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Design and Manufacture of Prototypes and Production Models, particularly Scale Aircraft

Introduction

Most models, not just those of aircraft, require replication of detailed shapes in a wide variety of configurations and sizes. Recently, imaginative use of lasers with either resin or paper has resulted in methods to produce detailed components from computer generated 3D models. However in many cases, these may not be used directly and require other processing before the finished part is obtained. Also, the 3D computer model is a prerequisite for the process, and the economics suit industrial environments best where there are significant production runs to absorb the prototyping costs.

The authors of this paper present a method using relatively conventional machining technologies combined with sophisticated computer control enabling rapid design and manufacture of prototypes and products relatively economically. Generally this can be done directly in the final material, rather than relying on an intermediate process. In many cases, 2D CAD technology is sufficient to derive the required data, though use of 3D computer modelling with built-in "slicing" may still be appropriate for certain complex sculptured shapes. The work reported in this paper builds on that reported last year [1].

Concepts

The essence of this approach involves two major concepts, both involving established technologies.

- A 3-axis cartesian robot is used to position a cutting head (normally employing a high speed rotating cutter) and drive it along a prescribed path thus shaping the required material.
- A 2D general arrangement of the part(s) is required. To be truly practical, this requires the use of a rapid, easy to use, but powerful CAD program. This is modified, as described later, to interface directly with the cutting machine requiring no programming intervention from the operator.

The combined specification of the machine, the 2D CAD software (RoboCAD) and the Axiomatic machine control software linking the two, results in an integrated system whereby all that is necessary to cut a part to the intended shape is just to draw it. Once drawn it is as good as cut, and to a very high accuracy. The post processing normally associated with CNC manufacture is achieved automatically within the control software, and needs no manual intervention apart from the input of variables such as effective tool offset, sort order, start position etc. Once set, these can be recalled instantly for the appropriate job.

The effect of this is that a model maker can very rapidly try out an idea before production, or produce a one-off final part, without requiring extensive CAD training, or any training at all in CNC techniques. Since the machine and the software, are very robust, it is equally suitable for round the clock production work.

The Robot

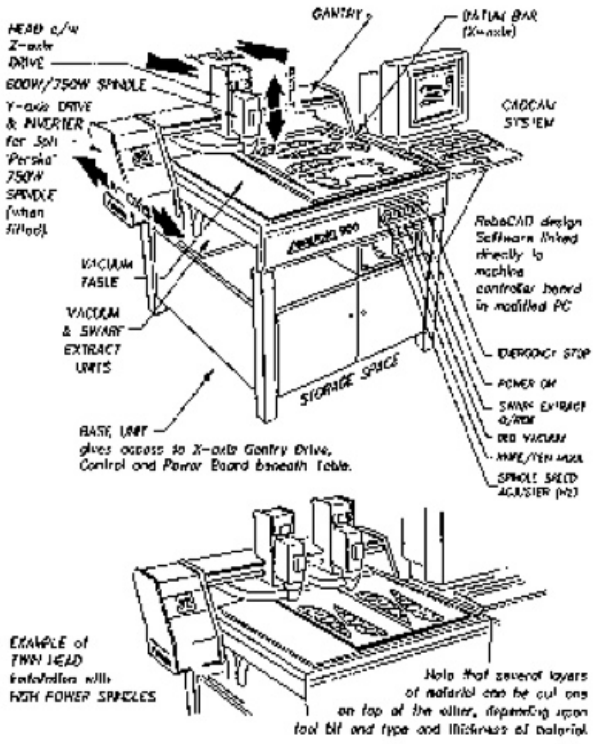

Figure 1: The Sequoia 900 machine, standard and twin-head versions

The machine (Fig 1) achieves high resolution drive through use of precision ground ball screws and stepper motor drives, giving a resolution of 0.0125mm, (0.0005"). Detailed attention is paid to all drive trains and tolerance of all moving parts to reduce hysteresis to minimal levels, resulting in a machine capable in practice of approaching the theoretical resolution.

In addition to positional accuracy, (achieved in all 3 axes), what is also extremely important is the method by which the software interprets the prescribed path, before effecting motion of the cutting head. Smooth Continuous Path Motion (SCPM), based on the work of Nottingham Trent University [2], [3], [4] implies that the actual movement of the cutting head, albeit broken into very many small steps, follows the path with minimum transverse acceleration, while still keeping within the resolution of the machine.

The effect of this is three-fold:

- Delicate cutting tools can be used with reduced risk of breakage
- Heavy cutting tools can be used without over stressing the spindle motor or bearings
- The drive to the stepper motor (in conjunction with other control algorithms), is optimised for the smoothest drive, resulting in consistent and reliable operation, with less vibration at the tool tip.

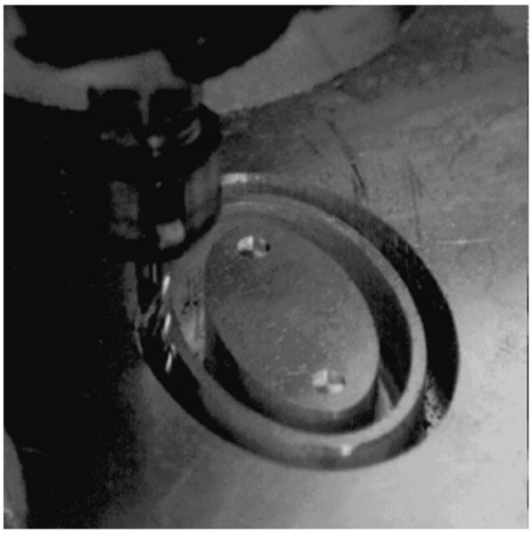

Figure 2: Cutting through 18mm aluminium with a 4mm cutter

For the greatest accuracy, the material itself has to be held firmly while cutting is in progress. Furthermore, as a part is cut from the base material, relative movement between that part and the material has to be prevented. A powerful vacuum bed with good leakage recovery is used to hold the base material firmly to the bed, which also controls vibration from the cutting process. An automatic tabbing system built into the software leaves the part connected to the base material by small bridges, (which can be cut through later), which also maximises the effect of the vacuum system. The machine is manufactured by Pacer Systems Ltd. [5].

The Scope

Parts may be complex or finely detailed in the x-y plane, or the x-z, y-z planes. In the x-y plane, fine detail requires the use of an appropriately fine cutter, and if this is to cut through a useful depth, it may be necessary to achieve this by a number of successively deeper cuts. Indeed this may be preferable in any case to achieve a finer surface finish, or to cut through materials which may otherwise melt if too much material is removed at one pass. The software incorporates a multi-pass facility to automatically make a number of passes increasing the cut depth each time until the desired depth is reached.

In the vertical plane, curved surfaces are also cut in a series of passes, each one deeper than the last. However, in this case the depth of each cut is determined by the required resolution of the curved surface. This will be a compromise between the time involved in preparing the data for each "slice", the time in machining, and the required surface finish together with the method of smoothing, if smoothing is required. In practice, this may vary from 0.2mm to approximately 3mm, but could be much less (0.012mm!) or more as appropriate. Parts so machined can be up to 75mm thick and may be joined to others with accurate registration via dowels or interlocking parts, and so build up large components. Figure 3 shows a 3-D letter "L" as an example.

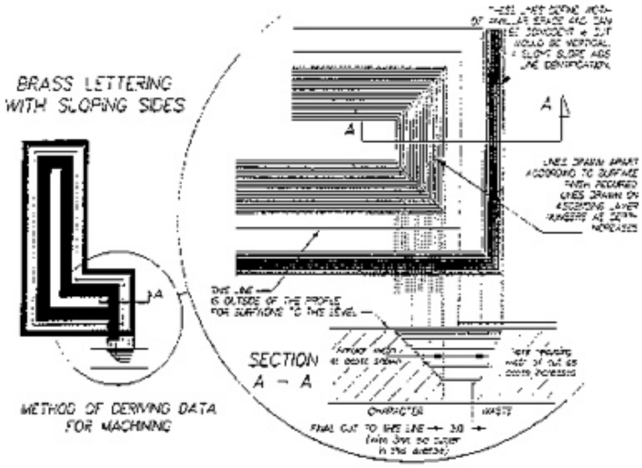

Figure 3: Letter "L" showing the concept of defining an annular space for area removal and technique for 3D surfaces

The data for each slice will be represented by a drawn boundary representing the profile at the height of the slice. This boundary in many cases can be achieved by using the Robocad spline functions joining points derived from 2D cross sections. However Robocad 3000 can also be used to define the article as a 3D solid model, and then "sliced up" to give the profiles required. These are then imported into the 2D system for the cutting operation. (Fig 4)

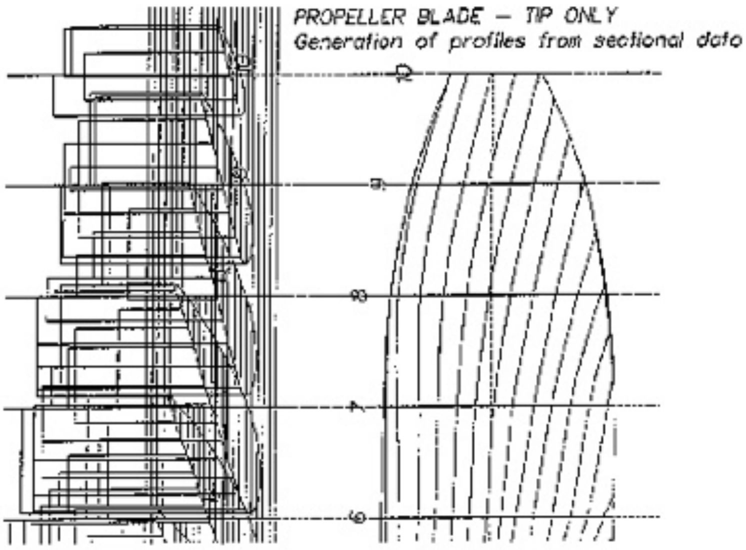

Figure 4: Illustration of product or prototype where the maching data could be derived from either sliced 3D of from 2D sections. Drawing shows derivation from 2D

The order in which layered profiles are cut is very important, and this is controlled by a layer numbering system. Layers are cut in ascending number order, up to 998 in a single sequence. (Fig 5)

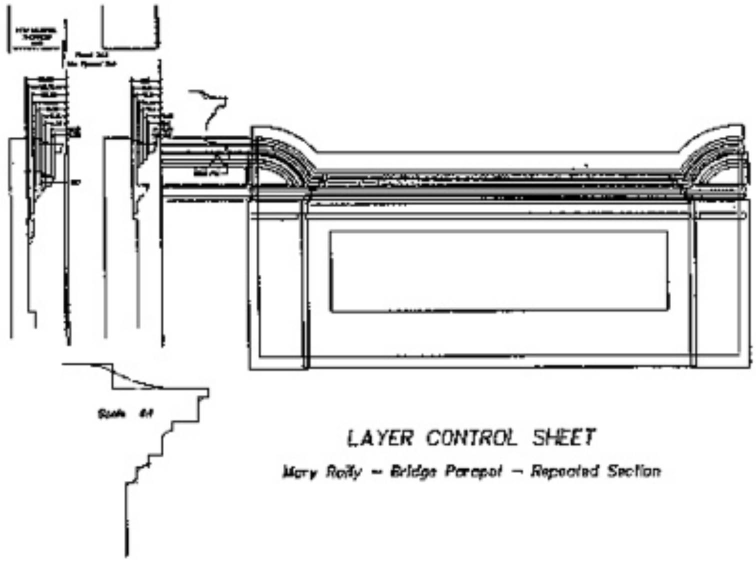

Figure 5: Bridge parapet drawing showing the different layers

Defining the Shape

Profiles for cutting either simple 2D shapes, simple rebating, or more complex 3D operations, can be easily drawn directly into the software integrated with the machine. Alternatively, files can be readily imported into this system from another CAD program using either DXF or HPGL file formats.

In addition, profiles which are available in printed hard copy may be scanned, and the resultant raster (dot image) data converted into vector form using appropriate conversion software. Until recently, the available software typically produced data rather less than suitable for CNC processing. Now however, Axiomatic Technology offers Axiscan which not only produces good vector files for further CAD processing but also clean output for CNC machines.

Once basic shape data is entered into the RoboCAD system, it can be optimised from both the product design and production point of view. There are three aspects to this:

a) improving design from a performance and visual aspect
b) facilitating ease of construction
c) creating data for the best cutting performance.

(a) and (b) are factors relevant to every manner of construction, so we consider here aspects of (c).

These will include:

- Setting up data (ie lines) on different layers for sequential, or individual cutting operations.
- Setting up closed loop annular boundaries for the cutter to work inside, (or outside), for the purpose of removing material over an area.
- Setting up start points for cutting each profile
- Providing markers on a special layer, (usually layer 999 reserved for this), which will be interpreted as the position for a "tab" to stabilise the workpiece.
- Where multiple items are to be cut, arranging them for minimum wastage from material available.

In all the above, easily used software tools are provided to rapidly optimise the situation in hand.

Additional Computer Tools

The machine controller is implemented through a custom-designed autonomous processor card connected to the bus of the design workstation. Using a dual port RAM interface to ensure highest performance, the controller communicates with the host CAD environment through a sophisticated bidirectional software driver. This allows the passing of sequential data files of machining information and direct interactive controls. The large memory capacity of the controller and its in-built processing power means that it imposes very little processing overhead on the CAD host.

While the above are essential elements in the CADCAM process, the author's approach differs in the degree of integration of the various elements. The host CAD facilitates customisation of pull down menus and the addition of "user" functionality either in the form of command strings or the running of external programs. The integrated system is known as VMC-CAD and uses this facility together with a suite of specially written programs by Axiomatic Technology Ltd. [6].

Simple programs are provided for interaction with the machine controller, for example to change the feed rate during cutting, an indispensable aid to achieving the best cutting conditions. The user simply clicks on the appropriate pull down menu, and modifies the feed rate which appears in the dialogue box. Many commands are direct and bypass any sequential commands which may be in the controller or communications buffer. Other direct commands include "Pause" for work inspection or tool change and "Cancel" to flush the current job and depth controls.

Initiating machining of a component is as simple as starting a plotter. The innovation here is the way in which the "PPD" preprocessing software is automatically invoked. It is obviously desirable that contours are cut in single operations regardless of what editing has taken place. Equally it is important for inner contours to be cut before the outer, and that each contour is cut in the appropriate direction to get the best quality cut edge.

All this and much more is automatically performed by the PPD software, and while this is virtually "transparent", the user is graphically informed of the results at each stage. For some operations particularly with complex components, a degree of interactive control is desirable, and the software allows all the features to be switchable to give the user complete control over the machining options.

2D & 3D Capabilities

With the above completed, the first prototype can be manufactured. Some examples are considered here to illustrate the scope available. Modelling work can be divided into three broad categories:

- 2D profiles with perhaps simple rebating,
- Spatial 3D,
- Solid 3D.

2D profile work does not always make interesting products or models, but there are notable exceptions - for example inlay work for furniture decoration, imaginative sign designs, pcb drilling, decorative screens and trophy designs.

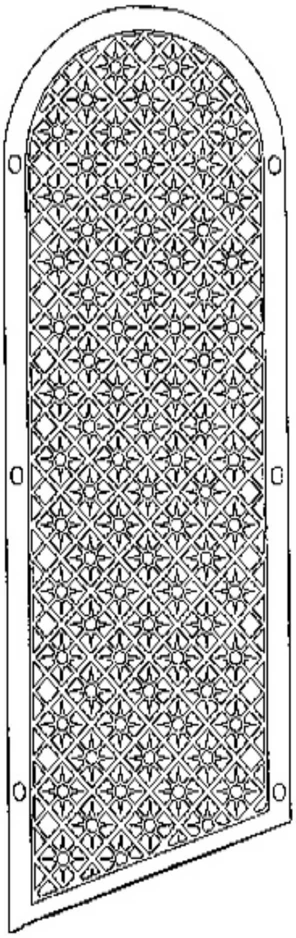

Figure 6: Screen for bridge arch infills for the film set of "Mary Reilly"

Spatial 3D covers products from simple box sections to complex space frames, where the individual components are themselves simple 2D profiles. Solid 3D refers to models composed of one or more parts, each of which may be machined to various profiles at a range of cross-sectional positions. The range of profiles may be few in the case of defining the function of the item, such as multiple rebates, steps, walls and so on, or very many if the purpose is to create a curved surface as described earlier.

There is a "grey area" between spatial 3D and solid 3D, which consists of work which is solid, but is made up of laminated or assembled simple 2D components. This technique is useful for producing mock-ups for commercial evaluation before commitment of resources to injection moulds.

Full size and model aircraft require both spatial and solid techniques. Wing and fuselage structures are usually space frames or semi-monocoque, although laminated foam and moulded parts are now sometimes used for stress bearing components such as wings. Moulded parts will also include canopies, cowls, wheel spats and so on, and these will all require mould plugs to be made.

Spatial 3D

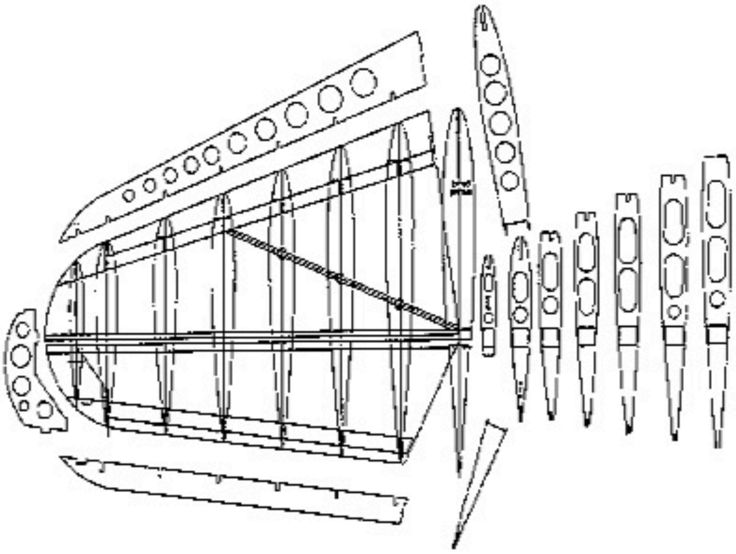

Figure 7: The tailplane from the Boeing Stearman

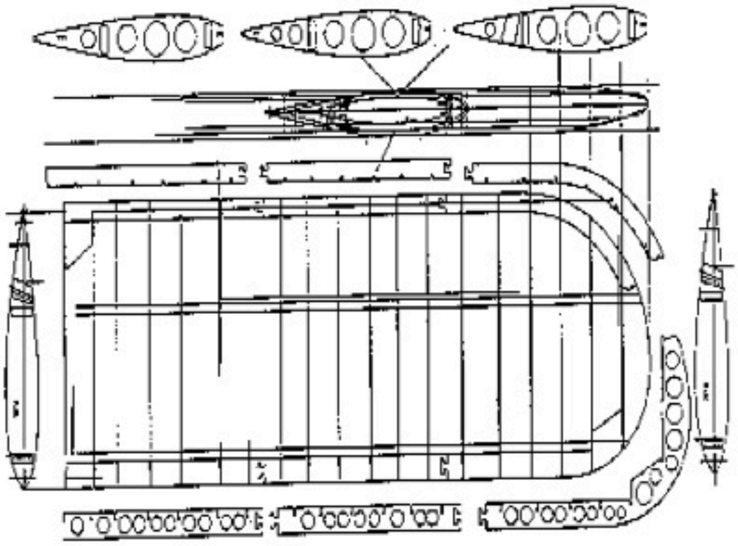

Figure 8: The main wing from the Boeing Stearman

Shown here (Figs 7 & 8) are the main wing and tailplane designed by one of the authors for a half scale Boeing Stearman biplane (wingspan 16 feet). At the other end of the size spectrum, a wing built with 1mm balsa for an indoor flying model, based on the 1930s American racers, wingspan 18 inches, has been designed along the same lines - the principle in both cases is identical. A general arrangement drawing is used to develop the design and the shape of the parts. Details concerning how the parts fit together can be shown in some detail here, or just indicated approximately for development in the next stage as follows.

The parts are "lifted off" the GA and laid out separately, at first on the same sheet if possible. Final detailing can be done here, then the part is saved in a visual filing system for easy recognition and retrieval. It is a feature of this filing system that it is possible to pick up a part from any desired point on the part concerned. This is vital for cross checking the fit of parts, because it means that a component can be picked up and accurately located at precise points, or on a datum line, on the GA to ensure consistent fit of the part, particularly as the design is developed and modified.

The root rib profile was known from the Boeing drawings, so transformation procedures in the CAD system were used to develop the tip rib profile since the chord and thickness were known, and then the intermediate rib profiles. Leading and trailing edges, and tip profile were then laid out, with the halving joint line drawn in, so that it is clear where the slots need to be taken on both rib and matching component, for a perfect fit.

Solid 3D

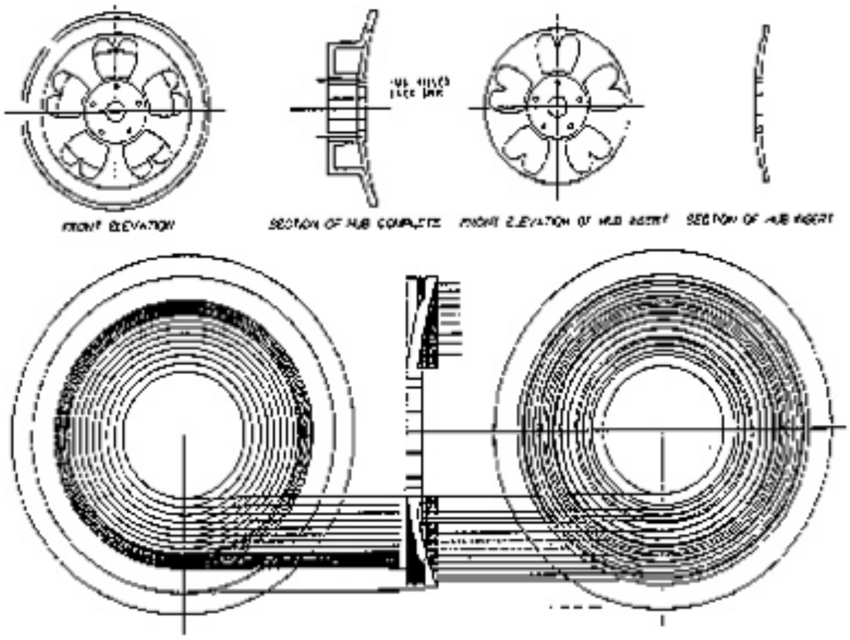

Figure 9: Drawings for the Spitfire wheel hub insert

Earlier the construction technique for a 3D letter "L" was illustrated, here is illustrated the technique used to machine the aluminium hub insert for the wheel of a 1/4 scale Spitfire (Fig 9). Because this is a dished section with heart shaped spokes cut into it, forming this component by normal workshop equipment presents significant difficulties.

The cross section of the hub drawing is divided by vertical lines, spaced apart by the resolution required for the curved surface. Where these lines cross the section surface gives the boundary for the profile at that level. The profiles are drawn in sequential layer numbers. The aluminium plate is secured to a sub-plate of ply or MDF, which is held by the bed vacuum. Simple sequential machining then gives the dished front face of the hub insert. Changing cutter to a drill produces the axle and wheel bolt holes. A screw through the axle hole prevents movement when the part is finally cut through. Switching back to the cutter the spokes are cut, and then finally the outer periphery.

Figure 10: The Spitfire wheel hub insert being cut

The hub is now dished on one side, but needs machining on the other since it has to match exactly the profile of the wheel rim. The technique here is to use the machine to cut a jig into the ply or MDF, in the shape of a circular recess with a raised portion in the middle. This will support the hub centre when it is placed inverted into the recess. A screw through the centre will once again hold the wheel steady during machining assisted by pins placed through the wheel bolt holes.

Since the machine has just cut the recess, all reference levels are known, so machining of the reverse side can be continued with no problems of registration in the three axes. The centre hub region is at first left unmachined so as to leave the screw undamaged, but finally the screw is removed, the wheel clamped around the periphery, and the centre portion machined to the correct level.

Similar multi-level techniques can be used for many architectural components. Illustrated here is the production development drawing for a bridge parapet, one of many such parts for a 1/12 scale bridge which was part of a film set. If a building elevation has been drawn by the architect using a CAD system, it is a simple matter to transfer the details to a production drawing where the desired model details can be reproduced at different levels, merely by assigning them to different layers. This could include window and door reveals, frames, even brick patterns engraved into the surface. This can of course be done by the architect in anticipation of the modelling technique, or done once the data is imported into the machine software.

Once this is done for each elevation, and the elevation cut from the base material, it is then straightforward to "erect" the walls to complete the building. This process can be further aided by cutting the floor plan at each floor level, from material of the scale thickness of the floor beams for example, and then assembling the floors with spacers through registered holes in each floor. The elevations can then be used to clad the edges of the floor panels. This method of building up architectural models is of course not new, but the accuracy of this combined design/machining system means that the parts really do fit together properly, making it more practical to consider. Furthermore, the speed of trying out new ideas lends a versatility to design which is a very valuable asset to a professional model maker who will be used to his clients changing the design when the model is in an advanced state of completion!

Conclusions

The work presented in this paper demonstrates a practical approach to the realisation of "desktop manufacture". The ease with which graphic design can be translated to machined 2 and 3 dimensional components, with examples from the production of miniature aircraft, indicates the validity of the approach. The versatility of a cartesian robot cutting machine, combined with powerful yet easy and quick to use design facility results in a competitive approach to the production of prototype and batch production components.

Due to the accuracy of manufacture, parts with complicated sections can be built up from smaller parts, which accurately lock together to form the final assembly. This can be used in conjunction with traditional techniques to get the best of both worlds, particularly with large sub-assemblies.

The accuracy and consistency of this machining system means that rapidly produced prototypes from it are consistent with production components from the most sophisticated production processes, particularly as the correct material can be used, giving a truly working prototype.

Acknowledgements

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