A Rapid Product Development Environment for Post-Graduate Student Aircraft Design Projects

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Abstract
Post-graduate education in aircraft design needs to prepare students for their future roles as professional engineers in the aerospace industry. A key requirement from industry is for students to learn how to deal with realistic open ended design problems during their University education, and group design projects have been shown to provide an excellent means to develop these skills.

Cranfield University has a long history of teaching aircraft design using group design projects. This paper describes a recent initiative to extend the scope of the group design projects at Cranfield to incorporate rapid prototyping activities and give students hands-on experience of translating a digital design into a physical prototype.

Keywords: Rapid Prototyping, Reverse Engineering, Aerospace, Design Education.

1 Introduction
There has been extensive debate in recent years about industry's requirements for engineering student design education. In his review lecture of 2005 John McMasters (McMasters) from the Boeing Corporation highlighted the importance of producing University graduates who are "system of system thinkers" to become the engineers of the future. McMasters emphasises the benefits of incorporating design-build-test projects in engineering courses to teach students how to deal with realistic open ended engineering problems. In 1993 Nicolai (Nicolai) from Lockheed stated that US Universities must review their engineering curricula to raise the importance of gaining design experience during the degree program. Nicolai reported that the result of an evaluation of engineering education at Arizona State University was that "the unanimous number one attribute desired for a newly graduated engineer was the ability to identify and define a problem, develop and evaluate alternative solutions, and effect one or more designs to solve the problem".

In his review of aerospace engineering education for the 21st century Fletcher (Fletcher) states that "The development of an aerospace curriculum for the next century must include increased opportunities for students to become involved in hands on experience. Further, there must be sufficient involvement in team related activities the acquire teamwork skills needed for employment in the international aerospace engineering workforce".

Several Universities have published their experiences of running group projects that follow the design-build-test philosophy. Sullivan and Watkins (Sullivan and Watkins) describe a design/ build/ test environment for undergraduate aerospace design students at Purdue University in the United States. Their aims in implementing the environment were to give students exposure to design and analysis software, and basic manufacturing tools; and to enhance teamwork and communications skills. They are enthusiastic about the benefits to students of participating in design-build projects, but also identify a number of problems including the time taken to build physical prototypes, the high level of support required from academic staff, the poor integration between tools and manufacturing equipment and the long learning curve for tools and processes.

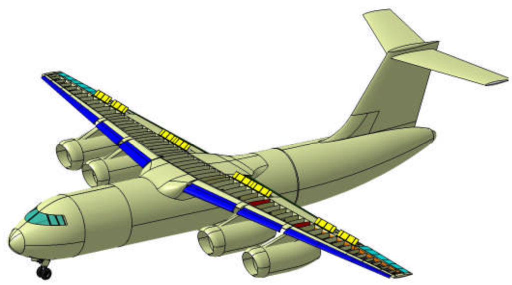
Mason *et al* (Mason, Robertshaw and Inman) published their experiences of group design project work with students at Virginia Tech in the United States and concluded that a hands-on approach to design generates more interest among the students and leads to a better appreciation of the course lectured material. At Cranfield University we have also gained experience of design-build-test projects through the part-time Aircraft Engineering MSc in which industry sponsored students design and build an unmanned air vehicle (Fielding). However the high cost and long lead times of these major aircraft design projects mean that it is not feasible to transfer experiences from them onto our full time courses.

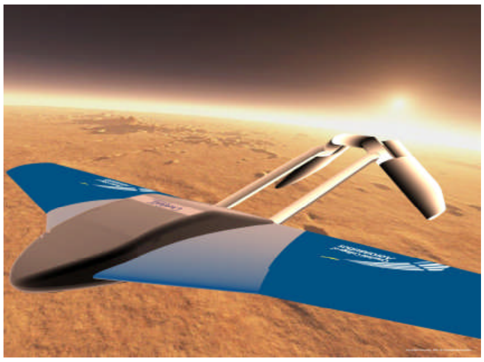
This paper describes a recent initiative to extend the scope of the aircraft group design projects at Cranfield University to incorporate physical prototyping tasks. The objective is to give students hands-on experience of translating a digital design into a physical prototype, and to close the loop from manufacturing back to design by using reverse engineering techniques for model inspection.

2 Background

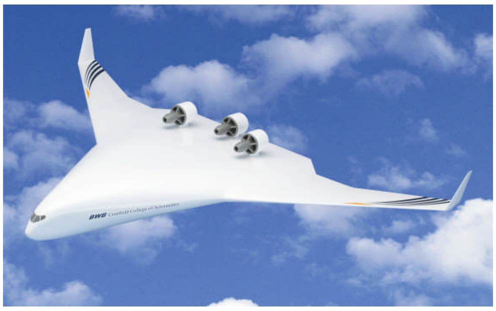
Cranfield University has a long history of using group design projects to teach aircraft design. The College of Aeronautics, the forerunner to Cranfield University was established in 1946 and the University has delivered post-graduate courses in aircraft design since that time. Today the MSc in Aerospace Vehicle Design is a one year taught Masters degree composed of taught modules, a group design project, and an individual research project. The group design project is a major focus of the course (representing 50% of the marks), and provides an opportunity for 30 students from many different countries to work together as a team to design an aircraft. The project runs for 7 months from the start of the course in parallel with the lecture modules in specialised aerospace design subjects.

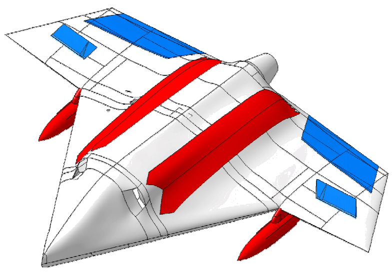
In contrast to design projects at many other universities the students are provided with a detailed project specification including a conceptual design for the aircraft, and their task is to take the design concept forward through preliminary design and into detailed design. Each student is allocated a component of the aircraft as their individual responsibility, and must also participate as a member of the project team. Figure 1 shows some examples of recent group design projects undertaken by the Aerospace Vehicle Design MSc.





(a) **(b)**





(c) **(d)**

Figure 1. Examples of Group Design Project Aircraft (a) F-02 Civil Freight Aircraft (Smith, 2003)(b) M4 Mars Plane (Stocking and Sumner) (c) BWB- 98 Blended Wing Body Passenger Aircraft (Smith, 1999) (d) U-3 Stealthy Unmanned Strike Aircraft (Stocking)

Since the early 1980s students have made increasing use of computer based tools to support their design and analysis work in the group design projects. CATIA v5 is used extensively to construct accurate 3D models of the aircraft for visualisation and engineering analysis. Figure 2 shows examples of the Computer Aided Design (CAD) models developed for the F-02 Civil Freight Aircraft project, in which the students used CAD software for a range of activities including developing preliminary layouts, modelling detailed component designs, and evaluating operational aspects of the aircraft. A typical CAD model for a group design project aircraft would be composed of 200 individual CAD models configured into 50 sub-assemblies.

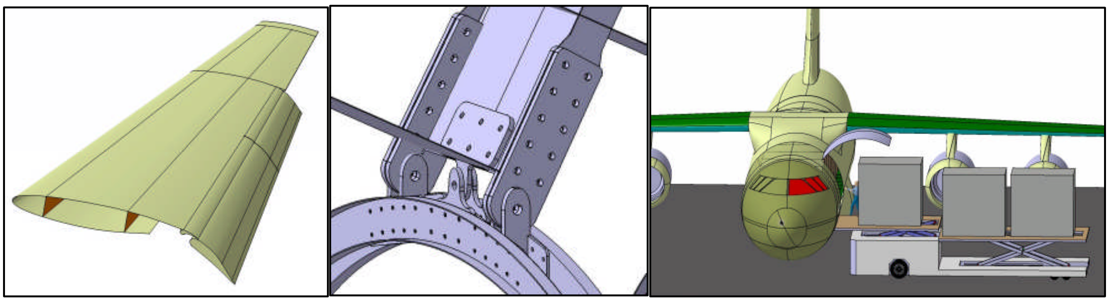


Figure 2 Example CAD models for F-02 Civil Freight Aircraft (Smith, 2003)

In the early 00s it was recognised that although the students were making extensive use of computer tools during project work, they were not gaining any experience of the challenges of converting a digital design into a physical product. In particular the students did not have a good understanding of the links between computer aided design and manufacturing. It was therefore proposed that physical prototyping tasks be integrated into the group design projects to give the students exposure to manufacturing issues.

3 Rapid Product Development Environment

The rapid product development environment is based around a student PC laboratory with 26 high specification Pentium 4 PCs and a rapid prototyping laboratory. The PCs are all configured with CATIA v5 for CAD/ CAM, MSC/ PATRAN and MSC/ NASTRAN for finite element analysis, MATLAB for simulation and Microsoft Office applications for report writing and spreadsheets.

The rapid prototyping laboratory has a 3-axis ISEL Computer Numerically Controlled (CNC) machine (model GPV 4830) with a 480mm x 300 mm x 350 mm working volume, and a Renishaw Cyclone contact scanning system which can scan up to 3 metres per minute, generating 400 points per second to an accuracy of 0.005mm. The equipment in the laboratory was selected for its relatively low start up and running costs, and its safe working environment that students can operate with minimal supervision after appropriate training.

All aircraft design students attend a 24 hour module in Computer Aided Design at the start of their MSc course. The module uses CATIA v5 for hands-on workshops, and students learn about parametric solid modelling, surface modelling, drafting and computer aided manufacture. Students can also attend an optional module in finite element analysis which comprises 20 hours of lectures and 10 hours of hands on tutorials using MSC/ PATRAN and NASTRAN finite element analysis. The students who join the manufacturing team are trained to use the manufacturing facilities as a small group, and receive support from technicians and research staff.

4 Student Prototyping Activities

Rapid prototyping was first introduced to the Aerospace Vehicle Design MSc group design project in the 2002 – 3 academic year, and reverse engineering was introduced in a follow on student research project in 2003 – 4. The students manufactured a 1/66 scale wind tunnel model of a civil freight aircraft from high density model board, and used 3D contact scanning techniques to check the model accuracy. The experiences of this first project are described in detail in the following sections.

4.1 Wind Tunnel Model Manufacture

A small team of students were allocated the task of manufacturing a wind tunnel model of the F-02 aircraft as a secondary task within the group design project. The students were introduced to the prototyping and wind tunnel facilities, and then given the responsibility of managing the manufacturing process to produce the wind tunnel model. This task was lead by two MSc students (D'Ozouville, Bourgoin). The prototyping task was deliberately open ended, to give the students the freedom to develop their own solutions, and learn from their experiences.

Figure 3 shows a flow chart of the wind tunnel model manufacturing process defined by the students. The first task was to determine an appropriate scale for the model based on the wind tunnel size and manufacturing capabilities, and to define an appropriate product breakdown structure for the wind tunnel model. The master CAD model for the aircraft was then scaled to the appropriate size, and subdivided into the component parts. The exploded CAD assembly for the wind tunnel model is shown in Figure 4.

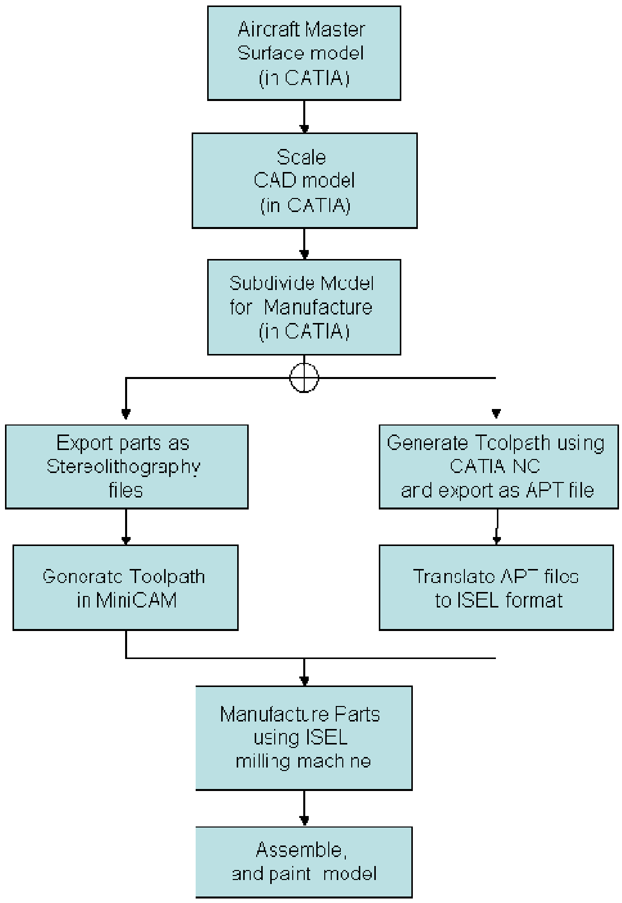


Figure 3 Flow Chart of Wind Tunnel Model Manufacturing Process

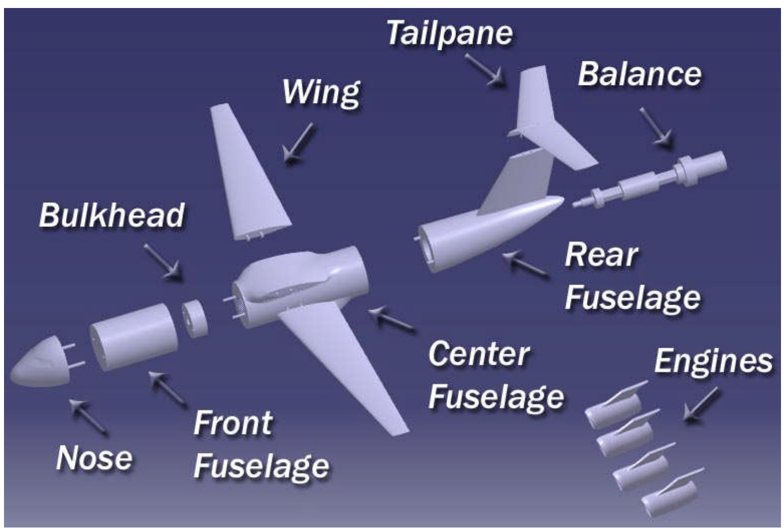


Figure 4. Exploded Assembly of F-02Wind Tunnel Model (D'Ozouville, 2003)

The students investigated two approaches for manufacturing tool path generation shown as the left and right branches in the flow chart. Initially they used a simple

Computer Aided Manufacturing (CAM) program called MiniCAM to generate the toolpaths. MiniCAM uses a stereolithography (STL) file of the part geometry as its input, and the software generates the manufacturing tool paths automatically based on the part orientation and tool geometry. The MiniCAM software has a very short learning curve, but the students found the software to be somewhat inflexible and the results for curved faces were sometimes facetted due to the STL file conversion. They then investigated using the CATIA v5 manufacturing applications to generate the toolpaths and found that it gave them increased flexibility, as well as allowing them to run accurate simulations of the toolpaths in software to verify the results before downloading them to the machine. The toolpaths were exported as Automatically Programmed Tool (APT) files, and translated into the ISEL machine format using a post-processor. The students achieved significantly better results using the CATIA machining capabilities, although the learning curve was longer.

The use of a 3-axis milling machine raised a number of challenges for wind tunnel model manufacture. In contrast to other rapid prototyping technologies it is necessary to plan a machining strategy for complex parts and several machining operations were required for each component. Figure 5 shows an example of machining the top surface of the F-02 wing. A mould was machined from scrap material to hold the wing securely while the lower surface of the wing was machined.

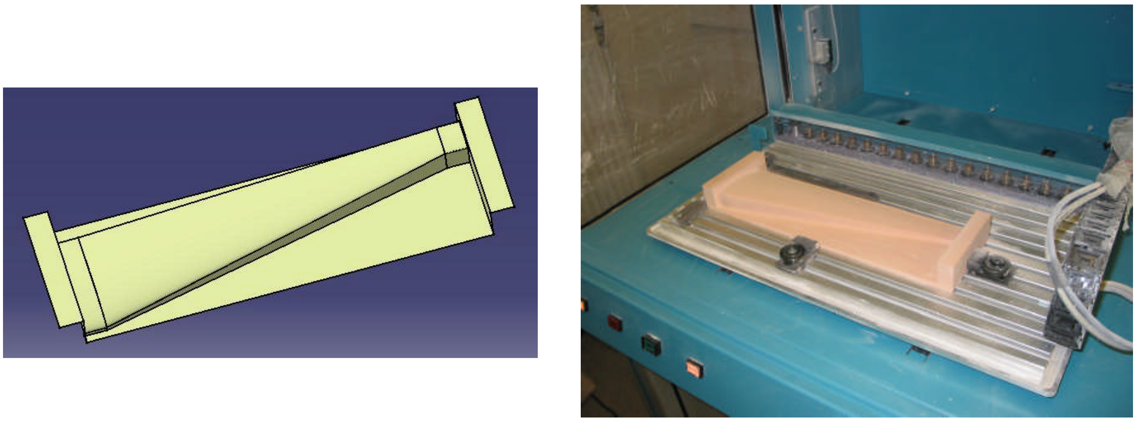


Figure 5 – Example of Machining F-02 Wing (First Side)

The wind tunnel model was assembled by hand, and the completed model was painted for wind tunnel testing. The completed model prior to painting is shown in Figure 6.

Figure 6 – Completed F-02 Wind Tunnel Model (Before Painting)

4.2 Model Quality Evaluation using Reverse Engineering

The second part of the prototyping activity used reverse engineering techniques to compare the “as built” wind tunnel model to the “as designed” aircraft, to close the loop from manufacture back to design.

The reverse engineering task was initially set as part of the 2002-3 group design project, but due to limited timescales in the project this task was undertaken the following year. The scanning work was undertaken by an MSc student (Stofft) as part of her research thesis, and the techniques she developed were integrated into later group projects. The process developed by Stofft is shown in Figure 7.

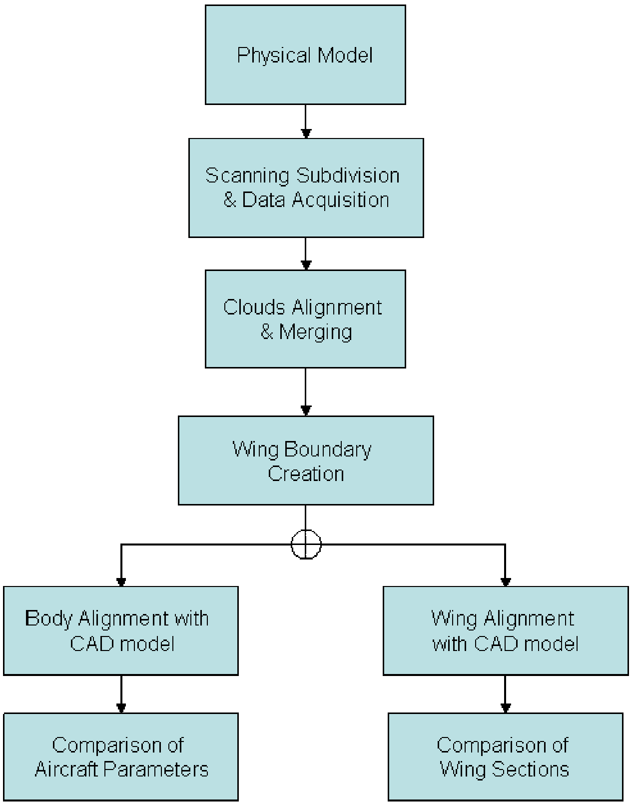


Figure 7. Reverse Engineering Process

The contact scanning machine can be programmed to scan the surfaces of an object, creating a dense grid of points as its output. Figure 8 shows the scanned points that were digitised from the forward fuselage and starboard wing of the F-02 wind-tunnel model. The scanning was performed in two operations – one for the upper surface and a second for the lower surface of the model (the engines were not included in the scanning), and the grid density was defined to capture a fine grid of points over the wing, and a coarser grid over the fuselage. The data generated from the two scanning operations was imported into CATIA v5 and merged to form a single cloud of points.

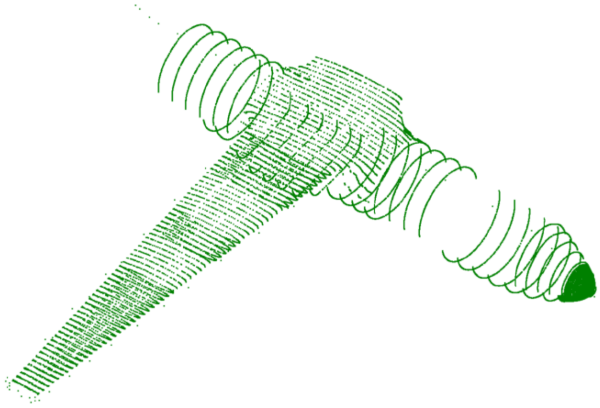


Figure 8. Scanned Wing and Fuselage of F-02 Model (Stofft).

In order to compare the “as built” model with the original CAD data, the scanned data was initially overlaid onto the CAD model as shown in Figure 9. From the figure it can be seen that there is generally good alignment between the two models although there is some deviation towards the wing tip.

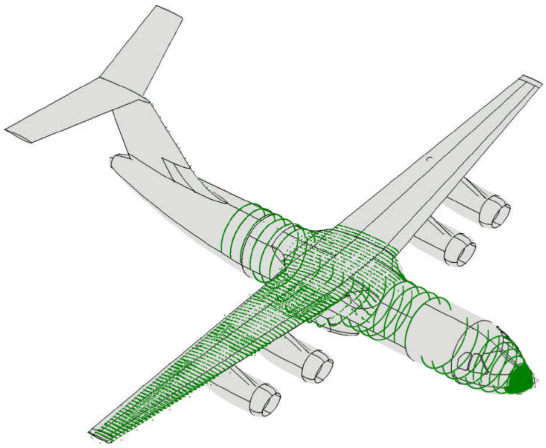


Figure 9 – Scanned Points Aligned on Original CAD model (Stofft).

It was difficult to accurately compare the two models using the scanned point data, so boundary curves were constructed through the scanned points of the aircraft wing to facilitate measuring the key dimensions of the scanned model; Figure 10 shows the scanned model, with the wing boundary curves constructed. Eighteen key parameters of the F-02 model were measured and compared to the original CAD model, and a summary of the results are shown in Figure 11. It is clear from the results that there is generally good agreement between the aircraft parameters of the scanned model and the CAD model, but there are also some significant differences between the two models. In particular it appears that the assembly of the wing onto the fuselage has introduced errors in wing vertical location, and wing setting angle.

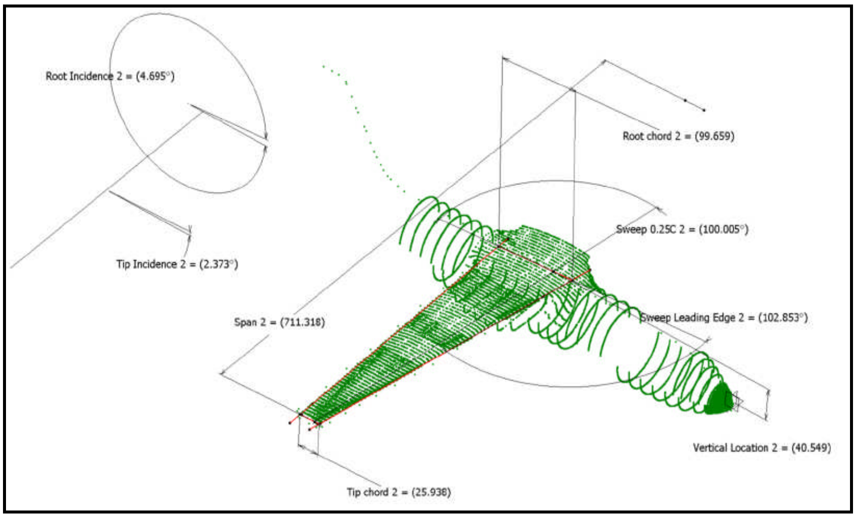


Figure 10. Aircraft Parameters Measured From Scanned Data (Stofft).

Parameters	CAD Model	Scanned Model
Tip Chord (mm)	28.49	25.93
Root Chord (mm)	102.00	99.66
Span (mm)	718.18	711.32
Sweep 0.25c line (deg)	10.1°	10.0°
Tip incidence (deg)	1.8°	2.4°
Root incidence (deg)	3.8°	4.7°
Dihedral (deg)	2.7°	3.7°
Vertical location (mm)	35.78	40.55
Tip Thickness (mm)	2.85	2.97
Root Thickness (mm)	14.50	13.44
Geometric Twist (deg)	2.0°	2.3°

Figure 11. Comparison of Aircraft Parameters on Scanned and CAD Models.

A second set of measurements were performed to compare the wing surfaces of the scanned and CAD models. The scanned wing was aligned with the CAD wing model and sections through the wing were compared at a number of spanwise locations. Figure 12 shows the results for the wing upper surface in which the maximum error was -2.188mm at the wing root where it is assembled to the fuselage. Along the majority of the wing span the error is less than 0.4mm, although there is a region with larger errors at the wing tip trailing edge.

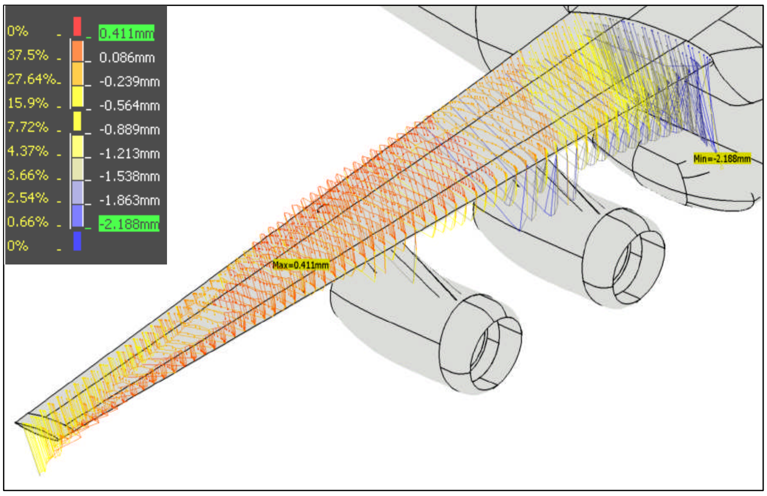


Figure 12 – Comparison of Upper Aerofoil Sections for Scanned and CAD Model (Stofft)

Stofft's results showed that for some parameters the errors between the specification and wind tunnel model were more than 30%, which could have a significant effect on the wind tunnel test results. Stofft identified a number of possible sources of errors:

- Errors in the CAD model construction with respect to the original specification
- Errors in the scanning measurements caused by flexing of thin wing sections during the scanning process
- Errors in component manufacture caused by flexing of the thin material sections during machining.
- Errors introduced during the manual assembly of the wind tunnel model after component manufacture

5 Student Learning Outcomes

The learning outcomes of the students who participated in the prototyping activities have been evaluated through informal student feedback and the students' final project theses/ presentations.

The students have in general shown great enthusiasm for the prototyping activities and have been highly motivated by the opportunity to make a physical model during their group design project. The students who participated in the prototyping activities gained specific knowledge of manufacturing tool path generation, machine control etc; but they also gained a wide range of other skills associated with the management and planning of a manufacturing task. In their project reports and presentations students have commented on a range of issues faced during the process. The issues raised include the time taken to prepare the CAD model prior to toolpath generation, difficulties associated with supporting the parts during machining, the time taken for model assembly, finishing and painting, and the importance of appropriate materials selection.

The reverse engineering facilities allow the students to compare their manufactured models with the CAD geometry to evaluate the wind tunnel model quality. The model evaluation results for the F-02 aircraft highlighted the importance of validating the prototype against its design specification, and the students were surprised by the extent of the differences between the designed and manufactured models; in fact there was an assumption that a CNC machined model would be identical to the source CAD data. It is hoped that in future projects it will be possible to undertake the model evaluation immediately after the manufacturing to allow any problems to be resolved prior to wind tunnel testing.

Overall, the introduction of rapid prototyping to group design projects has provided an effective method to teach students about the links between computer aided design and manufacturing. The hands-on project activities allow students to experience some of the challenges of manufacturing for themselves, rather than only learning about them in a lecture room.

6 Discussion and Conclusions

The introduction of rapid prototyping activities to group design projects at Cranfield has been successful and the students have produced wind tunnel models of each of the group design project aircraft over the last three years.

The prototyping task has proved to be challenging for the students, but they have managed to complete the task alongside their design responsibilities within the project schedule. The scope of the manufacturing task is sufficiently open ended to give the students the opportunity to learn wider skills associated with managing and planning the task, without being so large that it dominates the other aspects of the project. Although only a small group of students participate in the prototyping activities, they report their progress at regularly weekly project meetings, and all the students gain some exposure to the learning from the prototyping activities.

Using reverse engineering for manufacturing quality evaluation has allowed students to gain an understanding of the difficulties of manufacturing an accurate prototype, even with the use of CNC machines. The results have highlighted the care that needs to be taken during model assembly, as well as the effect of the model quality on the wind tunnel test results. To date the reverse engineering activities have not been fully integrated into the group design projects, but it is planned that the prototyping and reverse engineering will be fully integrated into next year's project.

The use of a 3-axis CNC machine as a rapid prototyping tool for student projects has raised some interesting issues. In comparison to stereolithography and 3D printing technologies it offers a much less automated prototyping facility, which requires a longer learning curve for the students and requires more staff support. However, as a teaching tool the CNC machine has proved to be extremely valuable because it introduces students directly to a range of issues associated with product manufacture and assembly. Using a CNC machine has also allowed us to implement a low cost prototyping laboratory which can produce functional wind tunnel models for a wide range of aircraft design concepts.

7 Acknowledgements

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