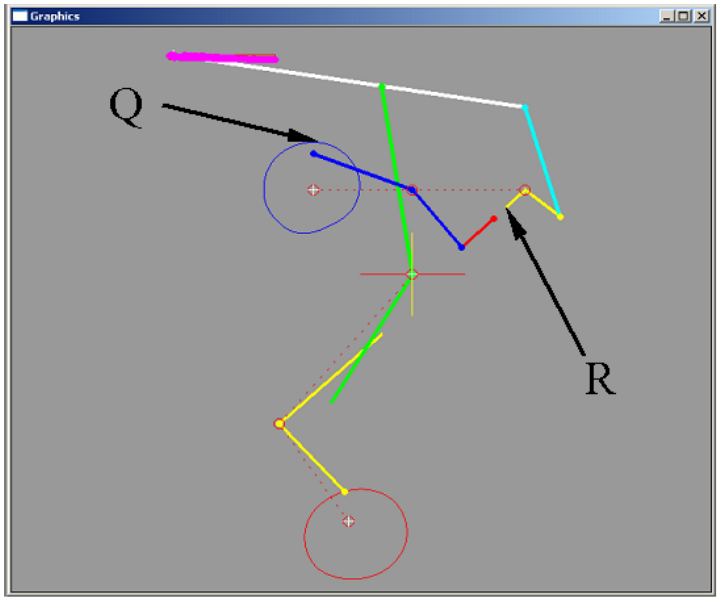

Figure 11. Deliberate failure of four-bar chain to lock the lift mechanism in position with breaks in assembly occurring at Q and R.

A good horizontal motion was thus seen to be achievable by effectively removing one of the cams and the lift mechanism from the design. The design could thus be greatly simplified by fixing the lower point of the second link of the pull-off device to the 'ground' of the machine.

This study thus showed that for a near horizontal motion the vertical motion mechanism was not required, even though it had been deliberately incorporated in the original design. This could have arisen as other requirements in this machine that had been overlooked in this study (and that a 'no lift' design would not work in practice) or that this whole mechanism had been taken from a previous design (where lift was required) and simply implanted in the new design.

An investigation of these two possibilities was undertaken which led to the conclusion that the machine would work without any lifting. The theory that the mechanism had been 'borrowed' from another machine was supported both by a recognition that these parts were given a different set of code numbers to the rest of the machine and the facts emerging from the bounding studies that the mechanism was close to the failure regions on many occasions.

In order to fully demonstrate that the mechanism would operate successfully with no lift a circular cam was made to replace the lifting cam (Figure 12). This was then run in the machine and gave good output motion, closely comparable to that predicted with no random vertical movement detectable.

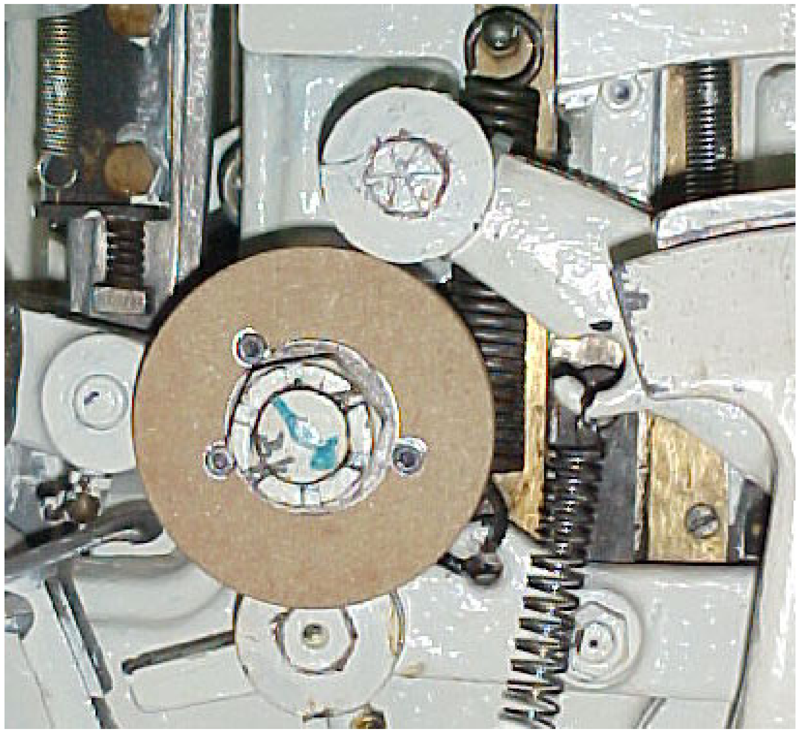

Figure 12. Circular cam used to demonstrate that lift mechanism was not required

8 Conclusions

This paper highlights the needs of machinery manufacturers and in particular the requirement for the creation of supportive tools and techniques that enable the identification and understanding of the performance limitations of existing systems. This is illustrated through the study of a machine that has evolved, without detailed analysis, until it has come close to its performance limits and to that of failure. To address these needs, a constraint based modelling approach was created, which also combines practical investigation was created. The approach described was illustrated by its application to the analysis and improvement of a machine element in this industrial case study.

The capability of the constraint modelling techniques to perform the analysis of the functional capabilities has been demonstrated. This allowed the performance limits of existing machines to be determined, design changes to be proposed and redesign strategies to be investigated. The application examples show the generality and potential scalability of the technique, which are essential for the creation and uptake of any new modelling approach.

It is through these activities that the design knowledge is created that is both machine specific and system generic. These then allow ideas and designs to be extended, transferred and modified in order to create successful adaptations of existing designs or to provide the springboard for the creation of new products.

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