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A CONSTRAINT-BASED APPROACH TO THE MODELLING AND ANALYSIS OF HIGH-SPEED MACHINERY

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Abstract

Machinery manufacturers, particularly small companies, often produce a basic range of products with a large number of variant designs. It is important for them to retain understanding of the design and its limitations. Methods based upon constraint modelling can be adopted to model existing and proposed new designs and the process of modelling acts as an aid to understanding. It also allows the effects of variations in the design parameters to be investigated and improved designs sought. The paper discusses a constraint-based modelling environment and its application to a number of design problems involving high-speed machinery.

Keywords: Constraint-based design, systems modelling, simulation in PD, design optimisation

1 Introduction

To enable machinery manufacturers to compete at an international level it is necessary to introduce them to more advanced design methods and technologies. For years, the evolution of high-speed machinery has relied heavily on trial-and-error methods [1, 2]. The demands for continual increases in the performance capabilities of the machines, escalating legislation, environmental directives and changes in the characteristics of the product, require rapid development of existing designs and the creation of new machines.

Machinery manufacturers require a systems modelling approach that provides support over the conceptual, embodiment and detailed design phases [3]. In order to meet these requirements a constraint-based approach to the design of high-speed machinery is proposed. This approach provides for the development of a greater understanding of proposed and existing designs, the identification and representation of design knowledge, and the determination of the limitations of an existing design. Furthermore, the approach allows for the evaluation of alternative designs and redesign strategies as well as the embodiment, refinement and optimisation of design solutions. The theory of constraint modelling is discussed and the various activities associated with building and analysing a constraint-based model are described.

The constraint-based approach for the support of systems design has grown from studies of the design process [4, 5]. Many attempts to decompose, classify and order the particular activities of a given design problem have been undertaken. However, many of these approaches are only successful if the problem is well understood, and in such cases they focus and direct the overall design process. However, when these process models are generalised, the reliability and suitability of the methods are less good and they may restrict the overall design process and creativity of the individuals involved.

By taking a higher level approach, which aims to provide for the representation of the design processes for the particular system being designed, many of these problems can be avoided. The approach used here focuses on representing and manipulating the particular constraints and design knowledge for a given problem or artefact. These constraints may include not only performance and physical requirements of the design but also constraints imposed by resources. In fact, it is these design constraints or goals which ultimately define the actual process for the design of the particular artefact. Thus, the design of the artefact is not process-led but goal orientated.

This paper presents the basic ideas of a computer-based constraint modelling environment and goes on to illustrate the use of the system in building and analysing models for a number of industrial problems. Throughout the model building process, design knowledge is captured and expanded through the process of refining constraints and manipulating models. Importantly, this process aids the designer in developing a fundamental understanding of the problem, no matter whether the problem is being reinvestigated or whether the design task is new, and the rules are not well understood or even known. Whilst the constraint modelling environment does not provide for the recording of every decision and alternative, the results and implications of these decisions are embodied in the various sets of constraint rules. In this manner, knowledge is captured as the design proceeds.

2 Constraint Modelling

The ideas of constraint modelling grew in part out of research into understanding the overall design process. If a designer is meeting a new design task for the first time, then the precise rules which govern the situation are not known. Information generally is incomplete. What are more obvious are some of the limitations that exist. These might imply bounds on the physical size of a component, its weight, the allowable motions it can perform and so on. Such bounds represent constraints on what can be done. Initially not all the constraints are known. As a design progresses, the designer’s understanding increases and more constraints become apparent.

Constraints can be viewed in set theoretic terms. Each constraint defines a region within the space of all possible designs and only those within that region are allowable. As more constraints are introduced, the allowable region is the intersection of these sets. If the design is “under-constrained” then there is a non-empty intersection (part (a) of figure 1) and designs within it are fully feasible. More often there is conflict between the constraints and they are mutually incompatible. In this case the intersection is empty (part (b) of figure 1). In such cases, the skill of the designer is in deciding which constraints can be safely relaxed without jeopardising the success of the design.

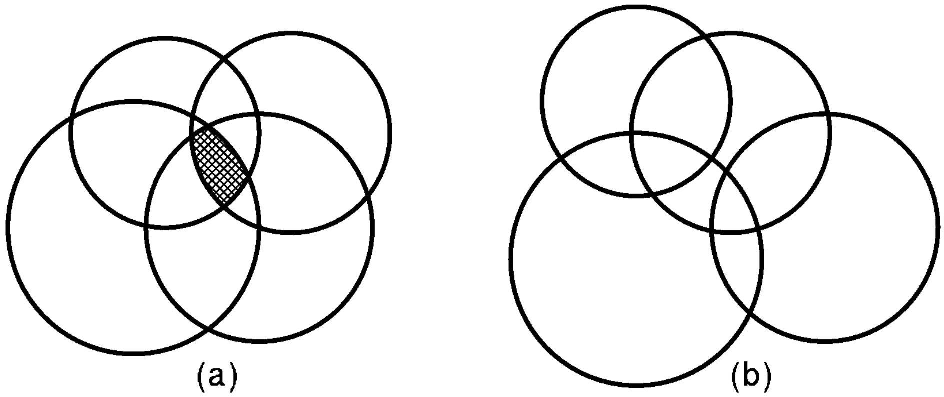

Figure 1. Overlapping constraint sets.

In order to understand these ideas more clearly, constraint modelling software has been created [6]. This aims to allow a designer to specify the parameters of a design and also the constraints that connect these. Once defined, the system can be used to investigate what the effects of the constraints are and to search for fully feasible design solutions. The aim has been not to create a "black box" over which the user has little control. Instead, the user is expected to interact with the system. This means adjusting values of design parameters, adding and removing constraints and so on. Through such interaction, the designer's understanding of the problem is increased. The remainder of this section gives an overview of the modelling software.

The constraint modelling code is set up to run on PC's and on UNIX workstations. It has its own interface language and it is via this that the user interacts with the system. The language is used to declare the parameters of a design and to assign values to these. In this respect the system works in the same way as any typical programming language. Once parameters have been defined, they can be processed using the usual mathematical operations and functions.

Where the approach starts to differ from a conventional programming language is in the use of constraints. In the system, a constraint is an expression involving the design parameters which is zero when it is true. A non-zero value is a measure of its "falseness". So, for example, if *F* is a design parameter representing a force and *alpha* is the angle from a given direction, a constraint to ensure that the component along the given direction is 10 units takes the following form.

```
rule( F*cos(alpha) - 10 );
```

Such constraint rules are formed as groups within the language together with the names of those design parameters which the system is allowed to vary when trying to find feasible solutions. The search process is based on optimisation principles. The sum of the squares of the values of the constraint rules is formed. If this is zero (or very close) then the constraints are already satisfied and no further work is required. If it is non-zero, then it is regarded as a function of the specified design parameters and these are adjusted using direct search techniques to try to find the minimum value.

If a minimum of zero is achieved then a feasible solution has been found. If this is not achieved then interaction with the user and further investigation is required. This may be to assign different values to the design parameters, to relax some of the constraints, or to allow more design parameters to be adjusted. Once a suitable configuration has been achieved, it is possible to fix some of the design parameters so that they cannot be modified when trying to satisfy other groups of design constraints. The value of the minimum achieved for each search is displayed so that the user has some guidance as to how well the constraints are satisfied. Also displayed is the number of iterations required for the search process. It is found that this gives an indication of the sensitivity of the design solution, with more iterations suggesting that the design is likely to lack robustness.

In principle, the constraints for any design application can be set up within the language of the modeller. Indeed the difficulty is often identifying what those constraints are rather than their implementation. Since the system has been applied extensively in the area of mechanism and machine design, a number of features have been incorporated to facilitate application in these areas. Among functions incorporated in the language are ones that use finite difference calculations to evaluate velocity and acceleration profiles. Also included within the system itself is simple wire-frame geometry. Geometric entities can be declared and manipulated. Since they form part of the language, constraints can be applied to them in the same way as for other design parameters.

As an example, consider the very simple case of fitting a line between two given points. If the line is denoted by the parameter *l* and the two points are *p1* and *p2*, then the two constraint rules for assembly appear as follows.

```
rule( l:e1 on p1 );
rule( l:e2 on p2 );
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These specify that the two ends of the line should lie on the given points. Here "on" is a built-in function of the system which determines the distance between two geometric entities, and the use of the colon allows access to information within the structure of the line entity, in this case giving the end points.

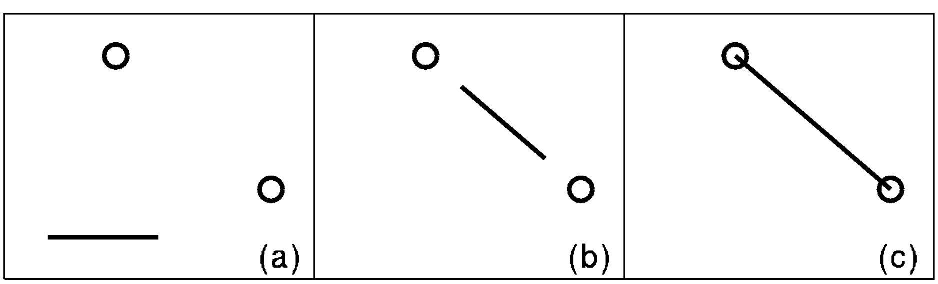

Figure 2. Fitting a line between two points.

Figure 2(a) shows the three items of geometry in an initial position and clearly the constraint rules are not valid. If they are applied and the system is allowed to translate and rotate the line, then the configuration in part (b) of the figure results. The constraints are not fully satisfied since the points are too far apart, but a "best compromise" has been reached in that the line lies midway between the points. If the system is allowed also to change the scale of the line, then it can be stretched to fit between the points as in part (c). In this way, the user has control over what parameters can be changed by the system.

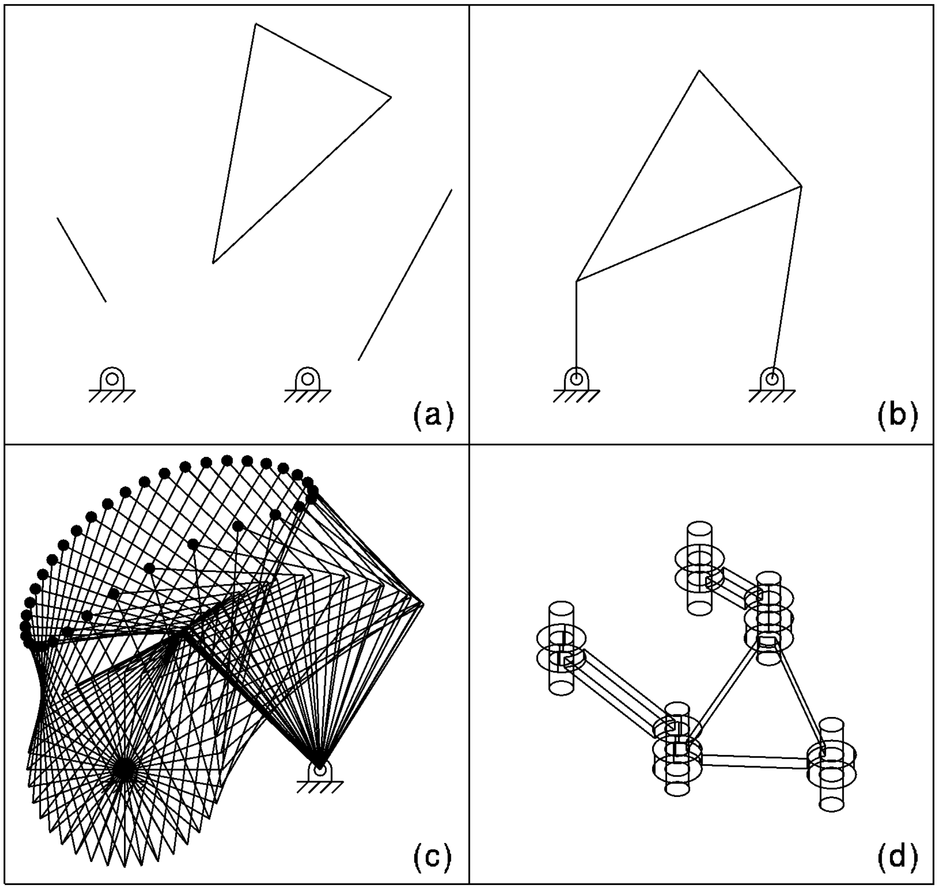

Figure 3. Assembly and simulation of a four bar mechanism.

Whilst this example is very simple, it does illustrate the basic constraints required to assemble a mechanism. Figure 3(a) shows two lines and one triangle that represent the moving links of a four bar mechanism together with two fixed pivot points. Applying constraint rules to bring the end points together results in the configuration shown in part (b) of the figure. If the short driver link is now rotated steadily and the mechanism reassembled at each stage, a simulation of the motion of the mechanism is achieved as in part (c) of the figure.

The modelling system also has built within it the ACIS core solid modeller. Variables can be created within the language which act as pointers to solid objects. These can be interrogated for their mass properties and the usual Boolean operations applied. If a solid object is associated with each link of the four bar mechanism, as in part (d) of figure 3, then these too can be moved during the motion simulation. This enables clash detection to be carried out to check for interference of the parts of a moving system with themselves and with their environment.

3 Machine applications

One of the problems faced by small companies that design and manufacture processing machines is simply maintaining an understanding of the products they produce. While there may be a core range of machines, there is often a need to produce variant designs to satisfy the requirements of particular customers. Often such changes are implemented on an ad hoc basis due to lack of resources and time to perform a full design analysis. This means that the company may be in the situation where it makes products which it knows work but does not fully understand why. In extreme cases for long established products, such a lack of awareness may be due to designers with the relevant expertise having left the company. This means that the company may not be able to move forward to a new generation of machines because it does not fully understand the current ones.

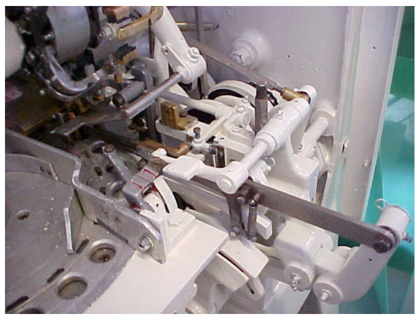

Figure 4. Part of a confectionery wrapping machine.

In such cases, one strategy for improving designs is to begin by modelling existing products and comparing the results with experimental data. The constraint environment is one way to carry out the modelling. The actual process of creating the model does mean that the user needs to measure and understand the basic operation of the machine.

To illustrate the modelling process, the case of a sweet wrapping machine is considered. The particular part considered here is the control of the grippers which pull a new piece of wrapping film over the next sweet. This is shown in figure 4. The grippers move forwards and backwards in a (roughly) horizontal direction and they are driven by a linkage mechanism which itself is driven using cams coupled to the main drive shaft.

The first stage of the modelling process is to obtain the positions of the drive shafts and other pivot points, and the lengths of the links as measured between pivots. This enables a "stick" diagram of the mechanism to be created. The advantage of the constraint-based approach is that it allows a model to be created even if the data is incomplete or incorrect: all that happens is that the mechanism fails to assemble in parts of the cycle. By observing the simulated motion, errors are immediately apparent and greater understanding of the operation is obtained.

The completed stick diagram is shown on the left in figure 5. This shows also the track of the tips of the gripper. The next stage in modelling is often to represent the links more exactly by the use of solid objects. One link is shown as a solid in the figure (enlarged view on right). Kinematic information can be obtained from the completed model. By tracking the centre of gravity of the solid link, the velocity components of this point can be found and also the angular velocity. These can be used to determine the kinetic energy of the link at points during the cycle. Velocity and energy profiles are shown in figure 6. One way to verify the accuracy of the model is by the use of high speed video techniques. This enables the velocity profiles of points on the physical mechanism to be determined experimentally. These can then be compared with predictions made from the model.

Once an acceptable model has been obtained, investigation can be made into the sensitivity of the design. This is done by interactively varying chosen design parameters, such as link lengths and pivot points, and evaluating their effects. Again this adds to the understanding of the design. From this the critical parameters can be identified. It is then possible to allow the modeller to adjust these automatically to search for improved design configurations. To do this, suitable measures of performance need to be identified.

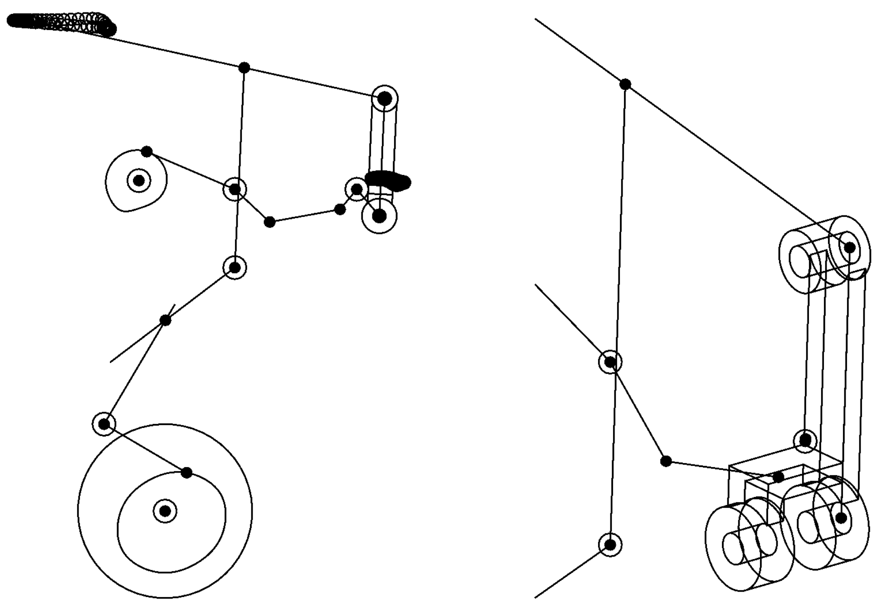

Figure 5. Model of film gripper mechanism.

To illustrate the use of the constraint modeller for improving designs, a second application example is considered. This concerns the transfer of batches of food product from one conveyor to another. These both move in the horizontal plane and are at right angles to each other. There is a speed change by approximately a factor of ten between the two. A block of ten items is to be taken from the faster conveyor (where they move in single file) and transferred onto the slower (where they move ten abreast). They then pass through an oven. A four bar chain arrangement is one potential means for moving the transfer arm. The arm needs to move in a roughly triangular path and match the speeds of the conveyors at the pick-up and set-down points.

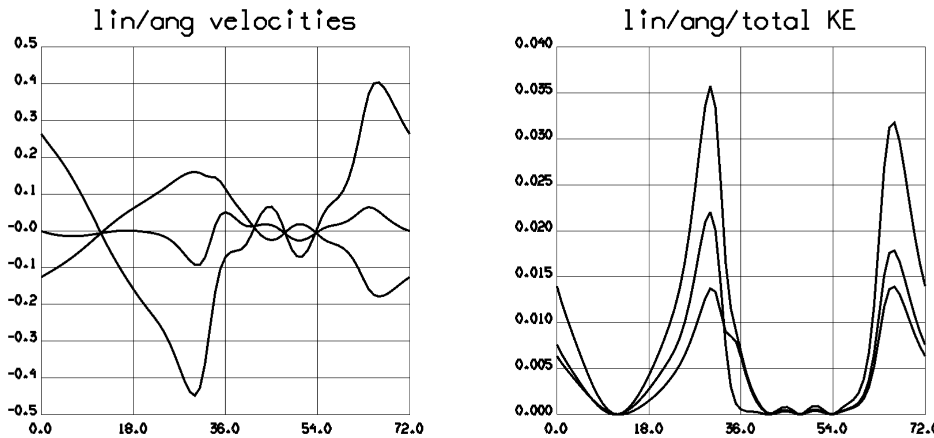

Figure 6. Velocity and energy plots.

The original design is shown in stick form in figure 7(a). This also shows the track of the transfer arm. The speeds at the critical points are not correct and the closeness to the requirements is used as a measure of performance of the design. The modeller is then used to vary automatically all the link lengths and the two pivot points in a search for an improved design configuration. Part (b) of the figure shows the search steps and part (c) shows the final design solution. This is very different from the original, but the speed matching is within 0.1% of the required values.

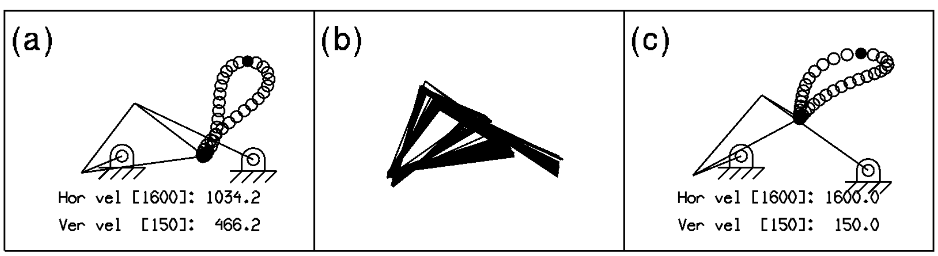

Figure 7. Optimisation of a transfer arm.

4 Discussion and conclusions

From the use of the constraint modelling system, a number of points arise which apply to the design analysis and improvement of high speed machines. Some of these concern specifically the use of the constraint-based system, but others hold in general for any modelling approach.

- The process of modelling an existing machine or a proposed design greatly aids the understanding of the designer. Information can certainly be gained from a conventional drawing or from viewing a machine operation. However, the procedure of collecting the required information and ensuring that the model assembles correctly and then operates, serves as a check that the key aspects of a design have been identified correctly and eliminates invalid assumptions.

- The constraint modelling system is set up to try to provide solutions for any set of constraints, even when they are mutually in conflict. This means that a model can be created iteratively, piece-by-piece. From a few basic dimensional parameters an initial model can be created. This gives the user some initial confidence. Gathering more information allows the model to be developed. The results can be readily checked and if the operation is not as required then it is straightforward to identify and correct the faulty information. In this way misconceptions about the operation are identified and resolved.

- Various different levels of model are required dependent upon subsequent design or redesign work. A simple "stick" model where the elements of a machine are represented by lines is often sufficient to describe the assembly and allow the kinematics of a machine to be determined. For clash detection or for estimation of power requirements, the creation of solid models of the elements is appropriate. The detail of these models needs only be sufficient for their required use. If force information is required then the model can be used as the basis of the geometry definition for analysis by a dedicated dynamics analysis package.

- To verify the accuracy of a model of an existing machine, some experimental work needs to be carried out. High speed video techniques allow images of parts of a machine to be obtained throughout the operation cycle and the positions and speeds of key points can be established. These can be compared directly with positional information from the constraint model. Accelerometers and strain gauges can be used to determine more about the kinematics and forces within the physical machine and compared with predictions obtained by analysis of the model.

- Often companies produce a set of variant designs of machines based around a few core examples. The modeller is essentially parametric since the description of the design is held within the underlying user language. This means that it is straightforward to modify a model of a core machine to represent other members of the family.

- Once a model of a design has been successfully created, it can be used to explore the limitations of that design. The designer can interact with the system to change design parameters and investigate the effects. In this way, the key design parameters are identified and some assessment of the robustness of a design is made. In the case of a range of parametrically equivalent designs, it is possible to determine how far the range can be extended. Rationalisation can be achieved by finding redundant members within the family whose operation can be produced by other designs.

- With the key design parameters identified, the optimisation techniques at the heart of the modeller can be used to search for improved designs. This requires that one or more suitable measures of performance be established. These may simply relate to the positioning of an end-effector or the speeds of components during a cycle. They may be concerned with estimates of internal forces and balancing. The modeller can then search to improve the measures by changing the selected parameters.

- Constraint-based modelling provides a structured approach to the design improvement of machines. This starts with a modelling stage with the model verified by experimental work. Sensitivity analysis is performed on the model and then changes to the design can be investigated using optimisation techniques.

The design changes required for improvement have been found to fall into three classes. The simplest is the change in a single component. This may merely require the replacement of a bought-in component by another more suitable one. It may involve changes to the geometry of a single link. The next class requires changes to a subassembly. A small group of elements may not operate together in an optimal manner. These then need to be redesigned together, but independently of the rest of the system. The final class is when major redesign of large parts of the system needs to be undertaken. This occurs when the sensitivity study shows that all design parameters are chosen as well as possible and there is no room for improvement within the frame of the existing design. A new design concept is then required.

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References

[1] Shigley, J. E. and Uicker, J. J., "Theory of Machines and Mechanisms", McGraw-Hill, London, 1980.

[2] Timoshenko, S. P. and Young, D. H., "Advanced Dynamics", Chapman Hall, London, 1948.

[3] Green, G. and Wood, B. M., "Rapid design and manufacture (RD&M) – meeting the needs of Scottish industry", Proceeding of ICED '01, Vol. 3, Glasgow, 2001, 11-18.

[4] O'Sullivan, B., "Constraint-Aided Conceptual Design", Professional Engineering Publishing, 2002.

[5] Bruderlin, B. and Roller, D. (eds.), "Geometric Constraint Solving and Applications", Springer-Verlag, Berlin, 1998.

[6] Mullineux, G., "Constraint resolution using optimisation techniques", Computers & Graphics, Vol. 25, 2001, pp. 483-492.

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