CRANFIELD UNIVERSITY

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On-board Visualisation of Machining Tool Paths Generated by Function Blocks

School of Aerospace, Transport and Manufacturing
(School of Applied Science)

MSc by Research

MSC THESIS
Academic Year: 2013-2014

Supervisor: Dr. Jörn Mehnen, Prof. Ashutosh Tiwari
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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

A solution for visualising the tool path generated by a function block system is introduced in this research. It facilitates the real-time monitoring of the behaviour of function blocks running on-board a CNC controller, and provides interactivity between the function block system and the shop floor users.

In order to improve computer aided process planning for milling operations, a distributed function block system is currently being developed by the project CAPP-4-SEMs (Collaborative and Adaptive Process Planning for Sustainable Manufacturing Environments). In this system, the function blocks are created in a Web-based Distributed Process Planning (Web-DPP) system built in a Cloud environment, and dispatched to CNC controllers to generate complex milling tool paths. This approach is different from the conventional off-line CAD-CAM-CNC approach driven by G-code. The ability of a real-time, on-board visualisation of the behaviour of function blocks is a very important feature for the evaluating and manipulating the behaviour of function block. It helps the users to understand the encapsulated process behaviour which the function block system is generating, and to acquire the confidence that the system is practical and reliable.

The aim of this research is to find a suitable solution to realise the visualisation for tool paths generated by a system of function block running on a CNC controller. The existing visualisation methods are researched, compared and selected to fit the purpose. A number of aspects have been investigated such as the program language, graphical user interface layout and the practical needs of the shop floor users. By a requirements survey from industries, the challenging practical needs of industries are collected, analysed and used for steering the development. An application with a 3D graphical user interface has been developed and tested. The developed visualizer is a light weight visualisation tool which is able to run directly on CNC controllers with Windows (or PC with Windows). It can be connected with a Cloud environment (optional) for real-time tool path visualisation.

Keywords: visualisation, function block, tool path, on-board, light weight, real-time, CNC controller

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LIST OF ABBREVIATIONS

API	Application Programming Interface
CAD	Computer Aided Design
CAM	Computer Aided Manufacture
CAPP	Computer Aided Process Planning
CAPP-4-SMEs	Collaborative and Adaptive Process Planning for Sustainable Manufacturing Environments
CNC	Computer Numerical Control
FB	Function Block
FBDK	Function Block Development Kit
FBRT	Function Block Run Time
GUI	Graphical User Interface
HMI	Human-Machine Interface
IEC	International Electro-technical Commission
OOONEIDA	An open, object-oriented knowledge economy for intelligent industrial automation
OP	Operation Planning
OS	Operating System
SP	Supervisory Planning
Web-DPP	Web-based Distributed Process Planning

1. Introduction

1.1 Background

In the world of industry, machining technology is the most fundamental element of almost every industry, from aerospace to automobile. The machining business has entered the digital age for a few decades. Computer Numerical Control (CNC) machines have been equipped in almost every field that needs precise manufacture. The typical work flow for numerical machining is CAD (Computer Aided Design) — CAM (Computer Aided Manufacture) — CNC. First, a precise 3D Model with all the information needed for manufacture is designed in CAD tool. Then, the model is sent to the next step, the CAM for process planning, which is usually accomplished by skilled engineers. Commands programed in G-code (programing language) are generated from CAM system, and dispatched to the CNC controller. Those codes control the machine executing the process of manufacture. However, this sequential flow is not able to adapt to changes efficiently enough. Once the tool path is generated and uploaded into the machine controller, it can no longer be changed. Any change, such as an accidental tool brake, tool changes to a similar one with slightly different features, or a slight modification of the CAD design will lead to a rework of the whole process through CAM. The tool path needs to be planned again, and G-code requires a re-generation. The distribution process to the CNC controller also needs to be done again. Those inflexible modifications and operations are time consuming and not easily finished within a short time.

New technologies and innovations are emerging. Computer Aided Process Planning (CAPP) is becoming the cutting edge field of research. Numerous researches have been carried out to find approaches for automated and adaptive process planning. A new approach utilizing Function Block (FB) which is defined in 61499-1 (IEC, 2005) has explored a new path of CAPP. Function blocks are able to deal with real-time information in the situation that dynamic decision making is required. When encountering different kinds of uncertain problems, the adaptive control capability of a function block allows it to make a reaction in a responsive and adaptive way. Embedding FBs in CNC controllers could make the machines more intelligent and autonomic to handle and adapt to changes in a very flexible manner (Wang et al., 2012). The concept of Web-based Distributed Process Planning (Web-DPP) system consisted of function block has been proposed by (Wang et al., 2012), as a close-loop, real-time, distributed and adaptive automatic process planning solution.

The project of Collaborative and Adaptive Process Planning for Sustainable Manufacturing Environments (CAPP-4-SEMs) cooperates with several universities and companies. The aim of this project is to build an innovative knowledge-based Computer Aided Process Planning to minimise cost, improve adaptability, responsiveness, robustness, and sustainability of manufacturing processes (CAPP-4-SEMs, 2014). A Web-DPP system in a cloud environment is built in this project to provide process planning with the advantages it pursuits, by utilizing an architecture containing function blocks.

1.2 Working Definitions

A number of terms with working definitions will be used in the following content. The meanings of them are only valid within the scope of this research. They are listed here for clear understanding.

- *Real-time (run-time)*

When referring to function block systems, real-time (run-time) means the attribute of their fast reaction and re-scheduling performance in the adaptive CAPP process;

When referring to the visualizer (the visualisation tool in this research), real-time (run-time) means the attribute of both the ability to respond immediately after receiving the input information and the ability to visualise the tool path within a short time (real-time attribute of the visualisation tool is described in Chapter 5 in detail). This attribute allows the visualizer to adapt to the changes made by function blocks.

- *Off-line (Off-line mode)*

In this thesis, off-line describes the work process between CAM system and CNC controller. Because the data flow in the process is one-way from CAM to CNC, it is not adaptive when situations requiring re-scheduling of the process plan happen. It is the contrary to the adaptive feature of function block system, so it is called “off-line” compared to “real-time”.

- *On-board*

In this thesis, on-board means that the subject is installed and working on a CNC controller (either function block or the visualizer).

- *Simulation (animation)*

The simulation (animation) in the thesis means displaying the manufacturing process in the form of 3D animation for the need of users, checking the tool path for example.

- *Light weight (visualisation) and heavy weight*

In this thesis, light weight means two attributes. The first one is uncomplicated structure and algorithm within the application, which allows the program to run fast. The other is less computational resource consumption and less space occupied on the storage devices. Heavy weight means complicated structure and algorithm, or more demanding for computational resource and memory space comparatively.

In the designs of CNC controllers, operating systems and control applications are commonly customized to allow the controller to achieve the goal of fast and precise actions. For example, up to 1000 program blocks are required to be processed within one second for the HAAS controller on ST-10. In order to work at high speed, computational resource for user applications on the controller is limited too. The other situation is that the user memory offered by the manufacturers of controllers is often limited and small compared to personal computers. For example, the HAAS controller above offers up to 750MB user memory; the FANUC series 0i controller offers up to 2GB user memory; the HEIDENHAIN controller CNC PILOT 640 offers up to 1.8GB user memory. These two concepts, “light weight” and “heavy weight”, are based on this on-board working environment of the visualisation tool, in which there are only limited computational and storage resources provided.

1.3 Problem Statement

In a Web-DPP system, function blocks control all the process planning work automatically. During this working process, human involvement is minimised and human-machine interaction is limited too. As a result, the system behaves like a black box. Researchers are not able to supervise the process without a friendly human-machine interface (HMI). The result of the process planning needs to be confirmed by experts to make sure the tool path is reasonable and reliable. An application for tool path visualisation would be a reasonable solution for monitoring and confirming the output of the function block system.

Numerous visualisation tools are ready for use both in academic and commercial fields. However, most of them only work in an off-line mode (details in Section 2.4). They are capable of visualising the finished process planning result (in the form of G-code file representing the tool path) which is generated by CAM systems. The real-time mode for visualisation, which means visualising the tool path from a dynamic process planning, is not supported in most of them. As shown in Figure 1.1, process planning in a function block system works in a different way from which in traditional CAD-CAM-CNC process. As explained in the background introduction, the CAD-CAM-CNC process works in a flow, without sufficient capability for adapting changes efficiently. Once the G-code is generated in a CAM system, the rest of the manufacturing process follows a sequential one-way, so do the visualisation tools which work with the CAM system.

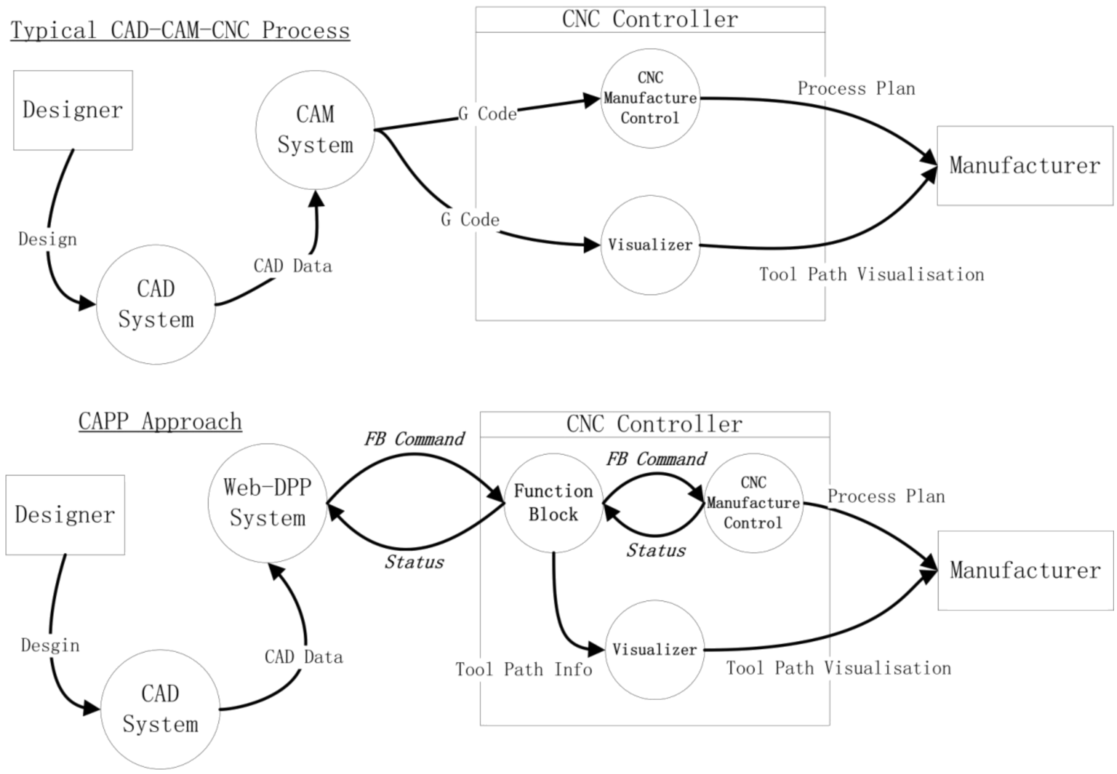

Figure 1.1 Comparison between typical process and CAPP approach

In the CAPP-4-SMEs approach, function blocks work and adapt the changes automatically (responding to CNC feedback, temporary change of manufacture plan or human involvement). The function blocks in both Web-DPP system and the CNC controller are always processing information, modifying or rebuilding the process plan whenever needed. They are "on-the-fly". This difference from CAM-CNC process requires collecting information and re-planning the process in a real-time manner. This is the reason why the feature of real-time is important in visualisation for function block system. The visualizer must keep pace with the function blocks. It is necessary for the visualisation tool to keep standby and to be able to process the "flying" information from function block as soon as it is produced. In order to work fast, being light weight is a vital attribute that the tool has to possess. Besides, it is better to have the visualisation tool working on the CNC controller, for the on-board attribute allows it to communicate with function blocks more efficiently. The internal communications among the components of Web-DPP system in CAPP-4-SMEs are based in a Cloud environment, so does the communication between the Web-DPP and CNC controller. In order to cooperate with them, the visualisation tool requires the ability of supporting the Cloud environment as well.

After investigating the existing visualisation tools and methods, the main target of this research is to propose a light weight, real-time and on-board solution for visualising the tool path generated by function blocks running on CNC-machine controllers. This research is also a subsidiary part of the EU project CAPP-4-SMEs. The research benefits the project by providing interactivity between the function block system and the shop floor user.

1.4 Aim & Objectives

Aim

The aim of this research is finding a suitable solution specifically for visualising the process planning result (tool paths) generated by the function block system in the manufacturing field involving milling operations.

Objectives

1. Understand and analyse the features of function blocks, CNC controllers and their current visualisation capabilities
2. Investigate practical industrial requirements for visualisation tools working with function block systems
3. Investigate existing visualisation methods and propose a suitable solution for tool paths generated by function block systems
4. Develop a visualisation tool and optimise it based on feedback from industry users
5. Validation of the visualisation tool through a set of case studies and expert evaluations

1.5 Thesis Structure

The thesis is divided into seven chapters. The first part introduction explains the overall background and purpose of this research, summarises the research gap, aim and objectives. Chapter 2 contains a literature review about function blocks, CAPP, Web-DPP, visualisation of tool path, programming language and platform. The methodology of this research is introduced in Chapter 3. In Chapter 4, the collection process of the requirement for the visualizer is described. The designs and analysis of a questionnaire survey and interviews are explained. The development process of the application is explained in detail in Chapter 5. Chapter 6 presents the validation procedures and the validation results. The last chapter summarises the research contribution, conclusion and future work.

2. Literature Review

2.1 Computer Aided Process Planning (CAPP)

The developing process of an industrial product contains two critical phases, design and manufacturing. What connects these two phases is process planning. Process planning is a significant process, determining a combination of necessary manufacturing processes and their sequences. The guide line for process planning is that it should follow the ideas of the designer and aiming to realize the ideal functionality of the final physical parts while satisfying, both, economic and competitive goals (Xu et al., 2011). According to Xu et al.(2011), in the domain of machining processes, the major process planning activities may include interpretation of design data, selection of machining operations, machine tools, cutting tools, datum, fixture, and calculation of both cost and production time.

The traditional approach to proceed process-planning is to hand them over to manufacturing experts. Their experience and practical knowledge, design specifications and available facilities will be the basis of the planning work they make. But this approach relies on personal skill and experience. Different expert may make different plans for the same part.

Computer Aided Process Planning (CAPP) offer a new solution to provide efficient, adaptive and intelligent process planning. CAPP is a link between CAD and CAM, which chooses manufacturing operations for producing a certain part and determines the sequence of them in the combination. The preparation cycle of a new part or product can be shorten by improving the efficiency and design quality of the process planning, which CAPP can provide.

Numerous researches about CAPP have been accomplished in the last three decades. Xu et al. (2011) summarize a category of related technologies in CAPP, which are: Knowledge-based systems, Neural networks, Genetic algorithms, Fuzzy set theory/logic, Petri nets, Agent-based technology, Internet-based technology, STEP-compliant CAPP, Emerging technologies. Researches by Tait (2005) and Wang (2013) are also in the field CAPP. Applications of CAPP are studied in the researches by Thramboulidis et al. (2007), Peltola et al. (2007), and Lepuschitz et al. (2009).

The EU project CAPP-4-SMEs, to which this research will contribute, aims at building an innovative knowledge-based CAPP to minimise cost, improve adaptability, responsiveness, robustness, and sustainability of manufacturing processes. In this project, Function Blocks are utilized in a Web-DPP system for providing the efficient, adaptive and intelligent process planning.

Summary

CAPP provides a new approach for manufacturing process planning, by improving it in an efficient, adaptive and intelligent way. In the project CAPP-4-SMEs, function blocks are utilised in the architecture of a Web-DPP system for CAPP.

2.2 Function Blocks

An International Electro-technical Commission (IEC) standard named IEC 61499-1 define the term of Function Block (FB) for distributed control and automation. A function block is an independent reusable functional module which is based on an event-driven model, with distributed, reconfigurable and programmable features (IEC, 2005). According to IEC-61499, there are two types of function blocks, basic function blocks and composite function blocks. Figure 2.1 shows the internal structures of a basic (left) and a composite (right) function blocks.

A basic Function Block is a 'functional unit of software application' (Wang et al., 2012). It can maintain multiple outputs depending on its internal state information. It contains a manner (execution control chart), with states, transitions and actions, which invokes the execution of algorithms in response to input events (Ferrarini et al., 2004). A combination of serious of basic function blocks consists a complex function block. The basic function blocks are properly organised through event and data connections in a complex function block. However, there are neither internal states nor embedded algorithms in a composite function block. The combination of the behaviours of the internal basic function blocks determines the behaviour of a composite function block.

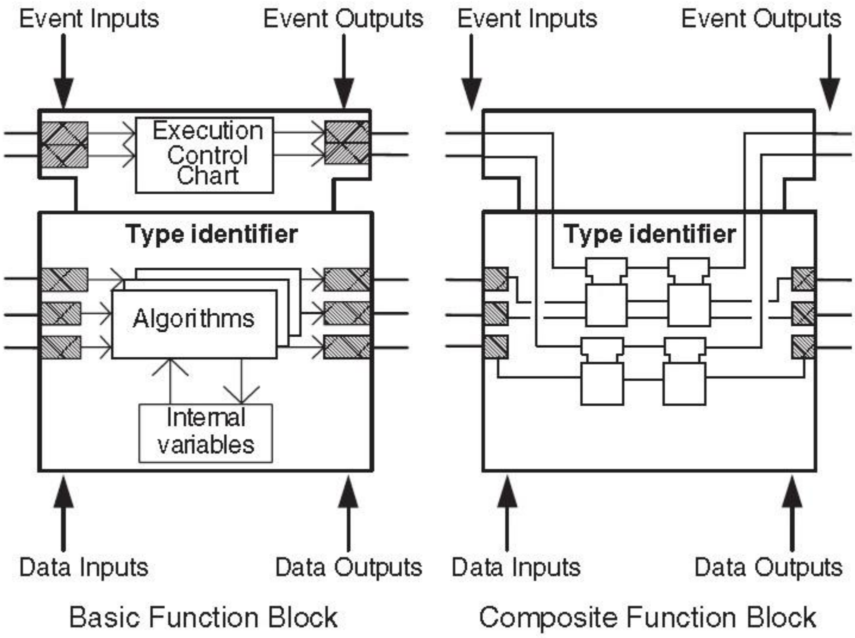

Figure 2.1 Internal structure of two types of function block following IEC-61499 (Wang et al., 2009)

The independency between function blocks allows different functions to be executed on different resources so that a distributed control system can be structured (Wang et al., 2012). The event-driven model relies on the occurrence of events to trigger program execution. That makes it more convenient and natural to describe control software which may need to simultaneously react to multiple events. Furthermore, IEC 61499 allows the programming languages prescribed in the former standard to be encapsulated within the new function blocks to support legacy algorithms (Yoong et al., 2009).

A popular tool with a friendly interface called Function Block Development Kit (FBDK) provides functionalities of edition, simulation and executable code generation of a FB application (Ferrarini et al., 2004). The Function Block Run Time (FBRT) environment is used to deploy FB based distributed control applications, as a continuous process (Hussain et al., 2004). The 4DIAC-IDE workbench and FORTE runtime environment have been successfully used to deploy code to a number of embedded devices, e.g. Digi and PC/104 embedded controller.

Numerous researches and applications using function block have been completed. For example, Vyatkin et al. (2005) introduced an application called OOONEIDA (an open, object-oriented knowledge economy for intelligent industrial automation), to create a new technological infrastructure for automation components or products, using ‘reusable portable software modules (function blocks)’. Hussain et al. (2004) created an application deployed on a network-enabled controller, on which implemented codes of the IEC 61499 model can be deployed. Wang et al. (2008) developed an application using function blocks to plan and control assembly process dynamically.

According to the review written by Vyatkin (2011), the first industrial deployment of IEC 61499 compliant devices was reported by Tait (2005, in Vyatkin, 2011) at a meat processing plant in New Zealand. A number of building management systems, where distributed control and visualisation of the entire building were implemented using IEC 61499, has reported by NxtControl. The largest project among those was a training centre building with 19 control devices controlling about 2500 I/Os (heating, ventilation, air-condition, lighting, etc.) with IEC 61499. In addition, a number of applications on the use of IEC 61499 in the process control area are presented by Peltola (2007, in Vyatkin, 2011), Lepuschitz (2009, in Vyatkin, 2011) and Thramboulidis (2007, in Vyatkin, 2011).

Summary

A Function Block, as defined in IEC 61499-1 for distributed control and automation, is an independent reusable event-driven functional module with distributed, reconfigurable and programmable features. It has been widely utilized for automatic control in both academic research and commercial projects.

2.3 Web-based Distributed Process Planning

A web-based and FB-enabled process planning and execution control system for Web-DPP, in the research of Wang et al. (2012), aims to improve the performance of machining process planning on dynamic shop floors. A two-layers architecture is used in the system, supervisory planning (SP) and operation planning (OP), as shown in Figure 2.2. SP focuses on high-level machining sequence generation, while OP focuses on machine-specific working step planning and execution. The main task of Web-DPP is to transform design information into machining operations and to determine an optimal sequence and parameters for machining. In addition, it enables adaptive execution control by means of FBs and two-way information flow for execution monitoring (Wang et al., 2012).

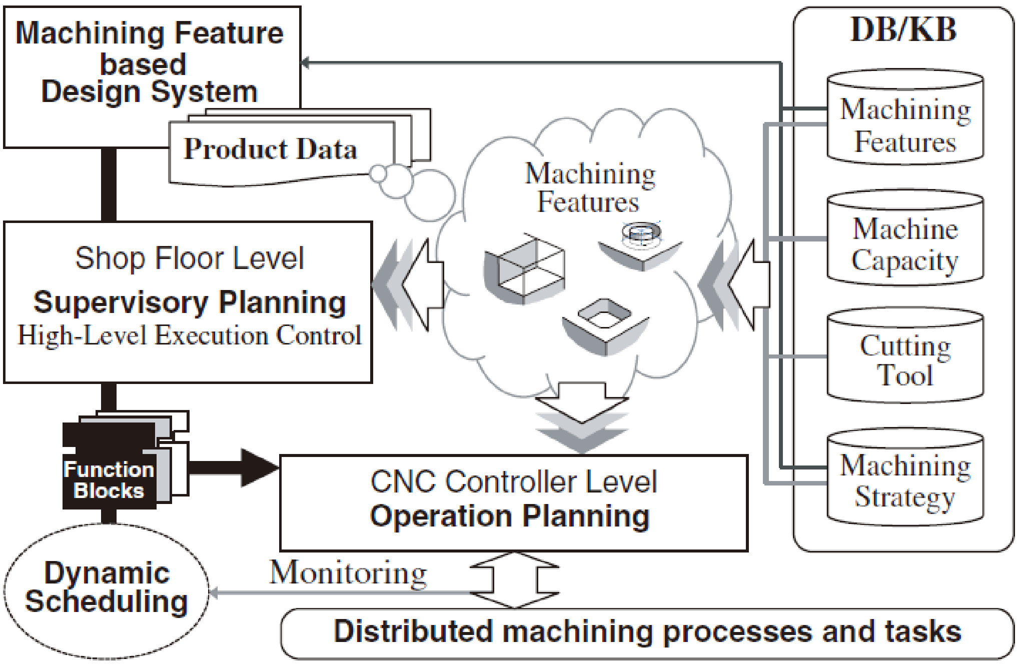

Figure 2.2 Function blocks for CNC machine (Wang et al., 2009).

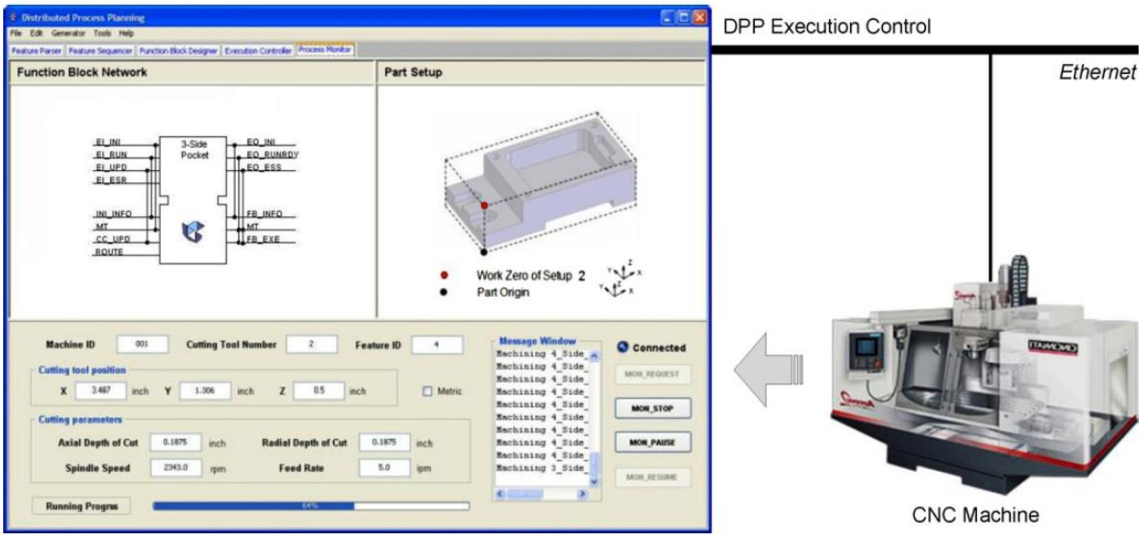

Figure 2.3 Web-DPP execution control (Wang et al., 2012)

Figure 2.3 shows a typical execution control process in Web-DPP. Machining features are created and maintained as part of product data by a machining feature-based design system (Wang et al., 2012). Then the SP deals with the sequencing of machining features, wraps it into function blocks which are dispatched to CNC controllers to carry out operation planning. The SP is generated based on the features of the part, and it is separated from the OP. That makes it possible to utilize the result of the SP to alternative machines on which OP is completed independently. Wang et al. (2012) suggested that a suitable solution for Web-DPP may have these features: (1) interactive graphic 3D models; (2) browser-based graphical user interface for distributed process planning; (3) deploying major planning and control logics in a secure application server.

Summary

Web-DPP system organises function blocks as its basic work modules in a two-layer architecture (supervisory planning (SP) and operation planning (OP)), and improve the performance of machining process planning on dynamic shop floors.

2.4 Visualisation of Tool Paths

A tool path is a series of coordinate positions that determine the movement of a tool during a machining operation. Visualisation of the tool path can provide a clear view of the operating process before the real one is carried out. Traditionally, in the CAD-CAM-CNC model, most of the CAM software provides a function of tool path visualisation and simulation. It helps engineers to debug errors and make adjustments before the real machining process. However, this function usually works in an off-line model. It is not possible to re-calculate the visualisation in a short time when the tool path is changed. These changes of the tool path are usually caused by a new part design, a new process plan or a tool break, which are unpredictable and happening even after a very thoughtful process planning. The purpose of this research is to provide a real-time performance visualisation solution for adapting the quick behaviour variation of the function block system which handles the process planning work as introduced in the previous part of the review.

There are numerous tool path visualisation tools for both commercial and academic purpose. For providing a background for this research, here key examples are listed and summarised in Table 2.1.

Software	Features			
	3D Tool Path Visualisation	FB Support	Work Object	Real-time/ Off-line
Openscam	Yes	No	G-code	Off-line
HSMWorks	Yes	No	G-code	Off-line
SolidCAM	Yes	No	G-code	Off-line
NCspeed	Yes	No	G-code	Off-line

Table 2.1 Software for Tool Path Visualisation

As an open-source software, Openscam (Cauldron Development LLC, 2014) provides fast 3-axis cut-work piece simulation with 3D visualisation; tool path 3D visualisation; G-Code parsing, simulation, verification and annotation. It can run on Windows and Linux platforms. The limitation of it is that the simulation only provides static snapshots of the cutting process. A run-time simulation is not supported.

Visualisation tools working with CAM systems are more popular approaches for tool path visualisation. For example, HSMWorks (Autodesk Inc., 2012) is a CAM tool with a function of tool path simulation developed for SolidWorks. It provides accurate tool path 3D visualisation for the cutting process utilizing the precise CAD models, as well as a vivid animation of the process. It works before the stage of handing over the data from CAM to CNC. So technically speaking, the simulation function is also an off-line model. Once the data is passed down to the CNC controller, any changes for the process planning will require a rework of the whole process, so does the visualisation. From another aspect, this system requires a demanding 3D calculation to simulate detailed material removal. SolidCAM (SolidCAM Inc., 2014) is a similar example.

The optimisation tool NCspeed (FORMTEC, 2014) developed by Formtec, provides optimisation of tool paths. It also provides online visualisation of the cutting process as one of the functions. Similar to the previously mentioned tools which work with CAM systems, the visualisation in NCspeed is accurate and powerful, but relatively resource demanding (online resources included). The software works between the CAM and CNC process too, and it is not special designed for real-time tool path visualisation which is able to adapt changes as soon as possible.

An open-source toolkit for visualisation, called Visualisation Toolkit (VTK) (Kitware Inc., 2014), is a freely available development tool for 3D computer graphics, image processing and visualisation. VTK consists of a C++ class library and several interpreted interface layers including Tcl/Tk, Java, and Python. VTK has an extensive information visualisation framework and a suite of 3D interaction widgets, and integrates with various databases on GUI toolkits such as Qt and Tk. VTK is available on Linux, Windows, Mac and Unix platforms. But it is not a specialised tool for tool path visualisation. It is widely used in scientific visualisation, and rather precise but resource and time consuming as a consequence. The various databases on GUI and visualisation methods are useful references for this research.

Ranges of researches focusing on visualisation solutions have been published in various fields. Guzman (2010) developed a 3D GUI application to generate and visualise natural-looking surface models for landscape creation using fractals. Plessis (2011) developed a real-time 3D GUI application for waste water management. Hendrix et al. (2004) developed a Java application which can generate dynamic 2D charts of data structure and adapt the changes on runtime. Silva et al. (2009) developed a 3D light weight navigation application which runs on pocket PC (C++ with OpenGL) or mobile phones (Java 3D).

Researches on light weight visualisations are also covered by papers. A Research of evaluating light weight visualisation 3D graphics formats had been carried out by Hartman (2009), involving 3DXML, STEP, U3D and JT. Holmberg et al. (2006) introduced a framework to evaluate several web-based visualization methods (Inc. SVG, DHTML, X3D, VRML97 and Java3D) in categories of technical capabilities, interactivity, support and application specific. Ma et al. (2004) present an interface suite called GODIVA to optimize the I/O processes for large scale of datasets for easier and faster performance by means of special data caching format.

Summary

As far as the background research reaches, it seems that a ready-to-use visualisation tool which is specifically designed for the tool path generated by function block systems has not been seen before in both academic research and commercial solutions. Solutions which utilise a combination of existing visualisation methods and a Graphical User Interface (GUI), seems to be a feasible approach for this research. The knowledge of the papers on light weight visualisation can be adopted and utilized in the research.

2.5 Programming Language, Platform and Developing Tool

2.5.1 Programming Language

To begin with, the program language is the foundation of every software development. The features of the language, in some degree, determine the features of the software in numerous ways. Specifically in 3D graphics, the technology capability and interactivity varies from language to language. Holmberg et al. (2006) built a framework to evaluate several web-based visualization methods (Including SVG, DHTML, X3D, VRML97 and Java3D) by categories of technical capabilities, interactivity, support and application specific. According to their research, we can see the capabilities of different program languages in different applications (shown in Table 2.2).

	SVG	DHTML	VRML97	X3D	Java3D
Technical Capabilities					
Communications	Limited	Very Limited	Limited	Limited	Yes
2D	Yes	Yes	Yes	Yes	Yes
3D	No	No	Yes	Yes	Yes
Compression	Yes	No	Yes	Yes - encrypt	Yes
Animation	Very Good	Limited	Interpolation	Interpolation	Programmable
Ease of Creation	Easy	Easy	Moderate	Moderate	Difficult
Interactivity					
Intra-element events	Event Model	Event Model	Route Model	Route Model	Composite
Scripting Support	Java/JavaScript	JavaScript	Java/JavaScript	Java/JavaScript	Java
Dynamic Update	Yes (w/ Adobe)	Yes-limits	Plug-in dpndnt	Plug-in dpndnt	Yes
Inter-element communication	Limited	Full	IE Only	IE Only	Full
Support					
Plug-in ubiquity	Very Good	n/a	OK	Poor	OK
Standards Based	Yes(2001)	Yes	Yes(1997)	Yes(2003)	Yes
Cross-Platform	Yes	Yes	Yes	Not Yet	Yes
Application Specific					
Native Structures	Simple	No	Good	Good	Programmable
Previous Use	Many	Many	Prevalent	Emerging	Emerging

Table 2.2 Analysis of web-based technologies using evaluation framework
(Holmberg et al., 2006)

3D displaying is an important feature for the visualisation tool. Among these five program languages, SVG and DHTML are excluded because of lacking the capability of 3D plotting. Among the three languages left, it can be seen that Java3D is more versatile than the other two, since it covers as many capabilities as they do and provides more compatibility for those functions. However, Java3D is the most demanding option in terms of the level of “ease of creation”. Even though, it seems that Java3D is the most suitable of these five so far for this research if there are no difficulties in handling the language.

Beyond Holmberg's research, Java3D has several other advantages itself, especially suitable for function blocks visualisation. Java is a worldwide prevalent program language, and grows extremely fast in web-based and mobile applications recently. It is fast and standards-based. It is platform independent, which is an important feature for this research. As explained in Chapter 1, for faster communication with on-board FBs, the ideal function of the visualizer would be an application which runs on the controller of CNC machines. However, in the field of CNC controllers, there are many manufacturers competing, and each of them has a series of controller models in their product line. The operation systems on controllers can be Windows, Linux, MS-DOS or their own systems (e.g. HEROS 5 real-time operating system for HEIDENHAIN controller CNC PILOT 640). A visualizer developed in Java, with the feature of platform independence, can be compatible with ranges of controllers when it comes to a mature application. Java supports deployments on embedded devices, and is optimized for these circumstances. It can provide high performances on portable devices, relatively speaking. Those features allow the visualizer to be deployed on different kinds of devices, such as computers, CNC controllers, servers, portable devices or embedded systems. Not only these features mentioned but also the prevalent use of web-based application can make the visualizer more versatile when it is based on Java. It allows the visualizer to run on any kind of platform on which browsers are supported. The versatility can be realized in this way for the function block visualisation we seek in this research.

Another well-known program language for 3D graphics is C++. Numerous applications are developed based on it, from commercial applications to entertainment applications like 3D games. There are many 3D engines developed in C++ with powerful capabilities to show explicit and astonishing virtual reality. However, in order to do that, massive computational resources, complex structures and large files are indispensable. C++ is a powerful developing language for complex visualisation work, and it is well supported for commercial use and standardised development. In comparison, Java3D is more suitable for the light weight 3D visualisation development for the research purpose we need.

2.5.2 Platform and Developing Tool

In the Web-DBB system, the manufacturing sequence is generated by supervisory planning (SP). It determines which function blocks should be wrapped and dispatched to the CNC controller. The function blocks in SP build the operation planning (OP) with function blocks used for the specific machining operations. The OP is then installed on the CNC controller for controlling the specific manufacturing process. The ideal visualisation of the tool path and the behaviour of the function block should be also working on the controller. Industrial CNC controllers work with many kinds of operation system, such as Windows, Linux, MS-DOS and OS designed by the manufacturer of the controller themselves (e.g. HEROS 5 real-time operating system). In order to realise on-board visualisation, the visualizer should be functional on all of these operation systems. But at the stage of research, it only needs to support at least one OS. The versatility could be gained after future work whenever it is required. Windows from Microsoft is known as the most popular OS for many years, and numerous computers work with it in almost everywhere. Additionally, there are also tremendous amount of applications which support Windows. Developing based on Windows almost needs no additional knowledge besides that of the developing tool itself, so does the deployment and testing on the CNC controllers which have Windows. The developing process and validation can be easily shown on any computer with Windows too, as it is easy to access for its prevalence. Because of its universality, Windows is assumed to be the most suitable and easy-to-reach developing platform for this research.

NetBeans is the official Integrated Development Environment (IDE) for Java 8. It provides a smart and fast way to develop Java applications with its editors, code analysers and converters. Especially, the GUI Builder of NetBeans provides an efficient and smooth drag-and-drop way to design GUI for Java applications, and automatically takes care of correct spacing and alignment. NetBeans IDE also supports cross-platform. Once it has been written, it can run anywhere from Windows to Linux to Mac OS. These features of NetBeans IDE make it the suitable development tool for this research.

2.6 Research Gap Analysis

Based on the literature review above, it seems that a real-time visualisation which runs on CNC controller for the tool path generated by function block system has not been designed before. The research gap is proposing a light weight visualisation solution for real-time situation, with the ability of running on CNC controllers and data exchanging through a Cloud environment. The visualisation tool also needs to fulfil the practical needs of the industrial shop floor user. Windows, Java3D and NetBeans are assumed appropriate platform, language and tool for developing this visualisation tool.

3. Methodology

This section illustrates the methodology prepared for the research. To achieve the aim and objectives, a research methodology consisted of five phases was proposed, as shown in Figure 3.1.

In the first phase, a literature review and the study of background knowledge are the main tasks. The purpose of this stage is to acquire a clear understanding of the knowledge related to the background of manufacture process planning. Function block and visualisation methods were two main fields focused on in the literature review. Besides, researches involving CNC controllers, GUI and programing language were also included. As a supplement to the literature review, exhibitions about advanced manufacturing technology were also a part of the background research. A literature review report was completed in Phase 1 as a deliverable.

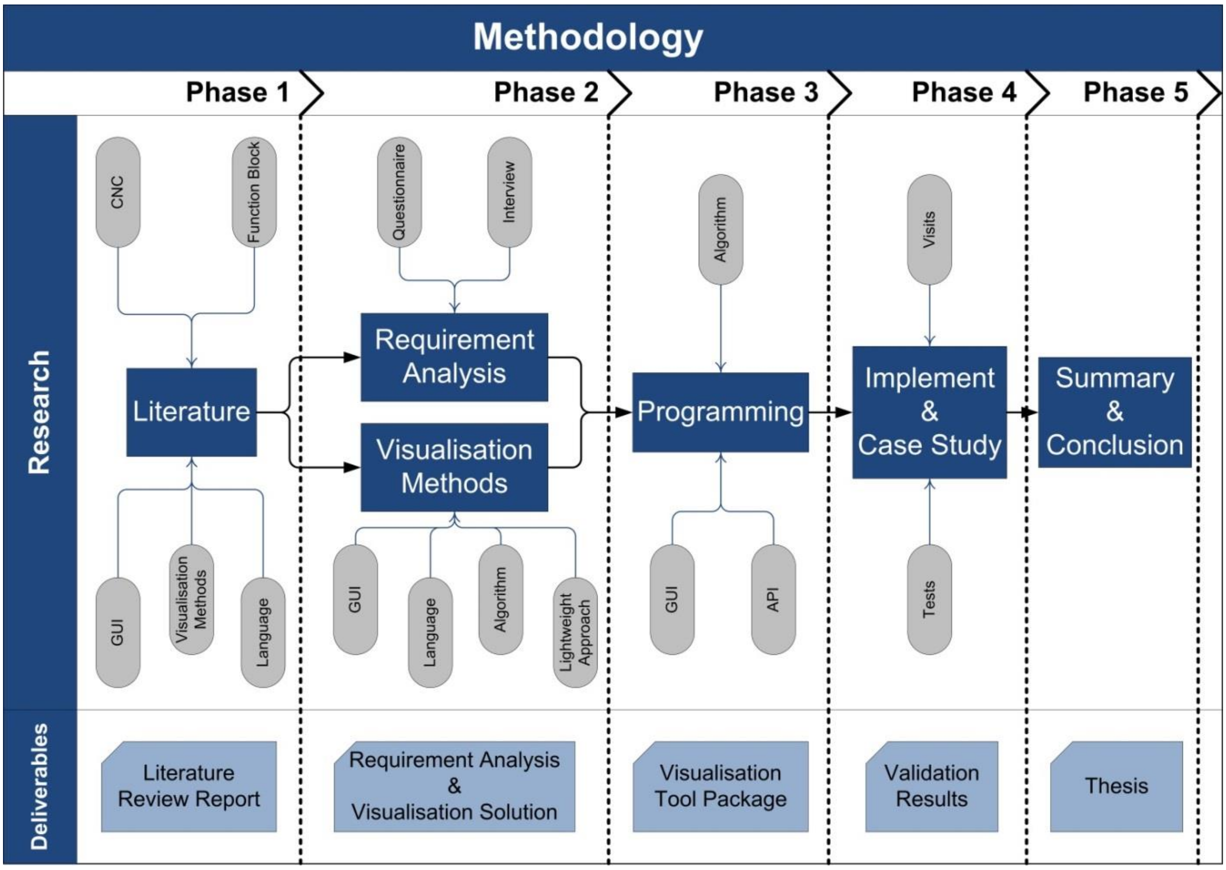

Figure 3.1 Methodology

Phase 2 contains two parts. The first one was investigating the practical needs of shop floor users. To achieve that, a questionnaire survey was designed to collect information from manufacture industries. An interview was planned and done during the visit of a domestic partner of the project. The information collected was sorted and analysed for the requirement analysis, which was the first step for developing a visualisation tool. It was the guideline for designing the application. The functions needed for visualisation were decided according to the demands. The other task in this stage was investigating the features of existing visualisation tools and methods, and choosing suitable programing language, developing platform, algorithm and visualisation methods for the development of the application. At the end of this phase, a solution based on rational choices was summarised for steering the following development as a blueprint in the next stage.

In Phase 3, the first task was learning the programing language chosen in Phase 2. Then the visualisation tool was developed module by module, and tested for debugging. The toolkit consists of 3 parts in general: the GUI, the visualisation algorithm and the Application Program Interface (API). The GUI deals with the interaction with users, and displays the visualisation of the tool path along with related information. The part of visualisation algorithm is the core of the visualizer, which contains all the algorithms for the calculation and rendering process of the entire virtual 3D scene. The API processes the communication between the inside of visualizer and the outside. After this stage, an application came into shape, and was ready for implementation and validation.

The main task of Phase 4 was to validate whether the results fulfilled the purpose of this research. At the beginning, a feasibility case study of the prototype was carried out. A case was designed to check if the basic functions in the software were working. In the next step, the same case study was tested by project partner PowerKut Ltd. UK, from the angle of an industrial user. In the meantime, an implementation case study was also taken on site for testing the performance of the visualizer on CNC controller. Comments from the partner, such as comments about the functionalities, the GUI, the performance and the implementation process, were collected and summarised for modification and optimisation. When the final version of the visualizer was completed, several experts in the manufacture business were invited for validating the research. The application, an introduction of the research and a demonstration video were sent to them by email, along with validation forms for collecting results and comments.

Finally, in Phase 5 the whole process of this research was summarised in this thesis. The literature review report, the requirement analysis, the development process, the introduction of the tool function, and the results of the validation are concluded in the thesis.

4. Requirement Analysis

4.1 Questionnaire Survey

The purpose of this research is to find a solution for visualising the tool path generated by function block system. As explained in the problem statement in Chapter 1, the visualisation is mainly for providing interactivity between the function block system and the shop floor users, by displaying the outcome in graphic figures (tool path) that reveal the underlying work currently being processed. What functions and features are needed in the tool for serving this purpose, is a critical question which needs to be answered before the development.

There are several approaches for data colleting: face-to-face interviews with a schedule, a telephone interview, postal questionnaires and face-to-face interviews in a free format (Sapsford et al., 1998). A reasonable way to acquire the requirement for this research is hearing the voice of the “customers” through a questionnaire survey, compared to the other approaches. Because postal questionnaire survey (by email) is easy for reaching out for the industries wherever they are, and it is efficient in both cost and time for both the researcher and the responders.

The role of a questionnaire survey is mainly about drawing accurate information from the respondents (Hague, 1993). To acquire information from the relevant voices, the targeting population is focused on experts in the manufacture industries. The participants of the questionnaire survey are employees of the following company: Asturfeito, Cameco AB, InconTec GmbH, Powerkut, Prodintec, Formtec and COMAC (introductions about the companies are provided in Appendix B). A part of them are from the CAPP-4SMEs project and the others are from an independent company from the project (COMAC, China). All of them are familiar with the field of manufacturing, and some of them are familiar with the field of CAPP. By targeting these voices in the survey, the information collected could be more relevant and better aimed. The sample size of the survey is expected to be 7-14, meaning 1-2 responds from each company in average. At this size, diversities in profession, experience and background should be sufficient for this research.

Indeed, a large sample size is better for the diversity, but the difficulties for reaching out and risks of the less relevant voices dominating the sound increase as consequences.

A semi-structured questionnaire was designed to acquire the information about the capabilities and features expected for the visualisation of tool path by function block system. Questions are mainly focused on the functionality and the GUI of the visualizer. It is expected that both preferred choices among predefined answers and further requirement beyond the predefined can be collected by this questionnaire. Then a results analysis based on the choices made in the survey could reveal the requirement for the visualizer.

4.1.1 Content of the Questionnaire

The questionnaire contains nine questions with choices and one open question. These questions are focused on three main aspects: the general information, functionalities expected and the operation convenience.

The first four questions collect the general information of the participants. In this survey, all the participants are staffs in companies which engage in manufacture business. But the details of the participants, such as his/her duty, position, specialty level, knowledge level about project CAPP-4-SMEs, vary from one to another. This information will affect the way how their answers are calculated in the result analysis, because it is rational to pay more attention to who is good at and familiar with the matter. The general information collected will be helpful to identify which kind of professionals the participants are, and different combinations of these choices may change the weights of their answers counted in the result analysis.

The most important question in this questionnaire is designed to collect information about the functions which the user expect from the visualizer based on its purpose, such as, visualising the tool path, displaying of the path parameters and simulation of the cutting process. There are predefined choices listed in each questions, and an open answer is welcome as well. The expecting outcome of these questions is functions particularly required for function block visualisation by the users, as well as other functions which they consider necessary. These results are an important part of the input of the requirement analysis.

The third part of the questionnaire comprises choices of preferences about the environment of the visualizer and the operation convenience, for understanding the need of shop floor users. The file format of the 3D model used for visualisation, the platform which the visualizer runs on, the navigation style of the 3D scene and the layout of user interface are discussed in these questions.

The last part is an open question. Participants are welcome to list their own ideas based on individual requirement and thoughts about the visualisation of tool path generated by function block system. Individual thinking and suggestions are expected in this question.

The complete questionnaire is presented in the Appendix A. The questionnaire for COMAC is not presented as it is written in Chinese. The contents are simply transcripts from the English version.

4.1.2 Result Analysis

Introduction

From the seven companies mentioned above (six project partners and one in aviation industry), 10 responds were received in total. Based on the answers in the responds, statistics had been made. From the summary of the general information (see Chart 4.1-4.3), in every section defined for profession, experience and background knowledge in the question, there is at least one respondent located, except “1-2 years” in specialty experience. The sample size and diversity have met the expectation at the beginning of the questionnaire survey.

The answers are sorted by categories of professions, and each category is represented by different colours in bar/pie charts to show a clear picture where the choices are located. The results are weighted according the different background, specialties and project awareness of each responder. After calculating the sum of the weighted answers, bar charts are used for displaying the final results. These analysed results will indicate the requirement which the end-users demand for the tool path visualisation of function block system.

In order to summarise the requirement, coefficients are defined to weight every choices made by responders. Different combinations of the profession, experience and background knowledge of the responder may change the coefficient counted in the result analysis. The more experienced, more awareness of CAPP and closer to machining operations, the bigger coefficient counted in the result analysis of certain questions. Identical logics are applied for each question. In the aspect of profession (P), there are 3 categories: 'Managing', 'Engineering' and 'Technical'; 4 categories of experience (E), 1-2 years, 3-5 years, 6-10 years, 10+ years; 4 categories of knowledge about the project (K), Expert, Good knowledge, General knowledge, No knowledge. The symbols for the coefficients are shown in Table 4.1.

Profession	Experience	Project Knowledge
P_M : Managing	E_1 : 1-3 years	K_{Ex} : Expert
P_E : Engineering	E_3 : 3-5 years	K_{Go} : Good Knowledge
P_T : Technical	E_6: 6-10 years	K_{Ge} : General Knowledge
	E_{10}: 10+ years	K_{No} : No Knowledge

Table 4.1 Coefficients for different categories

For example, "P_M, E_3, K_{Go}" indicates that the participant is in 'Managing' position with '3-5 years' experience and 'Good knowledge' level of CAPP. In the next step of result analysis, each answer made by one responder is weighted by the product of "P × E × K" which depending on the choices made for the first 4 questions, and then added into a sum. The definition of these coefficients for each question helps to collect the requirement more accurately from the most relevant personals. The coefficient E and K are defined separately as constants, and coefficient P is defined individually for each question. The values of the coefficient P, E, K for each question are shown in Table 4.2. The selection of values for P will be explained later in analysis of the result of each one. Taking the same example mentioned above, when the participant, who is in 'Managing' position with '3-5 years' experience and 'Good knowledge' level of CAPP, has chosen "A" in question Q05, "$P_M \times E_3 \times K_{Go} = 0.5 \times 0.8 \times 1 = 0.4$" is counted in the total of choice "A" in question Q05.

Question	Profession		
Q05	$P_M = 0.5$	$P_E = 1$	$P_T = 1$
Q06	$P_M = 0.5$	$P_E = 1$	$P_T = 0.5$
Q07	$P_M = 1$	$P_E = 0.8$	$P_T = 1$
Q08	$P_M = 0.5$	$P_E = 0.8$	$P_T = 1$
Q09	$P_M = 0.5$	$P_E = 0.8$	$P_T = 1$
Q05-Q09			
$E_1 = 0.5$	$E_3 = 0.8$	$E_6 = 1$	$E_{10} = 1.2$
$K_{Ex} = 1.2$	$K_{Go} = 1$	$K_{Ge} = 0.8$	$K_{No} = 0.5$

Table 4.2 Coefficients defined for every question

Results Analysis

In the following part, result of every question is shown and analysed respectively. The total amount responds is 10 in this questionnaire survey. The sorted results are represented by pie charts (Q01-Q04) and bar charts (weighted sum in Q05-Q09).

Chart 4.1 shows the distribution of the professions of participants. The portions of each profession are Engineering 70%, Technical 20% and Managing 10%. The statistic indicates that the majority of the participants are engineers and technicians, which is good for the survey. Because of their practical experiences on the shop floor, the answers from engineers and technicians contribute more in the weighted result in most of the questions.

Chart 4.2 shows the distribution of specialty experiences of the participants. The majority of the responders (60%) have 3-5 years of experience on their current job. Three years are sufficient for one to be familiar with the job in most circumstances, so the answers from him/her could represent the opinion of professionals. Besides, more experienced professionals take 40% (6+ years) of the total amount of the participants, which is very helpful for the questionnaire survey because of their abundant practical experiences.

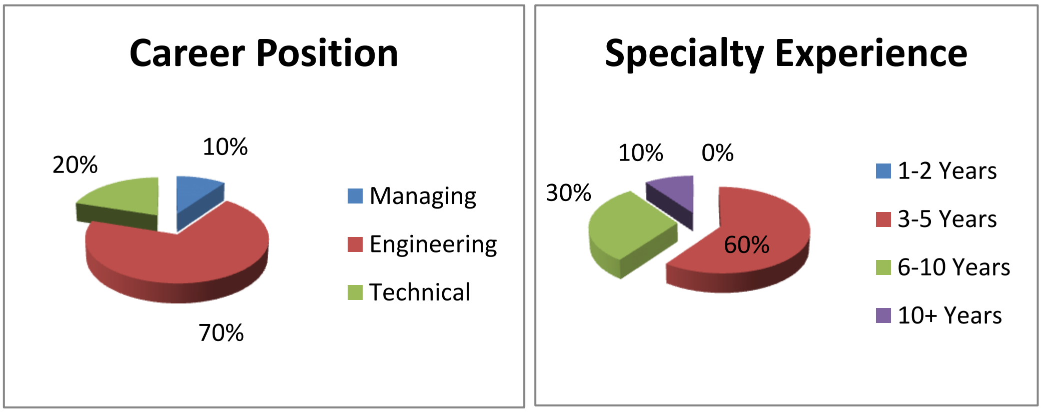

Chart 4.1 & 4.2 Career Position & Specialty Experience

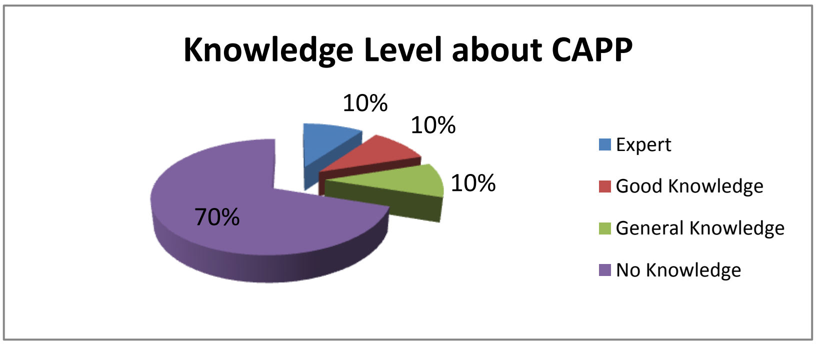

Chart 4.3 Knowledge Level about CAPP

Chart 4.3 shows the distribution of the level of knowledge awareness about CAPP. The portions of each knowledge level are Expert 10%, Good Knowledge 10%, General Knowledge 10%, and No Knowledge 70%. From the statistic, it seems like that the majority of participants are miss-targeted. But it is not the case. Those responders are also very experienced in the field of manufacturing, in spite of the lack of awareness of the CAPP project. Their opinions are valuable for the research too, but are calculated with a smaller coefficient in the weighted result.

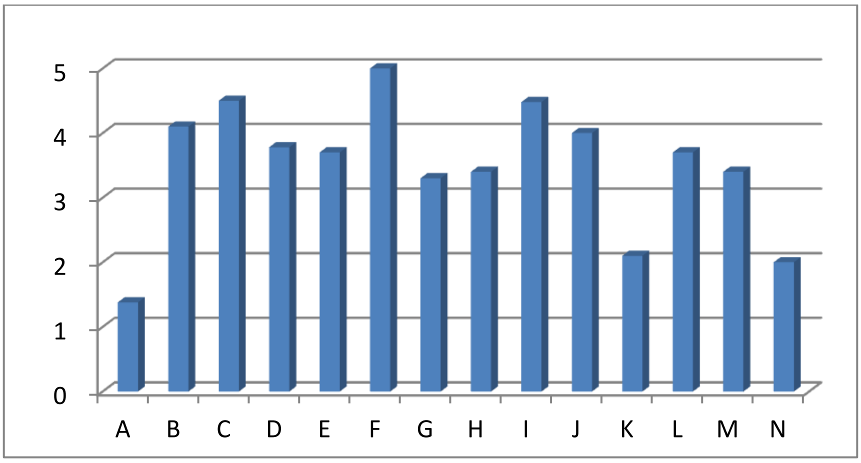

Chart 4.4 Results Weighted Sum of Required Functionalities (for 'A' to 'N' details see Appendix E)

The coefficients defined for question 5, "the required functions for visualisation", are P_M=0.5, P_E=1, P_T=1. The reason that P_M is smaller is that managers are assumed to pay less attention to the detailed functions of the machines than engineers and technicians in the most of circumstances. The weighted result about required functionalities for tool path visualisation is shown in Chart 4.4. It is clear that the most supported choice with the result of 5 is F, which is "Interactive manipulation of the function blocks". The results greater than the mid-number 2.5 are: (following the sequence from high to low) C, "Display the 3D model"; I, "Simulation of the manufacture process with the tool path"; B, "Display the 3D tool path and 3D model simultaneously"; D, "Display the output information from function block"; E, "Comparing features between optimised and un-optimised tool paths"; L "Display the parameters for cutting in the form of figures"; H, "Log & Display system log"; G, "Display the parameters for cutting in the form of numbers".

The smaller number of A, "Display the 3D tool path as it is being generated", indicates that this detailed generating process is not interesting to the participants compared to the generated tool path. It seems that the internal working process of the visualizer (generating the tool path) is not expected from it by most of the responders. It is assumed that the same reason for the smaller K, "Display the generation process of the tool path from function block system". Maybe this function is not expected in the visualizer either. For the last option N with the number of 1.8, “3D visualisation options”, perhaps the definition of the item itself is not clear for the responders to understand what it means.

The detail of the answers from the responders is listed in the Appendix E, so do those of the following questions.

Chart 4.5 shows the answers of the preference about CAD file format for tool path visualisation. Several prevalent CAD software systems with their own data formats are listed as choices. Those CAD systems are frequently used by manufacture companies for 3D designing. Another option is the STEP-file, which is a standardised format specially designed for 3D data exchange. The descriptions of these CAD tools and the format standard are listed in Appendix C.

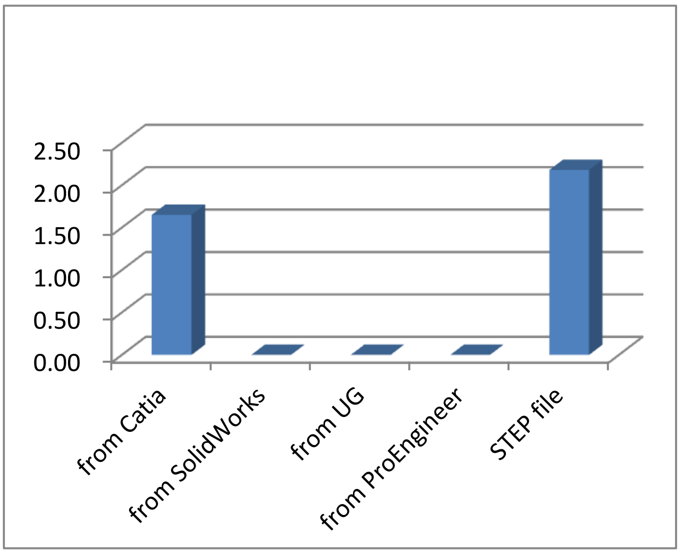

Chart 4.5 Results Weighted Sum of CAD Format Preference

The statistic shows that the STEP file format is the most preferable choice with a weighted result of 2.18. The second choice is the CATIA file format with a result of 1.62. All the participants within the project scope choose STEP file. There is also a reason given by one of the responders. He thinks the STEP file format is “common” in the manufacturing business. All of those excluded from the project choose the CATIA file standard, because their company uses CATIA in the manufacture process.

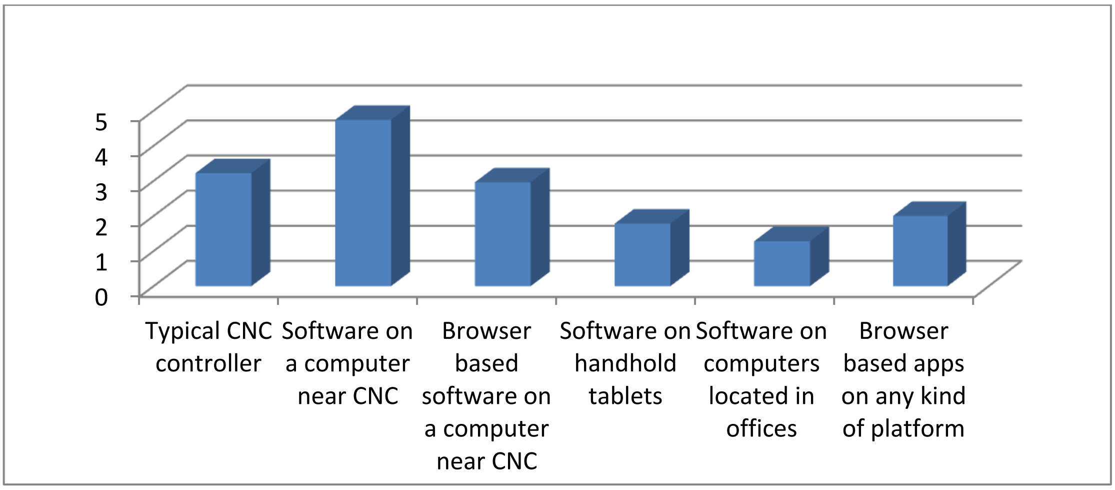

Chart 4.6 Results Weighted Sum of Terminal Preference

Chart 4.6 shows the answers of the preference about on which kind of devices the visualizer runs. As shown in the chart, "Software on a computer near CNC" is the most popular option; and "typical CNC controller" is the second popular one; "browser based software on a computer near CNC" takes the third place. "Operation on a tablet" is supported by a number of responders, but not accepted by the majority.

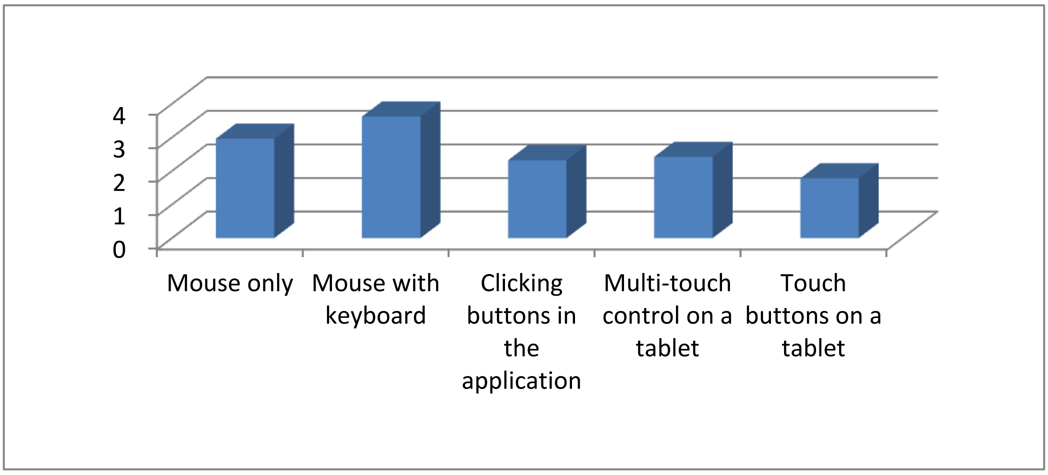

Chart 4.7 Results Weighted Sum of 3D Operation Preference

Chart 4.7 shows the answers about the operation style for 3D scene manipulation. "Mouse with keyboard" and "mouse only" are supported by the most of the responders. It seems that the typical operation style for PC based applications is still supported by the most of users. The option of operation by touch is also well accepted by quite a number of responders, just slightly behind the first two. Maybe when the style of mobile control is widespread, the distribution of the choices will be different.

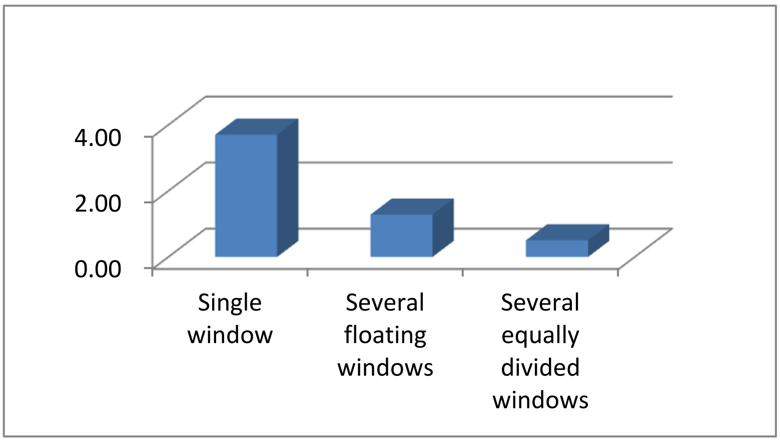

Chart 4.8 Results Weighted Sum of UI Preference

Chart 4.8 shows the weighted results of the preference about the layout of user interface. The typical layout of single window takes the most account.

In the last open question of the questionnaire, "If you could choose, what main features should your ideal tool path visualization software have?", two answers are collected, which are "Simply running without lots of many manual inputs, offering data as in Q05, offering simple 'playing' with optimization parameters" and "Flexibility and versatility".

Summary

Based on the analysis of the results of the questionnaires, requirements from the shop floor users become clear. The required functions of the visualizer include displaying the 3D model and the tool path, simulation of the manufacturing process related to the tool path, interactive manipulation of the function blocks, display of the output information from the function block, comparing features between optimised and non-optimised tool paths, and displaying the parameters of the cutting process and a system log. The format of the input 3D models is preferred to be in STEP format. The most acceptable platform running the visualizer is a computer near the CNC machine. The visualizer itself is preferred to be designed as a single window application with mouse and keyboard operation for easy 3D manipulation.

4.2 Interview

A visit to a domestic industrialist, PowerKut Ltd., was arranged after a prototype of the visualizer was ready for testing. During the visit, unstructured interviews with the staffs acquired a clearer understanding of the practical expectations from the software by the users. In the manufacture process in their company, process planning is made manually through a CAM system. G-code is generated by the CAM system and loaded into a CNC controller, in this case a Mazak controller with Windows as operation system (OS). A visualisation function for the tool path is available in an on-board application. However, this is 2D only and the view point cannot be changed, likely to cause confusion when the tool path is complex and overlapping. The technician we spoke mentioned that he would like to have an on-board 3D tool path visualizer so that he could get a clearer understanding of the tool path by a 3D representation. Moreover, if the tool path visualisation is available on the CNC controller, it's convenience for him to make the preparation of the manufacture process, as he no longer has to come to CAM systems for 3D tool path presentations.

In general, all interviewed thought the idea of on-board and light weight visualisation for tool paths from function blocks could be very helpful for business.

4.3 Summary

In this chapter, the collecting process for the requirements from industrial users through a questionnaire survey is reviewed. The results of the survey are analysed and summarised. The information collected from the interviews is also concluded here.

5. Application Development

Thanks to the highly developed computer graphics technology, there are hundreds of approaches to develop visualisation software and numerous mature tools developed. However, according to the literature and the research introduced previously, there is no mature visualisation tool which is able to provide all the functions we need for tool path visualisation of a function block system. The aim of this research is to find a suitable visualisation solution especially for function blocks, so explicit and elaborate selection of visualisation methods which serve the need of function blocks visualisation precisely are the most important process in the development. A number of aspects are focused on to build this tool, such as the layout strategy of GUI, the algorithm for plotting and software structure, the API and software operating convenience.

5.1 Graphical User Interface (GUI)

According to the result analysis of the questionnaire, the single-window style is preferred by most of the participants. And the mouse & keyboard style is the most acceptable way to operate the software. The choices correspond to the most common scene in a workshop that one can find, which is that single window applications runs on a PC with ordinary configuration aside a CNC machine. It seems that it is a reasonable, reliable and cost efficient way to run applications during the process of manufacturing. Although the trendy concept of using tablet in a mobile working scheme is also popular according to the questionnaire, which accounts for 40% of the result of the answer, the traditional way to operate an application is still the most practical for shop floor users.

The mainstream design style for the control panels of CNC controllers is a combination of displaying screen with keyboard and buttons. Some of the models provide the function of mouse through certain devices too. Usually, matrixes of buttons are placed both in the software interface and on the physical panel in most of the designs for CNC controllers. Clear and directive allocation of functions of those buttons makes it easier for technicians to operate the machine. As the visualizer is designed to be real-time and on-board, it is better to follow this clear and directive style. Buttons for frequently used functions are designed in the user interface of the visualizer. Considering the possible different operation ways of the pointing devices on different controllers, complicit operations may not work as conveniently as they do when using a real mouse. So, operations using mouse as the input device in the visualizer is restricted down to only two simple ways, click and drag with button pressed.

For a 3D visualisation tool, the layout of the interface, which displays models and tool path, is supposed to be directive to provide all the necessary information for a clear understanding of 3D objects for users. Most of the visualisation applications provide a single scene which contains all the information about the virtue world, and allow the users to navigate the view freely in it, such as in SolidCAM (SolidCAM Inc., 2014), Openscam (Cauldron Development LLC, 2014) and HSMWorks (Autodesk Inc., 2012). Usually, certain views can be displayed instead of the main window when it is required, such as front view, top view, side view, isometric view and custom view. The GUI layouts of mainstream CAM and CAD applications are similar and proved to be practical. So the GUI layout of the visualizer in this research is designed following the same style. As this visualizer is designed for controller on-board use and real-time visualisation, three separate rendering windows, front, top and side view, are displayed aside the main "scene" (isometric view) simultaneously in order to provide real-time information and clearer views of the objects.

In all of the four views, navigation operation is available, allowing the user to modify the view in the way they want. For the "main scene", the isometric view of the virtual world, two kinds of navigation functions are provided. One is driven by the drag movement of the mouse with either left or right button pressed. It controls two directions of rotations around Y axis or Z axis. The Y axis and Z axis refer to the axes in the absolute coordinate system of the virtual 3D world. Up-down movement controls the rotation around axis Y, and left-right controls the rotation around axis Z. Arbitrary movement leads to the combination of the effects made by both up-down and left-right movements. The second way of navigation is driven by a number of buttons to move the position of the camera in the absolute coordinate system of the virtual 3D world. There are four kinds of movements designed, along axis X, along axis Y, along axis Z and along a line which links the origin point of the absolute coordinate system of the virtual 3D world and the point of view. The view point is able to be move both positive and negative along those directions (zoom in and out for the last situation). Each click on those buttons will change the view point (position of the camera) by a certain distance along corresponding direction. The step (distance) is able to be defined by the user through a slider below the views. For the other three views, front, top and side view, only the latter functions by buttons are provided for navigation (except the zoom in/out).

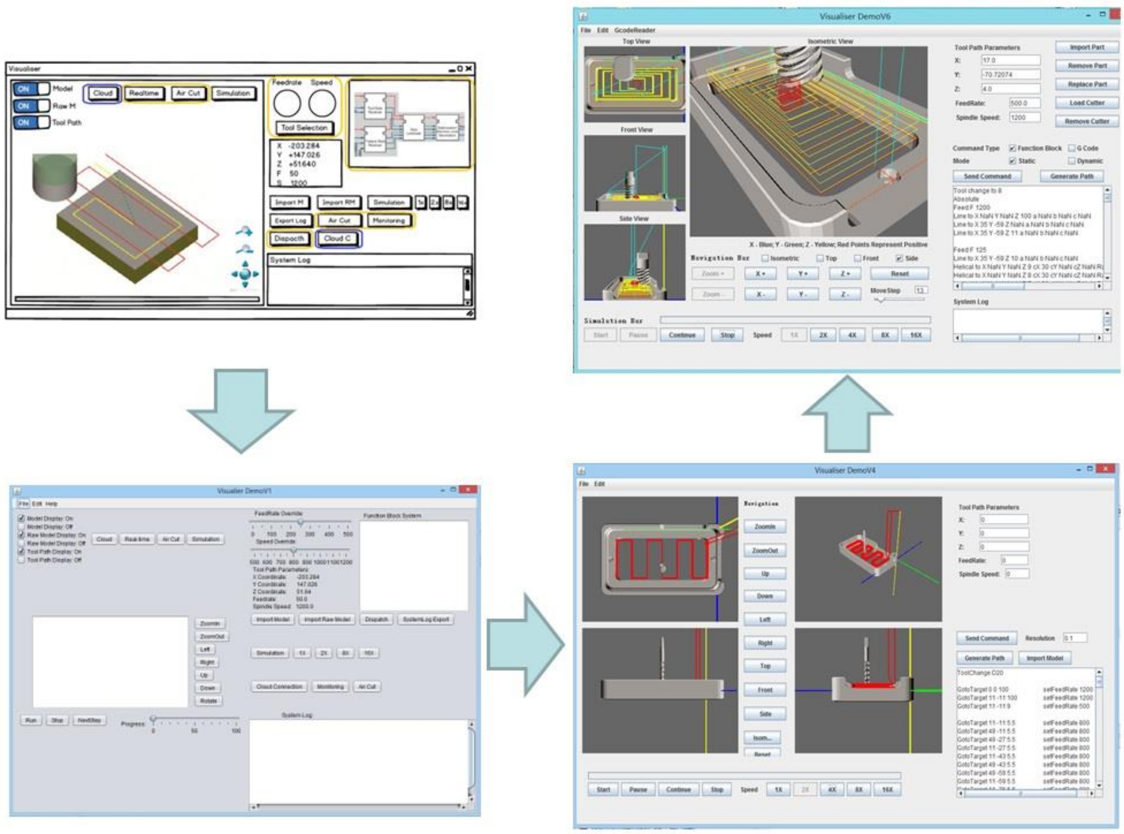

Figure 5.1 GUI development process

The GUI is developed step by step and forms its final version. The process is shown in Figure 5.1. The structure of the GUI and the function of each component will be explained later in details. The final version of the visualisation tool is shown in Figure 5.2.

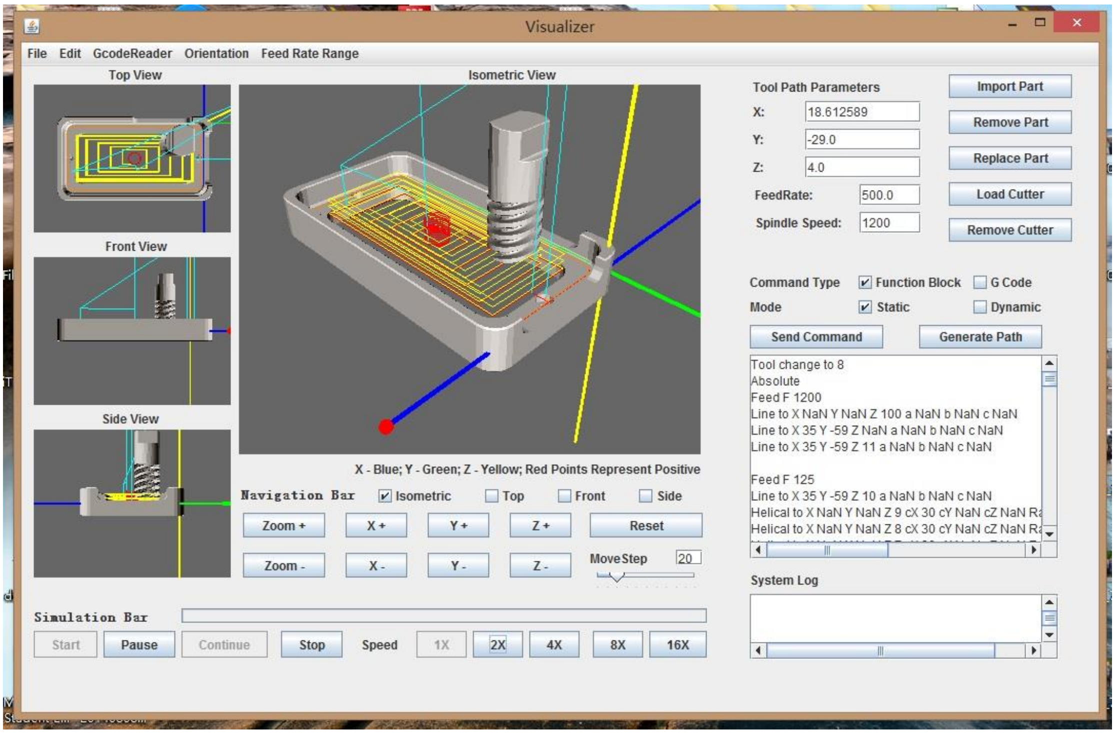

Figure 5.2 GUI of the final visualizer

5.2 Application Program Interface (API)

5.2.1 Input Command Formation

In the CAPP project, function blocks are designed and managed by one of the partners. After their function block system works out the process planning of a given part, the output codes will call corresponding methods written in Java for certain movements in the plan, which control the CNC operating the corresponding manufacturing processes. The methods called by function blocks are used in the interface of the visualizer, and listed in Appendix G as references. In the following content, those methods will be addressed as "function block commands". Every basic operation for CNC manufacture is contained in those methods called. The function block commands can also be represented by a designed format of text for displaying. In the following content, this format will be referred to as "function block format". The "commands" and "formats" both refer to the output of function block system. The difference between them is that "commands" are the methods written in Java while "formats" are written in text.

In the scope of this research, only milling process planed by function block system is discussed. All the commands generated by function block system, described in the following content, can be found in the example located in Appendix F. A number of commands will be explained in this part. For example, commands for liner movement, circular movement, feed rate setting, mode selection (absolute mode /incremental mode) and other functions are included in the format.

"Line to X 0.5 Y 24.2 Z 0 a NaN b NaN c NaN"

This is a typical function block command for a liner movement planed by the function block system automatically. It means the movement to the coordinate (0.5, 24.2, 0) from the current position and the three "NaN"s behind a, b, c mean keeping the current angle around the three axes (a, b, c) of the machine.

Other frequently used commands are circular movement "Helical to", feed rate setting "Feed", changing cutting tool "Tool change to" and mode selection "Absolute/Incremental".

"Helical to X 0.0 Y 0.0 Z -1.0 cX -4.0 cY 0.0 cZ NaN ccw true Plane XY" means drawing an arc/helix from the current position to (0.0, 0.0, -1.0) around (-4.0, 0.0, current Z) as the centre. The arc is in the clockwise direction on plane XOY. The axis is vertical against plane XOY in the case of helix.

"Feed F 152.33" means changing the feed rate from current value to 152.33.

"Tool change to 1" means changing to tool No 1.

"Absolute" / "Incremental" means changing the representation of the coordinates to absolute coordinates / relative coordinates.

All the function block commands in this format standard comprise the input of the visualizer. The visualizer is capable of visualising for tool path generated from function block systems, because the codes are designed to support the format and the commands from function blocks are able to drive the corresponding functions in the visualizer directly.

5.2.2 G-code Translator Interface

For analysing the process planning generated by function block system, manual programmed tool path written in G-code could be a good comparison for evaluating the outcome of the function blocks. In the meantime, G-code path is also a practical validation tool for the visualizer itself. It can test whether the visualizer is well functioned, even before it visualises the tool path generated by function blocks.

A G-code translator is designed for executing the translation from G-code to the function block format. It is integrated into the visualizer as a dialog window shown in Figure 5.3. It can be accessed through menu items in the application. A file chooser is provided at the left side of the dialog. TXT files storing the G-codes are supported by the translator. Two text areas are placed in the dialog too, for displaying and comparing the two formats. After the confirmation by the user, the input information in function block format is sent to the visualizer by clicking the "Send Commands" button. By this translator, tool path written in G-code is translated into the recognizable format (function block format) and directly fed into the visualizer as an input. The visualizer interprets the information in the function block format, and generates respective tool paths for displaying.

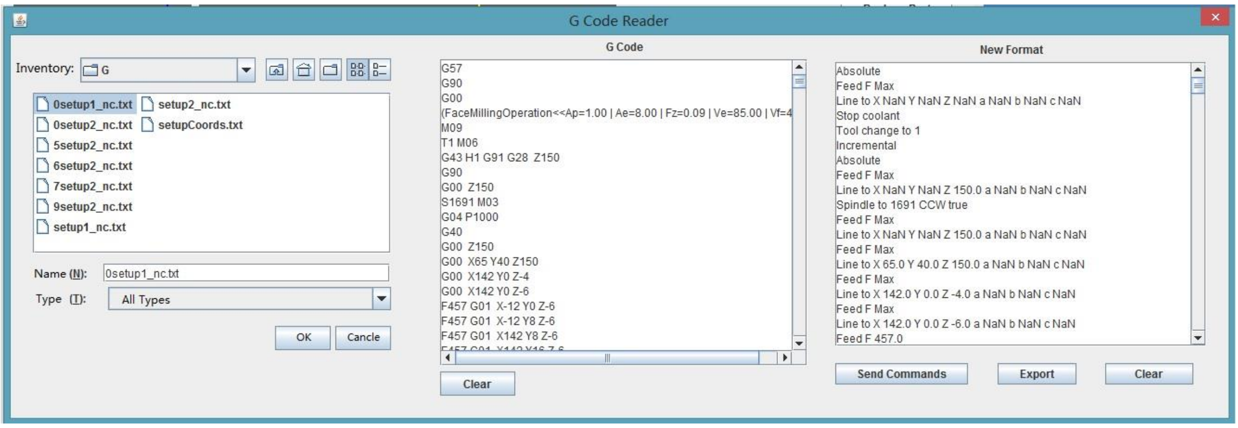

Figure 5.3. G-code reader dialog

5.2.3 Cloud Environment Data Exchange Interface

In the Web-DPP system of CAPP-4-SMEs, the entire process planning job is accomplished by distributed workstations collaboratively. Resources, software and information are shared within the network. The communication and data exchange are realised by connections in a Cloud environment. For the real-time work mode of the visualizer, input information should be dynamically fed into the application, such as commands which describe the tool path, feedback information of parameters of the cutting process from CNC machine. Potentially, the controlling signals for function blocks or CNC machines can be generated by the user through the visualizer, and then be sent back into the network. Due to the progress of the project development, the Cloud environment is still in preparing and not ready for use yet. In order to work with real-time input information, the commands translation module, tool path rendering module and animation control module are designed to be able to deal with input data blocks. The work mode can be either static commands or dynamic commands. The previous means that all the commands for the tool path is provided entirely at one time, and the latter one means that a series commands packages are provided to the visualizer continuously in a certain sequence. After the Cloud environment is set and the port for data exchange is defined, the real-time working mode of the visualizer can be realized by minor modifications.

5.3 Application Structure and Data Flow

5.3.1 Application Structure

The main structure of the application comprises three parts, GUI, API and graphics rendering. As shown in the data flow diagram for the application (Figure 5.4), each part consists of several modules which process the same function together.

The blue items represent the modules for processing the graphics rendering of the 3D virtual universe, which contains and displays everything to be visualized. The “Virtual Universe” module defined the structure of the entire 3D scene. The other six modules control the changes made to the 3D scene. “Model Importer” controls the importation of the 3D models of the parts and the cutting tools. In the requirement analysis, it is shown that the format STEP is the most popular one because it is generic and versatile. However, the importer for decoding the STEP file is difficult to program during the development. The knowledge of 3D computer graphics in a certain depth is needed to develop the loader. After a period of time for searching, it seems that it is difficult to find a ready-for-use STEP file loader too. So in the code of the visualizer, a native Object loader is substituted as the replacement of STEP loader. Object file, with the extension of .obj, is a kind of format which restores information of 3D models. The Object loader is provided in native Java library. The “Command Reader” reads the commands written in function block format, translates them into internal commands, and calls those corresponding methods in the “Command API”. “Data Generator” receives commands and generates data for every point in the tool path. It calculates all the information required for tool path rendering and the animation of cutting process, and stores it within itself. “Path Generator” renders the tool path, with different colours representing different feed rates. “Animation Controller” is a multi-thread module which controls the schedule of every frame for the manufacturing process animation. “Updater” draws data from “Data Generator” and updates a single frame when called by “Animation Controller”.

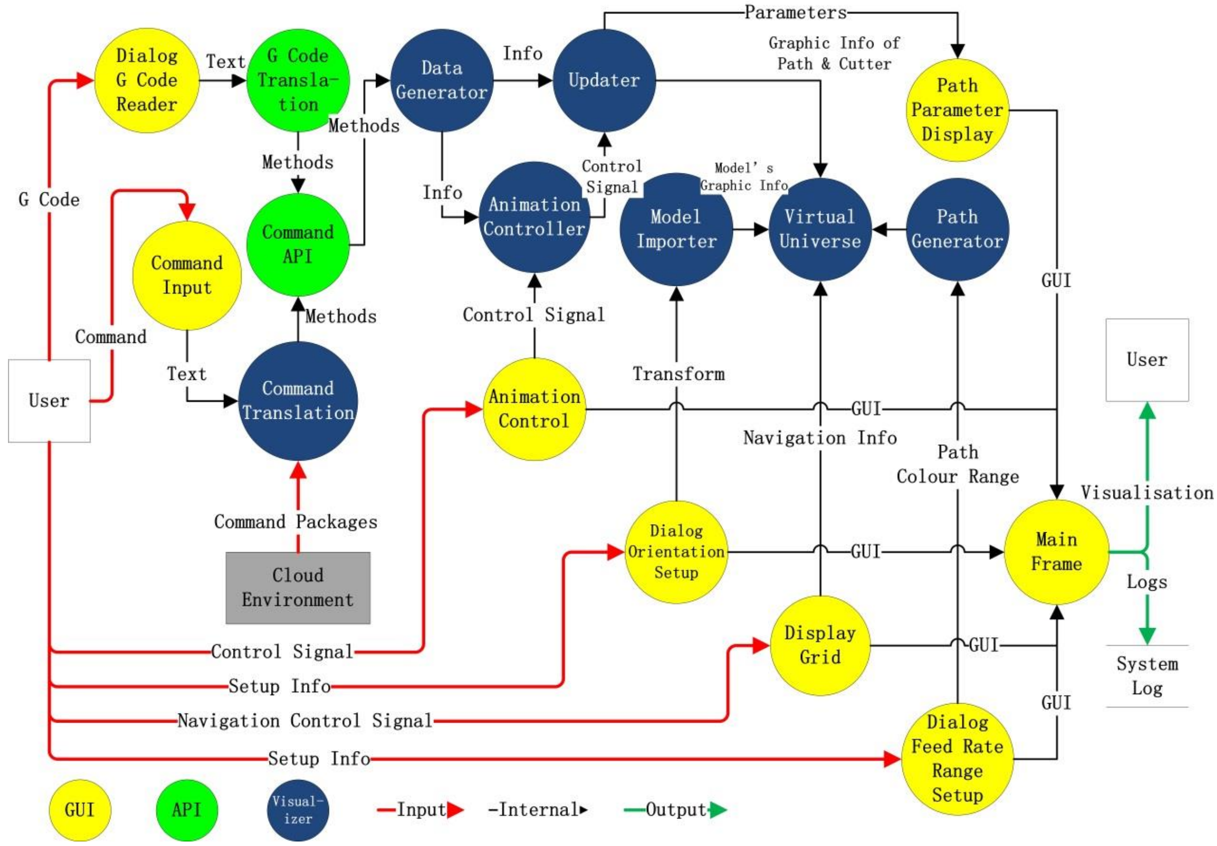

Figure 5.4 Data flow Diagram of the visualizer

Yellow items represent the displaying components of the "Main Frame", the GUI of the visualizer. Eight independent modules comprise the GUI, connected with corresponding rendering components or API components. As shown in Figure 5.5, "Display Grid" contains 4 canvases displaying the front, top, side and isometric view of the 3D scene rendered by the "Virtual Universe" module. The navigation function is also encapsulated in this module too. "Command Input" contains a text area which allows the user to type their commands directly in for visualisation. It is designed with work mode switches too, between Function Block and G-code, Static and Dynamic respectively. These two switches control the data processing paths inside the application structure, and the differences between them will be explained later. Component "Animation Control" provides basic control functions for the animation of the manufacturing process, such as start, pause, continue and stop. Five options of animation speeds are also available for user to control, 1x, 2x, 4x, 8x, 16x. "Path Parameters Display" monitors the parameters of the cutting process on run time, such as the coordinates where the cutting tool currently is, the feed rate and the spindle speed of the machine, when the animation is active. The “System Log” reports the status of the application when operations are made or errors happen.

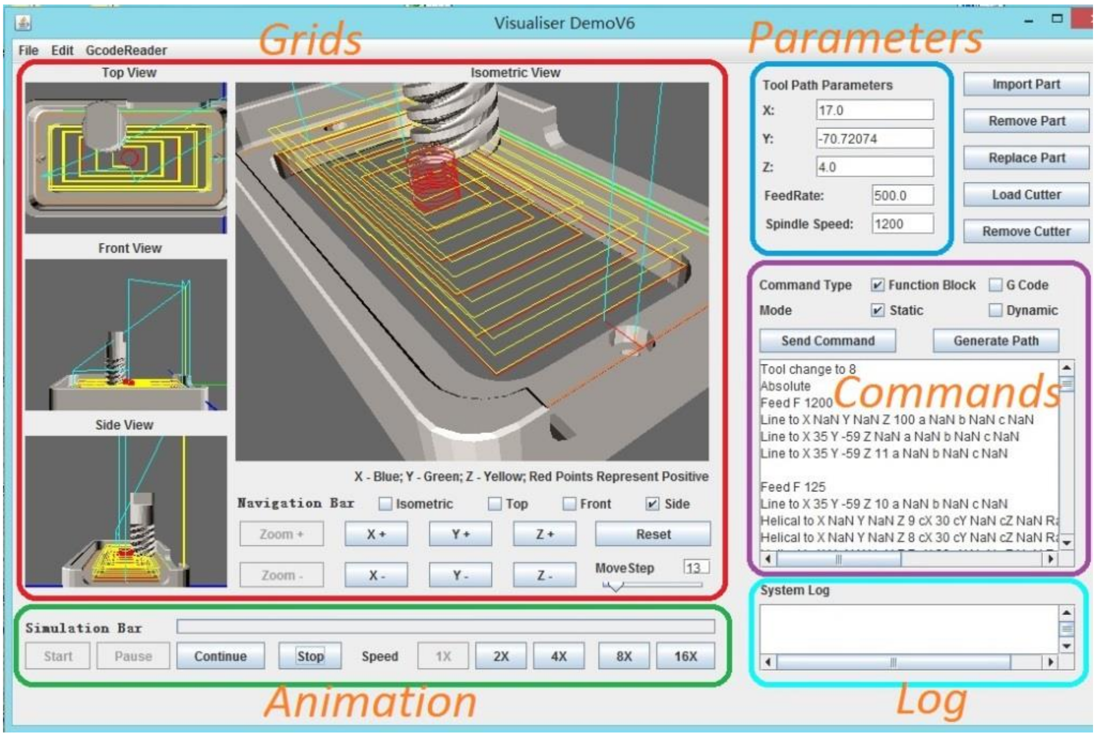

Figure 5.5 Components of the GUI

Besides the main window, there are three dialogs attached in the application, which are “G-code Reader”, “Feed Rate Range Setup” and “Orientation Setup”. The integrated G-code reader has already been introduced previously, as shown in Figure 5.3. The other two dialogs are designed for basic setups before the visualisation. “Feed Rate Range Setup” allows the user to set the range of the feed rate which defines how feed rate is represented by different colours in the “Path Generator” module. “Orientation Setup” is designed for placing the part to the right location as the tool path is planned. Offsets in three directions and rotations around the three axes can be defined here by changing the combination of the values.

The green items in Figure 5.4 represent the modules handling the exterior communication of the visualizer. The “Command API” translates the commands in function block format into the calling operations for corresponding methods in the visualizer. The "G-code Translation" module translates G-code into function block format. Two input formats for the visualizer are supported by these two modules.

5.3.2 3D Scene Structure

In the "Virtual Universe" module, every element in the 3D scene is structured, calculated and rendered. The "world structure" comprises three independent branches, "View Platform", "Imported Parts" and "Static Parts". In Static Parts branch, the background and the three axes of the absolute coordinates system of the universe are presented. Besides, illumination sources, including a directional light and an ambient light, are added in this branch too.

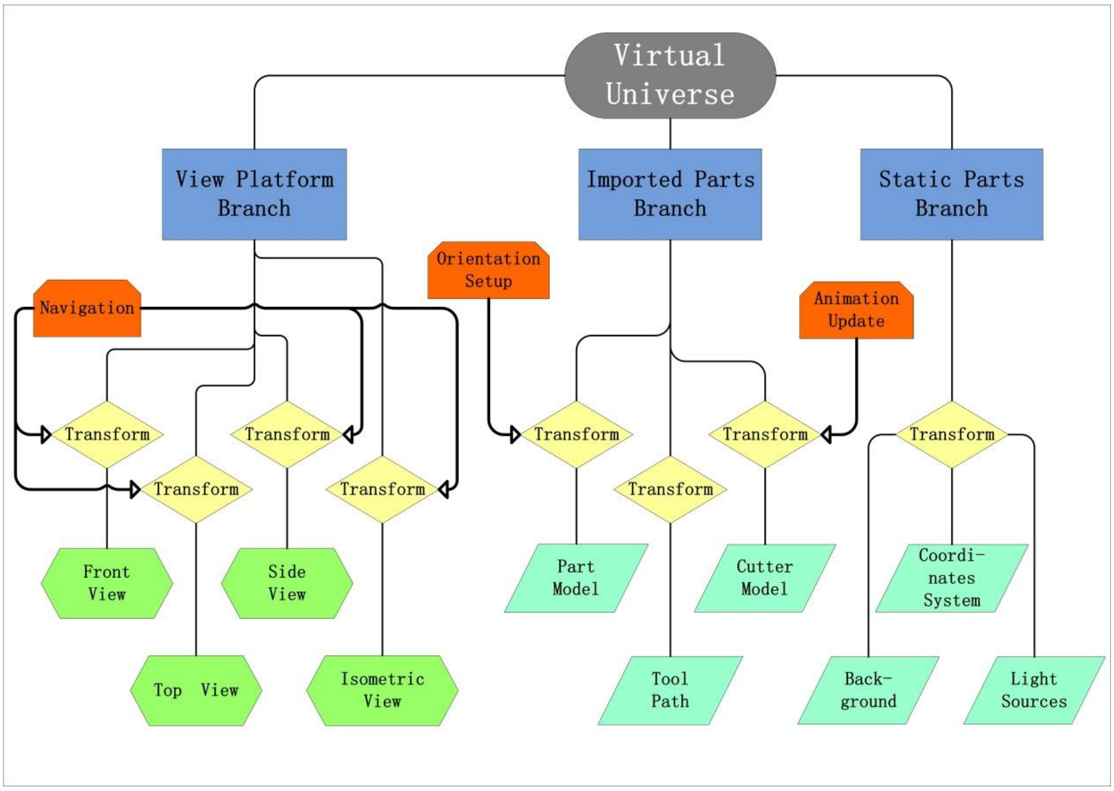

Figure 5.6 Structure of the 3D scene

The View Platform branch contains all the structures and information of four separate view points for rendering. The structure of each view point is attached to an independent Transform Group respectively, which contains the information of location and direction of the view. "Imported Parts" branch contains the main body for visualisation, which are the part model, the cutter model and the tool path.

Similarly, each of them is attached to a Transform Group too. The three orange cards, "Navigation", "Orientation Setup" and "Animation Update" represent control commands for those functions. The control commands are applied on the corresponding components, and eventually applied on these Transform Groups to become effective. Further information can be found in "Introduction for Computer Graphics" by Klawonn, K. (2008), for better understanding of the structure of Java3D.

5.3.3 Data Flow in the Visualizer

There are three kinds of information in the data flow of the visualizer, input, output and control. Three ways to feed information into the visualizer, direct commands input, dynamic input mode and G-code input mode, are designed to deliver data through different paths. As shown in Figure 5.4, input of direct information in function block format is acquired by the "Command Input" component of the GUI. The "Command Reader" receives the information, translates it into function block commands, and then sends them to the "Command API". The second way of input begins with "Dynamic Command Feed". It receives data from the Cloud Environment, packs the commands into packages of certain size, and then sends it to the "Command Reader" for translation. The capability of format translation in "G-code Reader" makes the third way of input possible. The input written in G-code is translated into the function block format, and sent to the "Command API" directly.

All three data flows feed information into the "Command API" eventually. After it receives the input, it manipulates the corresponding methods in "Data Generator" to generate the data for visualisation and animation. After calculation, the generator dispatches path information to "Path Generator", and send animation information to "Animation Controller" and "Updater". Afterwards, all the data is fed into the "Virtual Universe". Dynamic images are rendered from it and displayed in the "Display Grid" as the main output of the visualizer. Another part of output is the parameters of the tool path when animation is activated. The information about coordinates, feed rate and spindle speed are provided by "Updater" as the 3D graphics are being updated by it.

Control functions are located in several different stages in the feed-calculate-render process. At the beginning, information from "Feed Rate Range Setup" and "Orientation Setup" sets the visualisation configuration and original location of the part model. As the 3D scene is being rendered, commands from "Animation Control" component make adjustment of the animation process managed by "Animation Controller", and navigation commands from "Display Grid" manipulate the positioning of the four separate views in "Virtual Universe".

5.4 Optimisation for Light Weight

In order to improve the performance of the visualizer, the application should be light-weight and less computational resource demanding while running real-time visualisation. Another restriction which forces the visualizer to be light weight is the limited resource on both the hardware and the software of the CNC controller. As introduced in section 1.2, the OS of the controller (Windows, Linux, MS-DOS or special designed OS like HEROS 5) is usually customised to achieve the goal of fast and precise performance. In order to work at high speed, computational resource for user applications on the controller is often limited as well. Most of the computational resources are allocated for controlling the CNC machine. The user memory offered by the manufacturers of controllers is relatively limited and small. From the aspect of hardware, usually the graphic computation ability of the controller is not very good compared to the graphic cards on personal computers. On some controller models, certain visualisation functions are not supported by the hardware.

Considering the restricted working environment and the real-time performance required for the visualizer, the light weight attribute is vital for both the application and the research. After the elaborate selection of programing language, several optimisations have been made to help the visualizer "lose weight". Efforts have been made in two ways, GUI optimisation and data storage optimisation.

5.4.1 GUI optimisation

In the 3D scene, text labels represent x, y and z axis are commonly used in many circumstances. However, additional computational resources are required to realise the "billboard" effect, which allows the texts to be always facing the observer in the right direction. Distinct differentiation by representing the axes with different colours can lose some weight in the rendering process, as they are static. Red sphere models are added on the axes to show the positive directions.

In the calculation of the tool path, points are defined to draw lines. Curves are also approximated by series of short lines. In the first demo of the visualizer, each of those lines is allocated with a node (like the part model in the structure in Figure 5.6). Each node leads to a series of steps of calculation respectively. It is not an issue when the tool path is simple and in short length. But as the complexity and size grow, the data size for the tool path grows rapidly too. In order to help the visualizer lose some weight in the memory (taking less space), the tool path curves assigned with same feed rate are integrated into one node in the structure of the 3D scene. In this way, the amount of nodes has been significantly reduces, which improves the performance of the visualizer and costs less memories.

5.4.2 Data Storage optimisation

The data storage for the tool path was realised through numbers of arrays (data format in Java) in the beginning of the development. For better compatibility considering the data size, it is designed heavy and clumsy, which leads to more consumption of the memory space. The issue has been optimized in the final version of the application, through two translations of data format. "ArrayList" is a native class of Java, the size of which is elastic and controllable. It takes more space than arrays when the size of the format itself is taken account of. In the situation in which uncertainties present, applying this versatile format makes the memory consumption more economic. However, it is not suitable for the virtual universe to refer to. Because that it is necessary to keep the data in the virtual universe as long as the graphics it represents is in the structure of the scene. In this case, an array will be the most efficient way to keep data. On the contrary, an ArrayList lost its versatility in this static situation.

The optimisation is to define ArrayLists in the data storage in the initialising stage of the visualizer. After the exact information of the graphics received, the data will be transported into an array with the right size, and the ArrayLists will be emptied. Afterwards, the array will be sent into, stored and referred by the virtual universe. In the aspect of memory consumption, this optimisation keeps the light-weight style of the visualizer.

5.5 Summary

In Chapter 5, the whole process of the development of the visualisation tool is described in every aspect. The layout strategy for the GUI is explained in detail. The processes which the visualizer works internally and externally have been explained in the part for API, structure and data flow. Light weight optimisation has been made in two aspects to reduce the resource consumption.

The development process begins with learning the language of Java, Java3D, and developing tool NetBeans. Programming skills, which support the whole developing process of this visualisation tool, are adopted from learning and practicing. The entire application development is accomplished individually.

In the rest of this part, features specially designed for visualising the tool path from function block system are concluded into bullet points, and the capability of the application itself is summarised.

5.5.1 Features Designed for Visualising the Tool Path from Function Blocks

The purpose of this research is to find a suitable solution for visualising the tool path generated by function block system. A number of features in the visualizer are specially designed or optimised for the function block visualisation. They are summarised here.

Dynamic Input-Visualise Mode for Real-time

As described in problem statement in Chapter 1, in CAPP approach, function blocks work and adapt the changes automatically. The function blocks are always "on-the-fly", collecting information and re-planning the process in a real-time manner. The visualizer must keep pace with the function blocks, and be able to process the "flying" information from function block as soon as it arrives.

The dynamic input-visualise mode introduced in section 5.5.3, is designed to meet the requirement of real-time for the visualizer. Once a certain amount of commands from function block system have been received by the visualizer, they are packed in a bundle and sent to the rendering algorithm for visualisation. This work mode is able to visualise the changes of tool path shortly after they are made by function block system. Besides the time cost for visualisation, the size of the command package also determines the delay of reaction. The performance of the reaction can be adjusted by changing the package size. The reaction time also depends on the speed of the communication between visualizer and FB system, as well as the calculation capability of the CNC controller (or computer).

In one of the case study described in the next chapter, the total time consumption from receiving the input to finishing the visualisation of a complete tool path is around 2~3s (on a laptop). It is assumed to react and visualise small command packages in dynamic mode within one second (on a laptop). A real-time manner is realized in this research by this dynamic input-visualise mode of the visualizer.

Light Weight

Considering the real-time performance required and the restricted working environment, light weight is a vital attribute that the visualisation tool has to possess. The light weight attribute is pursued in every step of the development. The selection of Java language, the GUI and data storage structure optimisation are all following the idea of light weight. In the validation test explained in next chapter, the visualizer works smoothly and lightly. The average computational resource consumption of the visualizer is 2.5~5% CPU & 52MB~68MB of memory (on a laptop running Windows 8). These figures are according to the task manager of Windows, and support the accomplishment of the light weight goal by concrete evidence. A snapshot is presented in Appendix H. The consumption mentioned above includes the cost of Java Runtime Environment ("Java Platform SE Binary" in the snapshot). The actual lean consumption of the visualizer is not able to be shown by the task manager. It is believed that the consumption will be much smaller as long as the Java Runtime is supported and included natively in the OS.

On-board

In a Web-DPP system, function blocks responsible for operation planning are at the bottom of the architecture. They control the operation of CNC machines and receive adjusting orders from FBs responsible for supervisory planning. In order to act and react efficiently, the ideal approach is embedding the FBs in the CNC controller. In order to work with the on-board FBs, the ideal working environment for the visualizer should be on the CNC controller too. So far, the visualizer is able to deploy and run on CNC controllers which run Windows as their OS. Implementation test has been carried out to prove that it is functional on one of these controllers (Mazatrol Matrix), which will be explained in detail in the next chapter about validation.

Command Format Support

As explained in the literature review, process planning made by function block system no longer generates G-code for CNC machine to operate. It generates commands which directly work in the CNC controller to control the manufacturing process. These commands are standardized in a uniform format, which is described in part 5.4.1 (details in Appendix F & G). The "function block format" is well supported in the visualizer. Every kind of these commands can be directly fed into the visualizer for visualisation without any translation to other formats. So far as this research goes, it seems that no other application besides this one can do so.

5.5.2 Application Specification

- Platform:

  Computer installed Windows or CNC controller installed Windows

- System requirement:

  Java Runtime Environment (JRE) and Java3D Interface natively supported or installed.

  At least 70MB free system memory required for the application. (30MB estimated for the visualizer itself if Java Runtime Environment is native in the OS)

  At least 6.5MB free space in hard drives or user memory for the files of the application.

- Format for visualisation supported:

  Tool path represented in function block format, or in the form of G-code.

- Format of 3D model file supported:

  Object files with the extension ".obj".

- Function provided:

1. Displaying 3D objects in multiple views (top, front, side & isometric);
2. Importing, removing and replacing function for part model and cutter model;
3. Tool path plotting according to the input information in both static work mode and dynamic work mode. Real-time plotting and animation are supported;
4. Different colours using in tool path sections represent different feed rates. The range of feed rate can be set up in the dialog of "Feed Rate Range". The range is divided equally into 7 sections with 7 colours respectively;

5. Navigation operations for controlling the view in the 3D scene, such as movements along the axis X or Y or Z, zoom in/out referring the origin point. Views can be adjusted respectively, the movement of each adjustment is defined in the slider of “Move Step”;
6. Displaying the tool path in function block format. Tool path manually inputted is supported;
7. Simulation (animation) of the cutting process is provided. Basic functions like start, pause, continue, stop and speed adjustment are included;
8. Displaying the parameters of the tool path while simulation (animation);
9. Displaying the system log;
10. G-code Reader for translating the source from G-code into function block format;
11. Orientation setup for adjusting the beginning location and direction of the part model.

6. Validation

In order to validate the visualizer, five phases of validations were arranged during the research, including basic function test, implementation test, case studies, compatibility test and expert validation. They were arranged in separated periods located respectively after each milestone of the application development process. Firstly after the prototype of the application is finished, a case study for testing the basic visualisation functions came in. The next phase was an implementation test on an actual CNC controller, when the application itself and deployment procedures were finished. Then three more cases were studied. A compatibility test follows, the visualizer was tested on different platforms (different OS). The last phase was a research validation by experts from industries, who were the third party to the research.

6.1 Visualisation Functions Test

The first stage of validation test aims to prove that the core functions of the visualizer are working correctly. The functions for testing include: 1) 3D model importation and plotting; 2) tool path plotting; 3) 3D scene navigation; 4) tool path parameters displaying; 5) cutting process simulation (dynamic 3D plotting). A specific part (an iPhone case) and a pre-defined tool path (for pocket milling) in the function block format will be used in the test.

A checklist was prepared to evaluate the first case study.

Test Part: an iPhone case

Test Tool Path: pre-defined milling path of a pocket, involving rough milling tool and finishing milling with a smaller tool.

Test Computer: Laptop with a mid-level hardware set (Windows 8 installed)

Check List:

- The model is imported and plotted correctly
- The cutter is imported and plotted correctly

- The tool path is plotted correctly
- The navigation function is sufficient for use
- The basic function of cutting process simulation is provided
- The parameters of the tool path are displayed correctly

The basic function test was carried out successfully. The snapshot of the test is shown in Fig. 6.1. All the items in the checklist are matched, the functions were working correctly.

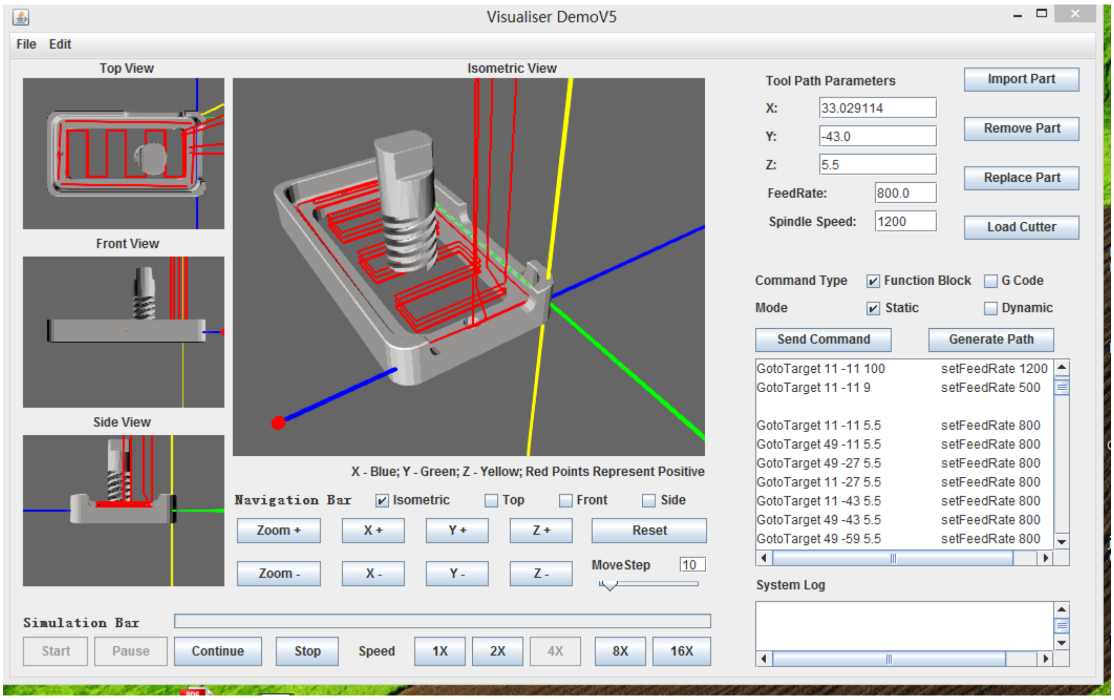

Figure 6.1 Snapshot in visualisation function test

6.2 Implementation Test

Since the on-board visualisation is a capability expected from the visualizer, the implementation test on the CNC controller is significant for the validation. Thanks to the help from PowerKut, the access to a Mazak controller “Mazatrol Matrix” (customised Windows XP running) is possible for the implementation of the visualizer. The procedures for installation were summarised in a visit plan to show the partner that what exactly were changed on their machine. The visit plan is shown in the Appendix I.

To make the visualizer functional on the CNC controller, the first requirement is the CNC controller must run Windows as its OS. Besides, Java Runtime Environment (support Java application) and Java3D interface (support Java3D application) must be installed in the Windows on the controller.

Figure 6.2 Visualizer running on the controller for implementation test

Figure 6.2 shows the test result. Unfortunately, the 3D module failed because the graphic card driver or DirectX (Microsoft graphic support application) was needed to be updated on that Windows machine. Except this unexpected error, the other part of the application worked fine. The reason of this error was likely to be that this Windows on the controller is customized to fit the job for a CNC controller for high speed performance. It is not like a normal Windows (home edition, professional edition and enterprise edition of Windows XP, 7 and 8) used in office or home, some components are not installed on it (maybe the multi-media support component). From the aspect of hardware, it is also possible that the graphic card of the controller was customised too, causing the lack of support for 3D graphics. There are two approaches to solve this problem. The first one is updating the graphic card driver and DirectX as it required. The second one is to add local graphic library in the visualizer itself, rendering the graphics by software acceleration. It is assumed to be the solution too for the situation that the hardware does not support 3D graphics at all. After either of these two is done, the 3D part of the visualizer is expected to work as it does on other Windows systems in the validation tests.

6.3 Case Studies

According to the feedback in the implementation test, the interface and the core function of the application were modified. New Functions were added, including orientation setup (adjusting the position of the part), feed rate range setup (allocating colours for different feed rates), G-code translator (into function block format). With this version of visualizer, 3 more cases other than the case in basic function testing were planned. The test platform was the same as described previously in the basic function test.

In the first case, another part was used for importation for testing the import function of the visualizer. In the second one, a piece of tool path which was generated by the function blocks of KTH, in the format of G-code, was imported through the G-code translator for testing the tool path plotting function. In the last one, the part “iPhone case” was used again with a different tool path. The function of tool path plotting, cutting process simulation and colour allocation for different feed rate were tested in this case.

All of the three case studies were successfully completed. The results (snapshots) are presented in the Appendix J.

6.4 Compatibility Test

Since the visualizer developed in this research is designed to run on Windows based platforms, its compatibility on different versions of Windows OSs is also an important feature required. Four versions of Windows were selected for testing, including the customized Windows XP on the CNC controller, Windows XP, Windows 7 and Windows 8. Windows 7 and Windows 8 are the most widespread systems currently. Windows XP is widely used on the computers connected with CNC machines in industries, especially on old computers with old hardware sets. There are several other versions excluded from the selection. Windows 95 and 98 are becoming unlikely to be chosen by industry in the trend, because they are very old. Windows 2000 is also very old and more likely used for servers. Windows Vista is nearly the same age of Windows 7, but not very popular compared to Windows 7.

The task for the visualizer in this compatibility test was the same as the last case described in the previous part, which was the iPhone case with a tool path for pocket machining, except the test of the customized Windows XP on the CNC controller. The test on the CNC controller was completed in the implementation test, and the result is explained in the previous part (section 6.2). The results of the other tests (snapshots) are presented in Appendix K.

For Windows XP, 7 and 8, the visualizer passed the compatibility test. Every function worked correctly on those platforms. For the Windows on CNC controller, it is expected that the 3D rendering process of the visualizer will work after procedures mentioned previously in the part for implementation test (section 6.2.). In the compatibility test of Windows XP, virtual machine software (VMplayer by VMware, as a free software for non-commercial use) was used to simulate the OS, and the test was successfully passed.

6.5 Expert Validation

For validating the research from an objective angle, experts from manufacture industries were invited to validate the research. The files needed were emailed to the experts. The visualizer and the support environment (Java Runtime Environment and Java3D) were provided to each expert. An introduction document and a demonstration video were also provided for explanation. A validation sheet was designed to collect the feedback. The introduction document is presented in Appendix L.

There were 11 experts invited for validation. They are also the participants in the questionnaire survey for the requirement collection (Chapter 4). Six of them responded, and five validation sheets were sent back along with other comments. Figure 6.3 shows one validation sheet as an example. All the received validation sheets are presented in Appendix M.

Validation Sheet

Test Date:	Test Platform: MAZAK UTC 800/20SR / ON LAPTOP.		
Test Items	**Description**	**Yes / No**	**Grade (0-10)**
Model Import	Whether the model displayed correctly	YES ~~NO SEE NOTE~~	6
Suggestion	NEED TO LOOK AT WHAT TYPES OF FILE WILL RUN ON CONTROLLER		
Cutter Import	Whether the cutter imported correctly	NO-SEE NOTE	6
Suggestion	WORKED IN PLAN VIEWS BUT DID NOT DISPLAY ALWAYS ON 3D. VIEW		
Tool Path Generation	Please grade the speed of generation process		8
Suggestion			
	Whether the path meet the requirement for visualisation correctly	YES.	8
Suggestion	BASED ON FUNCTION INFORMATION SEEN		
Navigation	Whether the navigation function is sufficient for use	YES.	8
Suggestion			
	Please grade the navigation function	GOOD.	8
Suggestion			
Cutting Process Simulation	Whether the basic function of animation provided	YES.	8
Suggestion			
	Please grade the simulation function	GOOD.	8
Suggestion			
Parameter Display	Whether all the parameters needed for tool path displayed	NO	6
Suggestion	TOOL HOLDING FOR CRASH DETECTION NEEDED.		
GUI (Graphic User Interface)	Does the GUI layout meet the practical requirement? Please grade the GUI.	YES	9
Suggestion			
Visualisation	Does the visualiser obtain the necessary functions for tool path generated from function blocks? Please grade the visualiser.	N/A.	
Suggestion			
	Do you think the visualiser can pass the validation case study for basic functions?	YES	

Name: [redacted] Job Title: MANAGING DIRECTOR

By filling this sheet, you are consenting for your data (except personal information) to be used for internal MSc research only. Your answer will be treated confidential and all data will be anonymized.

Thank you for your participation in this research, your contribution is much appreciated.

Figure 6.3 Expert validation sheet example

As shown in the figure, a check list about functions of the visualizer was filled and graded by the expert. Suggestion and comment were given in the blanks below the relevant aspects.

Generally speaking, all five validation responds agreed that the visualizer, as the deliverable, had fulfilled the purpose of this research and the industrial expectations. There were a number of comments and suggestions from the experts for improving the application, which were mainly focused on the user experience and expectation.

The following are the summary of the comments:

1. Support more 3D model file formats, and consider the file supported by CNC controllers.
2. Function of tool hold for crash detection is needed.
3. Use white background colour after loading the model.
4. Use mouse wheel to control the zoom in/out operation.
5. Axial depth of cut and radial depth of cut could be added as parameters of the tool path.
6. The forward and backward movement control of the animation function should be provided, and the adjustment of speed can be changed to any number between 1 and 16.
7. The step which is current running should be displayed.
8. Use G-code text stream as a neutral interface between the visualizer and external sources.

6.6 Summary

The visualizer, as the main deliverable of the research, was validated through the five phases of validations arranged during the research. It is verified to be a functional visualisation tool for the tool path generated by function block system. The visualizer works on platforms with Windows (four versions tested), provides main functions including tool path plotting and cutting process simulation. It matches the purpose of this research, which is finding a suitable solution specifically for visualising the process planning result (tool path) generated from function block system, in the manufacturing field involving milling operation.

7. Conclusion

Research Summary

In this research, a light weight 3D visualisation solution, which is designed for visualising the tool path generated by function block system, is proposed, developed and tested. The visualizer developed in this research is different from the numerous existing tool path visualisation applications which work with CAM systems, as it works in a real-time behaviour in order to keep pace with function blocks instead of in an off-line mode with CAM systems. A questionnaire survey and interviews were carried out for collecting the requirement to ensure that the practical needs from shop floor users are satisfied. The visualizer is developed based on Java3D and encapsulated within a 3D graphical user interface with multiple views. The core capability of the visualizer is directly processing the process planning by function block system in the form of tool path visualisation. It is able to adapt to changes following the pace of function block system in a real-time manner. To facilitate the real-time feature, the visualizer is designed in light weight style and capable of working on the CNC controllers with Windows installed.

Contribution

Based on the background research, it is assumed that the visualizer developed in this research is the first visualisation tool which supports the function block system in a real-time manner. This visualisation solution provides interactivity between the function block system and the users through a friendly HMI as a platform for communication. The output of the function block system, the process planning, is presented in front of the users in a direct and vivid way. The behaviour of the function block system in real-time situations can be observed through this visualisation tool. Once the other way of controlling channel is completed after derivative future work, the manipulation of the function behaviour will also be realised through this platform. Then the visualisation tool will became a real “communication centre” providing the whole function of interactivity between the “machine” and “human”. The research process is introduced thoroughly. The methodology and the outcome of the research can be adopted for further researches focusing the visualisation of function blocks.

Conclusion

A light weight real-time 3D visualisation solution, which is designed for visualising the tool path generated by function block system in the manufacturing field involving milling operations, is provided in this research.

Limitation

Limitations exist in the current development of the visualizer. Only the format of Object file (3D model format) is supported by the visualizer currently. According to the questionnaire survey, the STEP file is the most welcomed format for 3D model. The visualizer could be more versatile when a STEP file reader is added or even more formats are supported. The parameters of the tool path displayed in the interface are not sufficient for advanced users. As suggested by an expert in the validation process, the axial depth of cut and radial depth of cut could be useful parameters for describing the tool path as well. More useful functions should be offered by the visualizer as suggested by experts, such as the navigation for animation process and collision test between the cutting tool and the part.

Future Work

Future works can be carried out on the exploration of the potentials of improving the interactivity between the function block system and the user. More functions can be added into the visualisation tool, such as the manipulation of the function block behaviour and the comparison between optimised and un-optimised tool paths. Integrating interactive channels bridging the Web-DPP system, local function blocks and CNC controller in the visualisation tool might be a workable direction in the future, for the purpose of providing the "communication centre" of the CAPP architecture for shop floor use.

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APPENDICES

Appendix A Questionnaire

Light Weight Visualization Questionnaire

Introduction

This project aims at helping the user to visualize the behaviour of function blocks running on CNC machines. The concept of function blocks generating tool paths on-the-fly at the controller level is new and process critical and, hence a visual feedback to the user is imperative. The function proposed for the visualization software comprises tool path visualization, simplified process simulation and FB work process monitoring.

This questionnaire is part of the MSc research project feeding into a larger project called “CAPP-4-SMEs” which is supported by the EU.

This questionnaire will take about 10 minutes. Thank you for your participation in this research, your contribution is much appreciated. By participating in this survey, you are consenting for your data to be used for the purpose stated and for internal MSc research only. Your answers will be treated confidential and all data will remain anonymous.

Note: Please write the letter of your choice(s) (e.g. A, B, or C …) in the box or write your answer on the line below the question. If other, please list it out.

Questions

1. General Information

Q01: What is your position in the company?

Q02: Please, briefly describe your job role.

Q03: How long have you been in this job? [ ]

A. 1-2 years

B. 3-5 years

C. 6-10 years

D. 10+ years

2. Tool path visualization

Q04: How much do you know about CAPP (Computer Aided Process Planning)? [ ]

A. Expert

B. Good knowledge

C. General knowledge

D. No knowledge

Q05: Considering Algorithm in Function Blocks as a black box, what kind of information or parameters do you need to confirm the process condition of the function blocks, the rationality of the generated tool path and if the CNC is operating correctly? (Multi-choices) [ ]

A. Display the 3D tool path as it is being generated

B. Display the tool path after is has been generated

C. Display the 3D model

D. Display the 3D tool path and 3D model simultaneously

E. Display the output information from the function block

F. Interactive manipulation of the function blocks

G. Display the parameters for cutting in the form of numbers

H. Display the parameters for cutting in the form of figures (colours or charts)

I. Simulation of the manufacture process with the tool path

J. Air cut (physical simulation of the manufacture process)

K. Display the generation process of the tool path

L. Comparison features between optimised and un-optimised tool paths

M. Log & Display system log (recording the changes and reactions of the function blocks)

N. 3D displaying options (model on/off, path on/off etc.)

Others:

Q06: Which data format for 3D model do you prefer for tool path visualization (light weight prospective), please explain why? [ ]

A. format from Catia

B. format from Solidworks

C. format from UG

D. format from ProEngineer

E. Step files

Other: Reason:

Q07: If you could choose, which terminals running visualization process would you prefer for checking the work process of your CNC machines? Please explain your choice briefly. (Multi-choices) [ ]

A. Typical CNC controller

B. Software on a computer near CNC

C. Browser based software on a computer near CNC

D. Software on a handhold tablet

E. Software on computers located in offices

F. Browser based apps on any kind of platform

G. Other: Reason:

Q08: Which kind of operation style do you prefer to operate a 3D model or a 3D tool path?   [   ]

A. Mouse only

B. Mouse with keyboard

C. Clicking buttons in the application

D. Multi-touch control on a tablet

E. Touch buttons on a tablet

F. Other:

Q09: What kind of User Interface do you prefer to use?   [   ]

A. Single window

B. Several floating windows

C. Several equally divided windows

Other:

Q10: If you could choose, what main features should your ideal tool path visualization software have?

Thank you very much for your participation

Appendix B Company Introduction

Asturfeito, a Spanish industrial company, involves in engineering, manufacturing and commissioning of capital goods. Its business activities are widespread in countries all around the world: Europe, America and Asia. Asturfeito offers whole process of projects: from design, project management, manufacture, supply, installation and implementation, to thorough quality control of the equipment and its components. Their field of expertise includes: manufacturing engineering, mechanics, hydraulics, pneumatics engineering, machining, welding, assembly and adjustment, verification and functional testing, logistics.

Website: http://www.asturfeito.com/seccion/company (accessed in August, 2014)

COMAC (Commercial Aircraft Corporation of China) is a State-owned company in China, which cooperates widely with aircraft manufacturers and suppliers worldwide. Aircraft design, manufacture, marketing and acquisition of certification are all included. The goal of COMAC is to develop a world-class civil aircraft industry which is safe, economical, comfortable and environmentally friendly. The manufacture department, as an important centre of COMAC, has studied CAPP for more than 10 years. Thus, all the techniques and processes which can improve the performance of manufacture are of interest.

Website: http://english.comac.cc/ (accessed in August, 2014)

Cameco AB is a machine shop located in Sandviken, and was founded in 1993. Their specialty is working in Horizontal 4 and 5-axis machining centers, as well as 3-axis vertical machine and a CNC lathe with driven tools. The company has extensive experience in performing machining of complex work pieces and processing of cast slabs in both steel and aluminium. Their customers are mainly large and medium sized companies in need of machining in CNC machining centers.

Website: http://www.cameco.se/ (accessed in August, 2014)

FORMTEC GmbH (FT) was developed in 1997, supplying services and software development for the CAD-CAM-CNC process chain. The core software NCspeed is able to simulate, verify and optimise tool path for milling machines. It enables manufacturers to adjust the feed rate to optimise machining processes according to the cutting conditions automatically, which can shorten the processing time by 20%.

Website: http://www.formtec.de/index.htm (accessed in August, 2014)

InconTec GmbH is a research and innovation company that is active in industry and public research projects. The company was founded in the year 2007 to offer and perform consulting and development services in the areas of requirements analysis, market research, road mapping, proposal support, software specification, design and implementation as well as software integration. InConTec can draw upon many years of long-term relationships to and networks of research partners in national and international academic and industrial R&D fields.

Website: http://www.incontec.de/i00.html (accessed in August, 2014)

PowerKut Limited is a family-run business which designs and manufactures products for the Mining, Rail, Construction, Aerospace, Automotive, Marine, Defence, Nuclear, Plastics and General Engineering sectors of industry. "Engineering Excellence" is the company's goal (CAPP-4-SMEs, 2012b). It participates in the CAPP-4-SMEs as specialised in tooling, gauging and machined components.

Website: http://www.powerkut.co.uk/ (accessed in August, 2014)

Prodintec is a technology centre specialized in industrial design and production. The mission of Prodintec is to foster the competitiveness of industrial firms by applying technological advances both to their products and to their manufacturing and management processes. Prodintec is a private non-profit entity created in 2004 on the initiative of a group of firms in the region and the Regional Government and forms part of the network of Technology Centres of the Principality of Asturias. PRODINTEC was registered as an Innovation and Technology Centre (no. 99) by the Spanish Ministry of Industry on 27th March 2007.

Website: http://www.prodintec.es/prodintec/en/Home (accessed in August, 2014)

Appendix C Description for formats of 3D model

CATIA (Computer Aided Three-dimensional Interactive Application) is a multi-platform CAD/CAM/CAE commercial software suite developed by the French company Dassault Systèmes. CATIA facilitates the design of electronic, electrical, and distributed systems such as fluid and HVAC systems, all the way to the production of documentation for manufacturing.

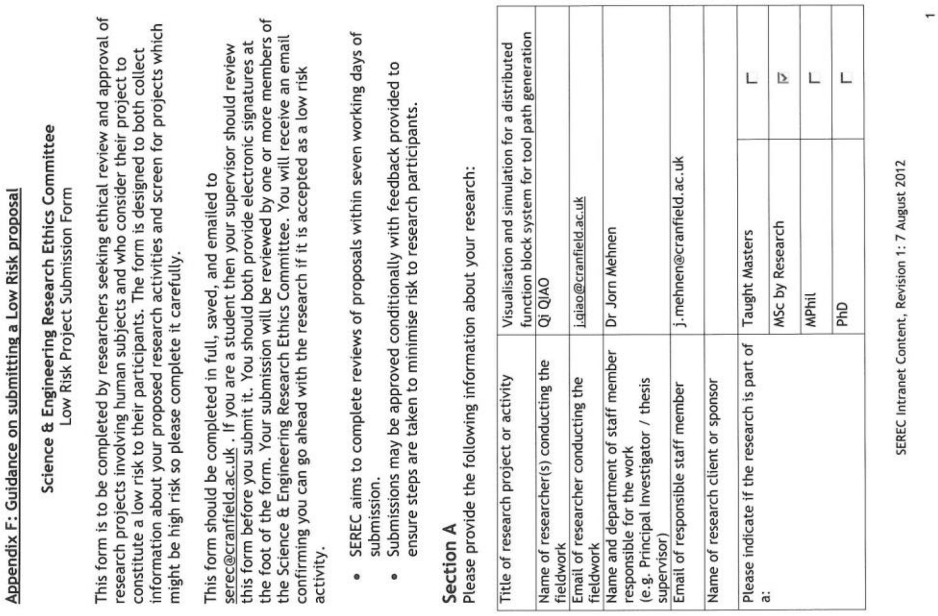
SolidWorks is solid modeling CAD software produced by Dassault Systèmes. SolidWorks is currently used by millions of engineers and designers at more than thousands of companies worldwide. SolidWorks solutions cover all aspects of the development process, including 3D design, simulation, electrical design, product data management, technical communication and conceptual design.

NX, formerly known as NX Unigraphics or usually just **U-G**, is an advanced high-end CAD/CAM/CAE software package developed by Siemens PLM Software. It is used, among other tasks, for: design (parametric and direct solid/surface modelling); engineering analysis (static, dynamic, electro-magnetic, thermal, using the Finite Element Method, and fluid using the finite volume method); manufacturing finished design by using included machining modules.

PTC Creo is a family or suite of design software supporting product design for discrete manufacturers and is developed by PTC. The suite consists of apps, each delivering a distinct set of capabilities for a user role within product development. Creo runs on Microsoft Windows and provides apps for 2D design, 3D CAD parametric feature solid modeling, 3D direct modeling, Finite Element Analysis and simulation, schematic design, technical illustrations, and viewing and visualization. The Creo suite of apps replace and supersede PTC's products formerly known as **Pro/ENGINEER**, CoCreate, and ProductView.

STEP-File is the most widely used data exchange form of STEP. Due to its ASCII structure it is easy to read with typically one instance per line. The format of a STEP-File is defined in ISO 10303-21 Clear Text Encoding of the Exchange Structure. ISO 10303-21 defines the encoding mechanism on how to represent data according to a given EXPRESS schema, but not the EXPRESS schema itself. A STEP-File is also called p21-File and STEP Physical File. The file extensions .stp and .step indicates that the file contain data conforming to STEP Application Protocols while the extension .p21 should be used for all other purposes.

Appendix D
SEREC Low Risk Project Submission Form & SEREC Approval



Appendix F: Guidance on submitting a Low Risk proposal

Science & Engineering Research Ethics Committee
Low Risk Project Submission Form

This form is to be completed by researchers seeking ethical review and approval of research projects involving human subjects and who consider their project to constitute a low risk to their participants. The form is designed to both collect information about your proposed research activities and screen for projects which might be high risk so please complete it carefully.

This form should be completed in full, saved, and emailed to serec@cranfield.ac.uk . If you are a student then your supervisor should review this form before you submit it. You should both provide electronic signatures at the foot of the form. Your submission will be reviewed by one or more members of the Science & Engineering Research Ethics Committee. You will receive an email confirming you can go ahead with the research if it is accepted as a low risk activity.

- SEREC aims to complete reviews of proposals within seven working days of submission.
- Submissions may be approved conditionally with feedback provided to ensure steps are taken to minimise risk to research participants.

Section A
Please provide the following information about your research:

Title of research project or activity	Visualisation and simulation for a distributed function block system for tool path generation	
Name of researcher(s) conducting the fieldwork	Qi QIAO	
Email of researcher conducting the fieldwork	j.qiao@cranfield.ac.uk	
Name and department of staff member responsible for the work (e.g. Principal Investigator / thesis supervisor)	Dr Jorn Mehnen	
Email of responsible staff member	j.mehnen@cranfield.ac.uk	
Name of research client or sponsor		
Please indicate if the research is part of a:	Taught Masters	☐
	MSc by Research	☑
	MPhil	☐
	PhD	☐

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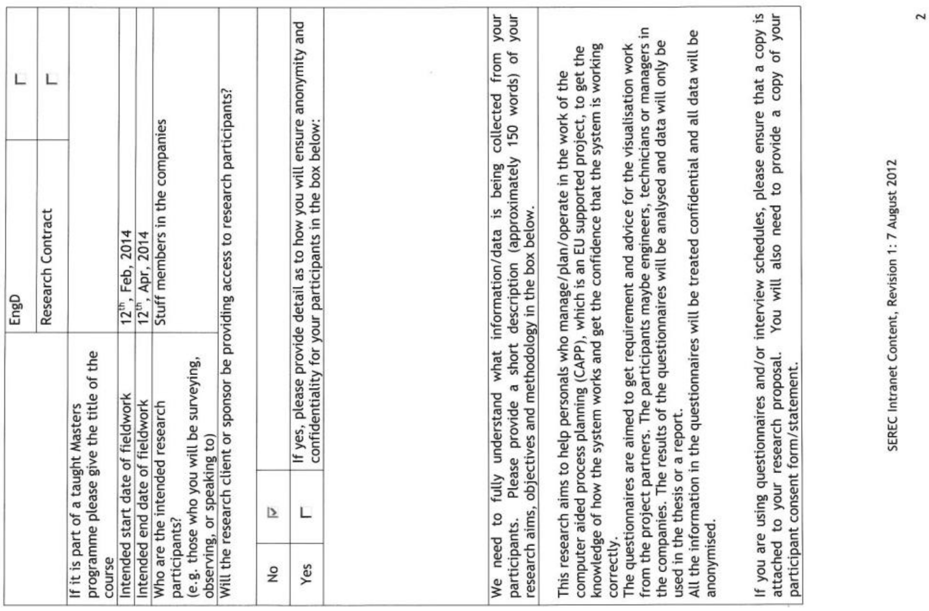
Figure D.1 Application form part 1



	EngD	☐
	Research Contract	☐
If it is part of a taught Masters programme please give the title of the course		
Intended start date of fieldwork	12th, Feb, 2014	
Intended end date of fieldwork	12th, Apr, 2014	
Who are the intended research participants? (e.g. those who you will be surveying, observing, or speaking to)	Stuff members in the companies	

Will the research client or sponsor be providing access to research participants?

No	☑	
Yes	☐	If yes, please provide detail as to how you will ensure anonymity and confidentiality for your participants in the box below:

We need to fully understand what information/data is being collected from your participants. Please provide a short description (approximately 150 words) of your research aims, objectives and methodology in the box below.

This research aims to help personals who manage/plan/operate in the work of the computer aided process planning (CAPP), which is an EU supported project, to get the knowledge of how the system works and get the confidence that the system is working correctly.
The questionnaires are aimed to get requirement and advice for the visualisation work from the project partners. The participants maybe engineers, technicians or managers in the companies. The results of the questionnaires will be analysed and data will only be used in the thesis or a report.
All the information in the questionnaires will be treated confidential and all data will be anonymised.

If you are using questionnaires and/or interview schedules, please ensure that a copy is attached to your research proposal. You will also need to provide a copy of your participant consent form/statement.

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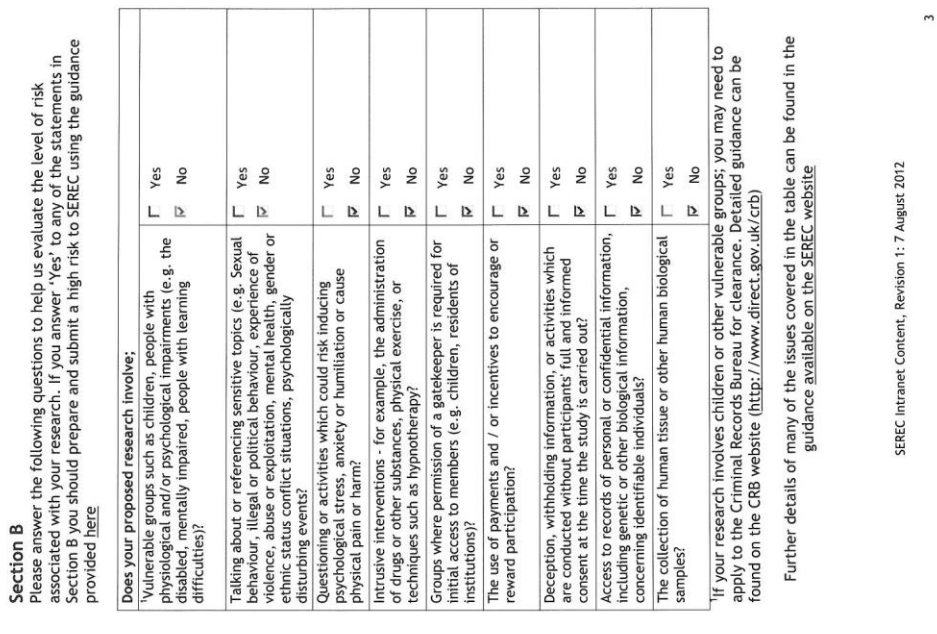
Figure D.2 Application form part 2



Section B

Please answer the following questions to help us evaluate the level of risk associated with your research. If you answer 'Yes' to any of the statements in Section B you should prepare and submit a high risk to SEREC using the guidance provided here

Does your proposed research involve;	
[1]Vulnerable groups such as children, people with physiological and/or psychological impairments (e.g. the disabled, mentally impaired, people with learning difficulties)?	☐ Yes ☑ No
Talking about or referencing sensitive topics (e.g. Sexual behaviour, illegal or political behaviour, experience of violence, abuse or exploitation, mental health, gender or ethnic status conflict situations, psychologically disturbing events?	☐ Yes ☑ No
Questioning or activities which could risk inducing psychological stress, anxiety or humiliation or cause physical pain or harm?	☐ Yes ☑ No
Intrusive interventions - for example, the administration of drugs or other substances, physical exercise, or techniques such as hypnotherapy?	☐ Yes ☑ No
Groups where permission of a gatekeeper is required for initial access to members (e.g. children, residents of institutions)?	☐ Yes ☑ No
The use of payments and / or incentives to encourage or reward participation?	☐ Yes ☑ No
Deception, withholding information, or activities which are conducted without participants' full and informed consent at the time the study is carried out?	☐ Yes ☑ No
Access to records of personal or confidential information, including genetic or other biological information, concerning identifiable individuals?	☐ Yes ☑ No
The collection of human tissue or other human biological samples?	☐ Yes ☑ No

[1]If your research involves children or other vulnerable groups; you may need to apply to the Criminal Records Bureau for clearance. Detailed guidance can be found on the CRB website (http://www.direct.gov.uk/crb)

Further details of many of the issues covered in the table can be found in the guidance available on the SEREC website

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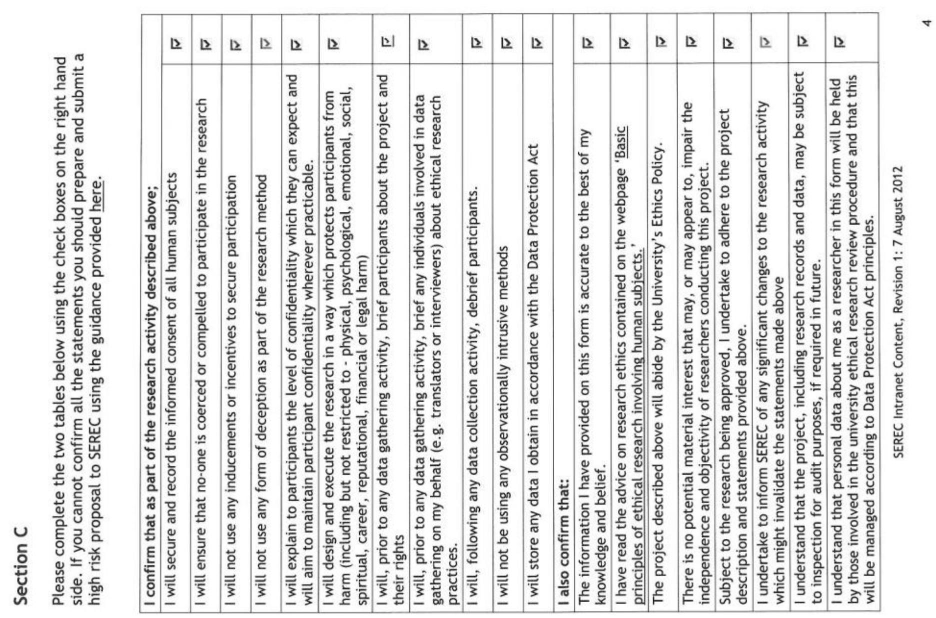
Figure D.3 Application form part 3



Section C

Please complete the two tables below using the check boxes on the right hand side. If you cannot confirm all the statements you should prepare and submit a high risk proposal to SEREC using the guidance provided here.

I confirm that as part of the research activity described above;	
I will secure and record the informed consent of all human subjects	☑
I will ensure that no-one is coerced or compelled to participate in the research	☑
I will not use any inducements or incentives to secure participation	☑
I will not use any form of deception as part of the research method	☑
I will explain to participants the level of confidentiality which they can expect and will aim to maintain participant confidentiality wherever practicable.	☑
I will design and execute the research in a way which protects participants from harm (including but not restricted to - physical, psychological, emotional, social, spiritual, career, reputational, financial or legal harm)	☑
I will, prior to any data gathering activity, brief participants about the project and their rights	☑
I will, prior to any data gathering activity, brief any individuals involved in data gathering on my behalf (e.g. translators or interviewers) about ethical research practices.	☑
I will, following any data collection activity, debrief participants.	☑
I will not be using any observationally intrusive methods	☑
I will store any data I obtain in accordance with the Data Protection Act	☑
I also confirm that:	
The information I have provided on this form is accurate to the best of my knowledge and belief.	☑
I have read the advice on research ethics contained on the webpage 'Basic principles of ethical research involving human subjects.'	☑
The project described above will abide by the University's Ethics Policy.	☑
There is no potential material interest that may, or may appear to, impair the independence and objectivity of researchers conducting this project.	☑
Subject to the research being approved, I undertake to adhere to the project description and statements provided above.	☑
I undertake to inform SEREC of any significant changes to the research activity which might invalidate the statements made above	☑
I understand that the project, including research records and data, may be subject to inspection for audit purposes, if required in future.	☑
I understand that personal data about me as a researcher in this form will be held by those involved in the university ethical research review procedure and that this will be managed according to Data Protection Act principles.	☑

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Figure D.4 Application form part 4

The person completing this form is the:

Researcher conducting the work ☑

Supervisor of the project ☐

Electronic signature of the researcher conducting the work

Electronic signature of the project supervisor — Dr. Jörn Mehnen 6th Feb. 2014

If you have any queries about this form or the SEREC review process, please email the SEREC administrator at serec@cranfield.ac.uk.

Please email your completed form to serec@cranfield.ac.uk

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Figure D.5 Application form part 5

Ethics Proposal 013-2014
SEREC
Sent: 11 February 2014 9:50
To: Qiao, Qi
Cc: Mehnen, Jorn

Dear Qi

Your proposed research activity "Visualisation and simulation for a distributed function block system for tool path generation" has been reviewed by SEREC and confirmed as posing a low risk in terms of research ethics. You can now proceed with the research activities you have sought approval for and we wish you a successful project.

Please remember that SEREC occasionally conducts audits of low risk projects and we may therefore contact you during or following execution of your fieldwork to verify that you are following good practice.

Guidance on good practice is available at:
https://intranet.cranfield.ac.uk/researchethics/Pages/SEREC.aspx

With best regards

Sue

Sue Garrod
Secretary
Centre for Advanced Systems
Aerospace Engineering Division
School of Engineering
01234 754165

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Figure D.6 Approval email from SEREC

Appendix E Result Statistic of the Questionnaires

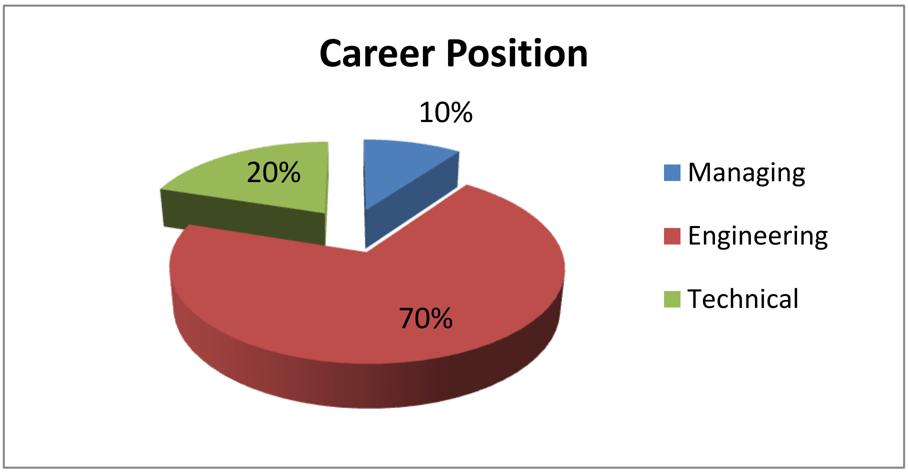


Chart E.1 Career Position

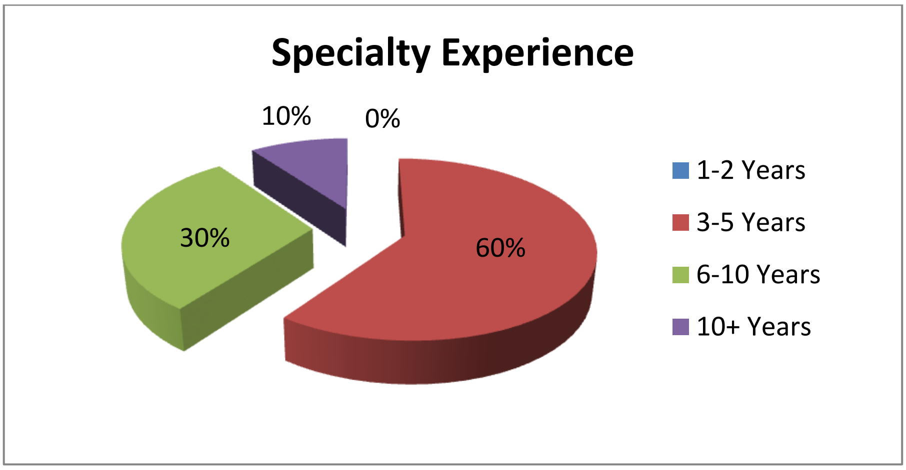


Chart E.2 Specialty Experience

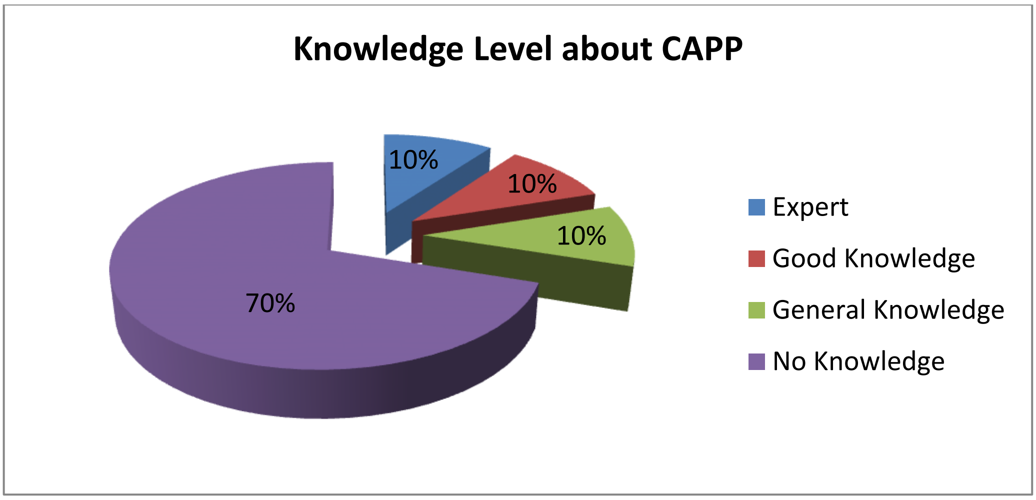


Chart E.3 Knowledge Level about CAPP

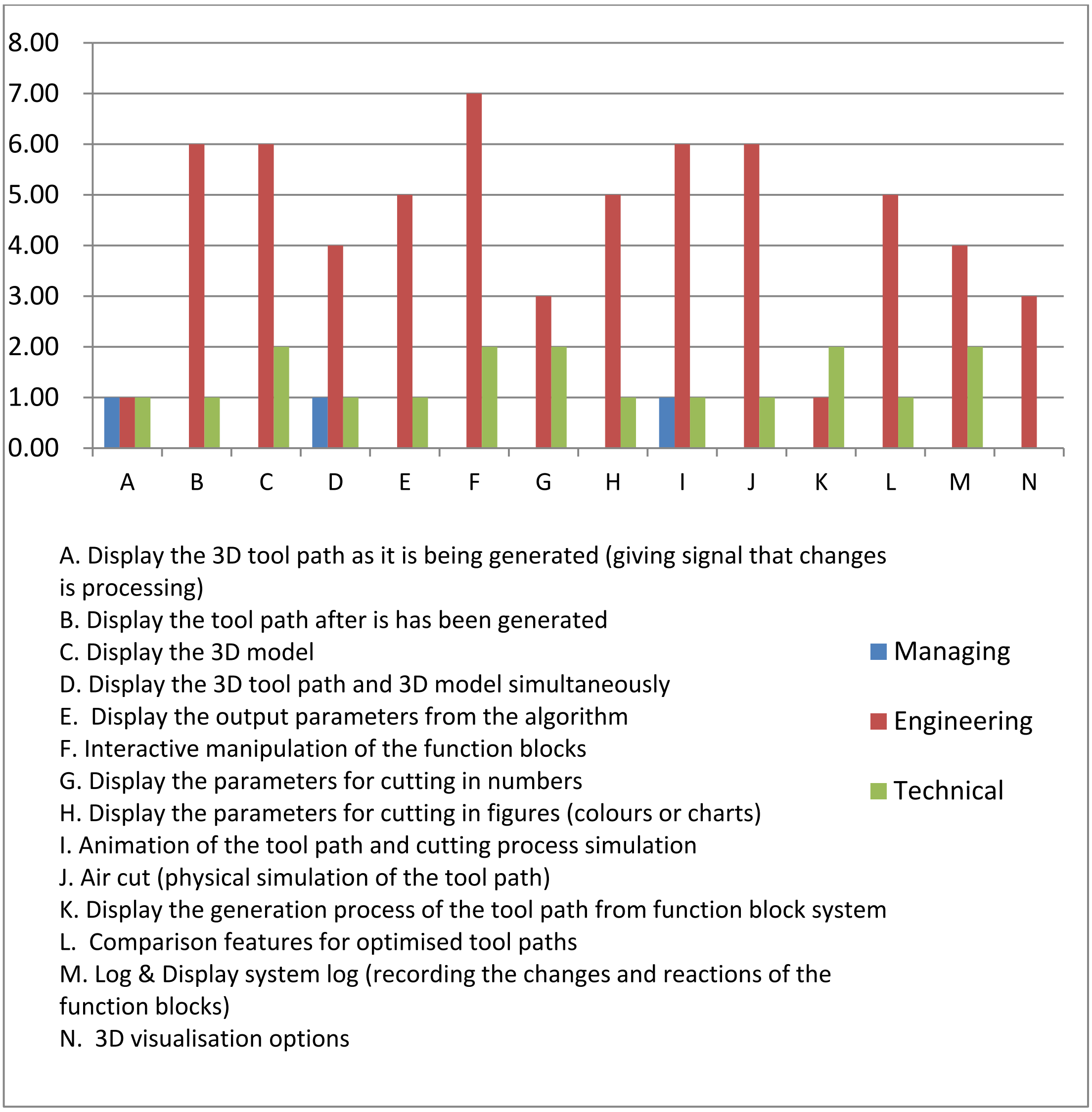


Chart E.4 Results Distribution of Required Functionalities

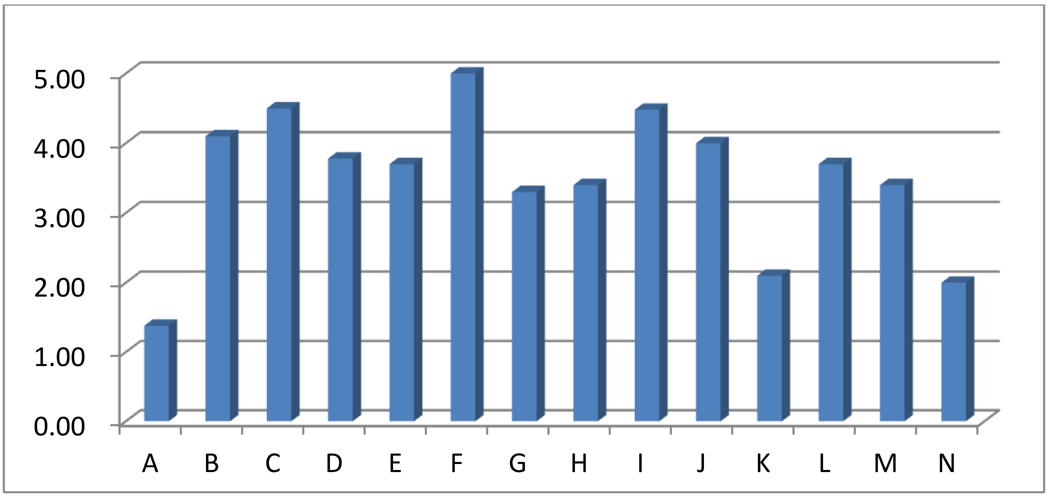


Chart E.5 Results Weighted Sum of Required Functionalities

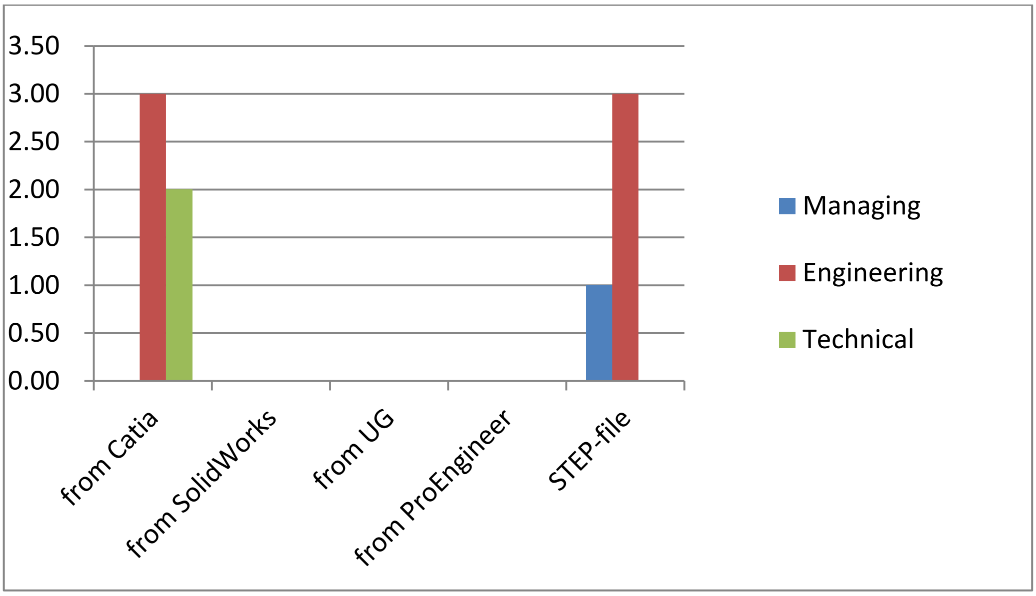


Chart E.6 Results Distribution of CAD Format Preference

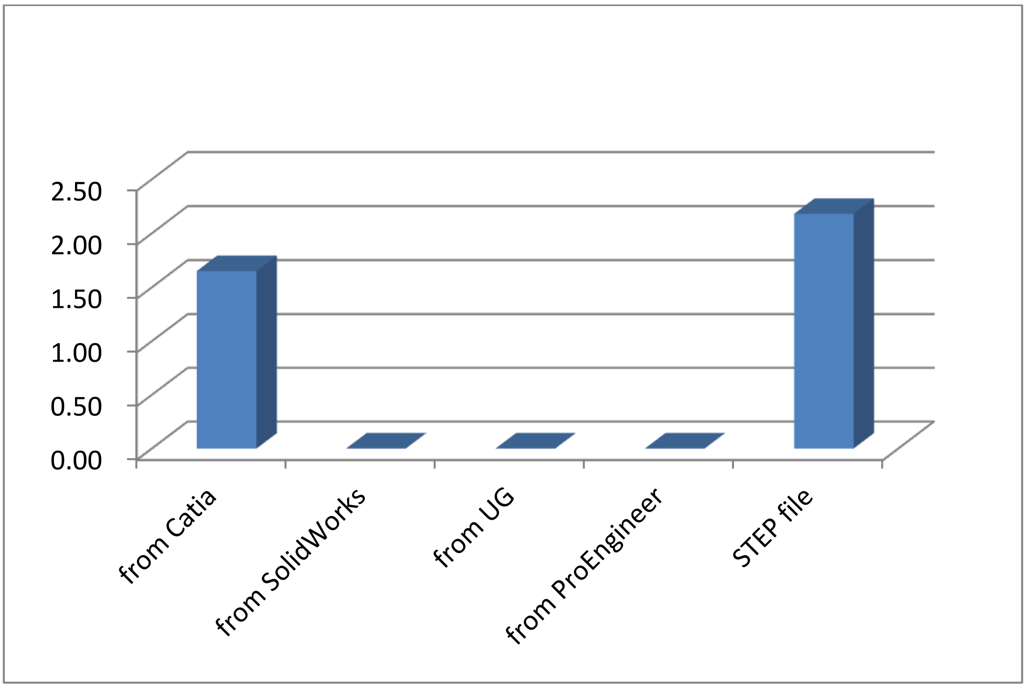


Chart E.7 Results Weighted Sum of CAD Format Preference

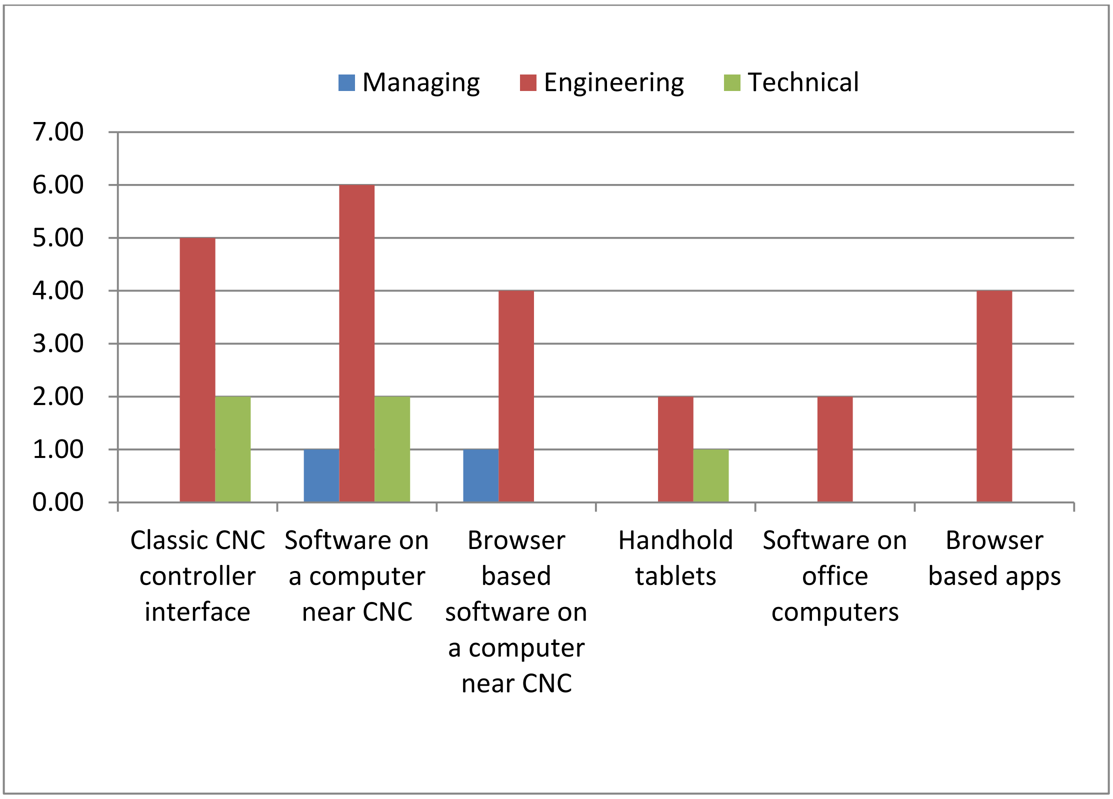


Chart E.8 Results Distribution of Terminal Preference

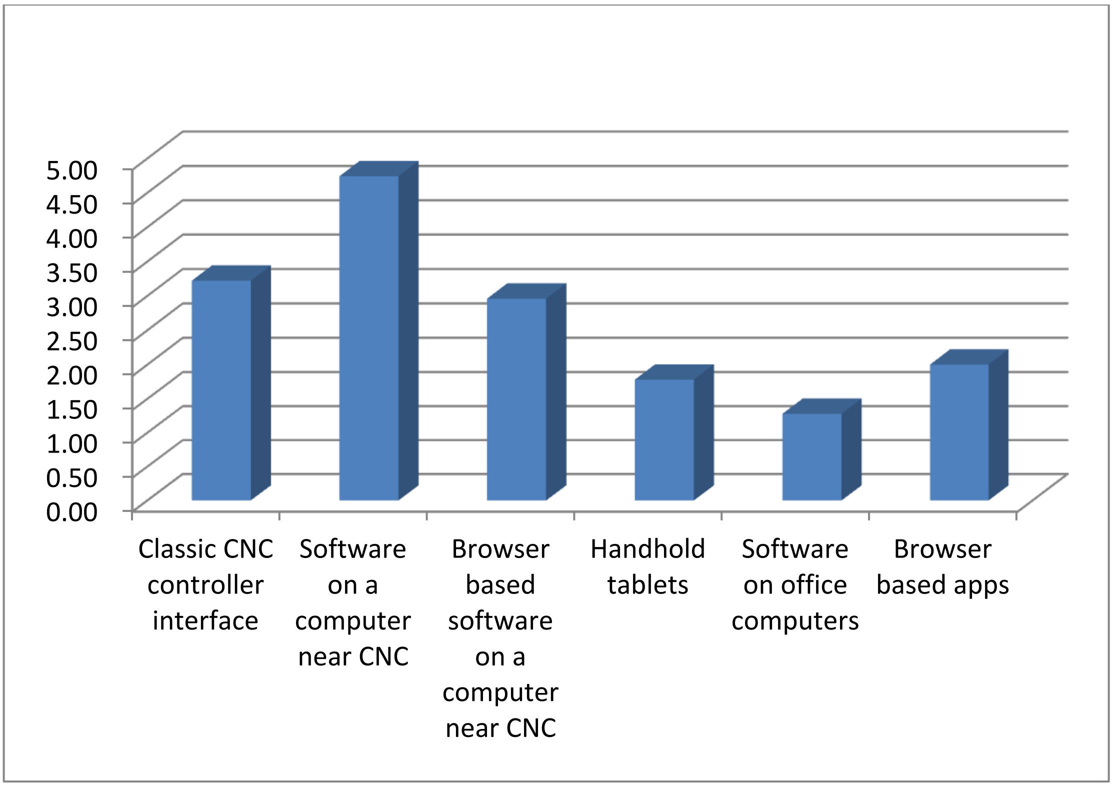


Chart E.9 Results Weighted Sum of Terminal Preference

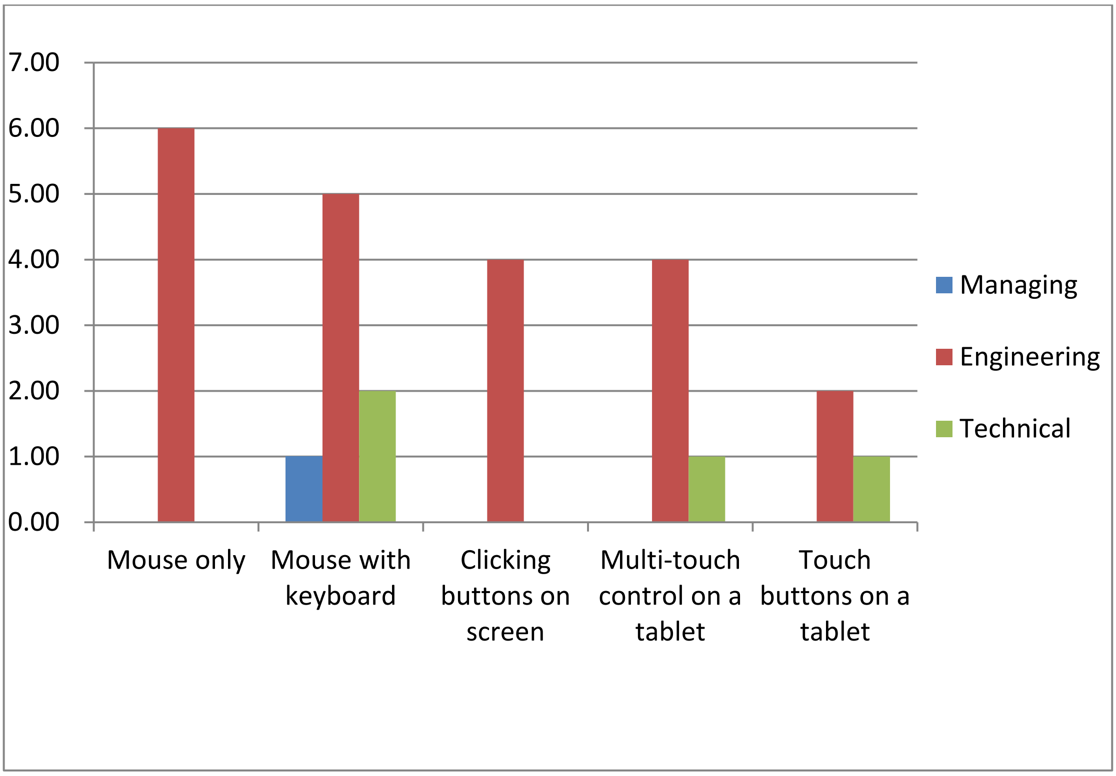


Chart E.10 Results Distribution of 3D Operation Preference

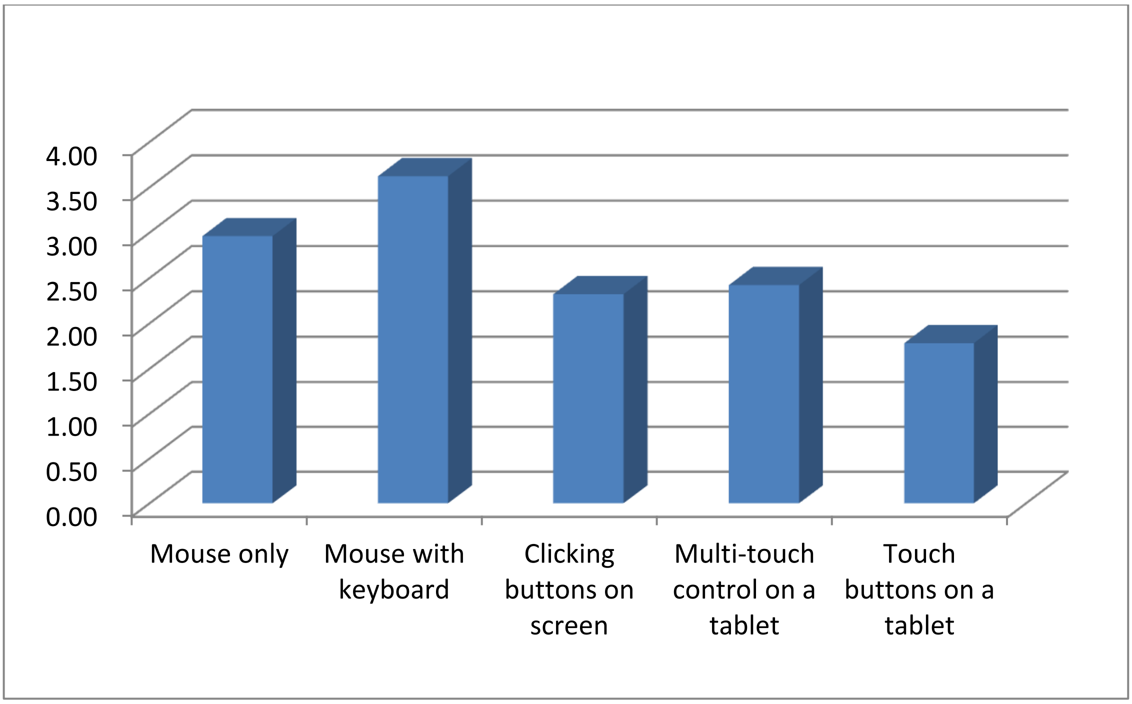


Chart E.11 Results Weighted Sum of 3D Operation Preference

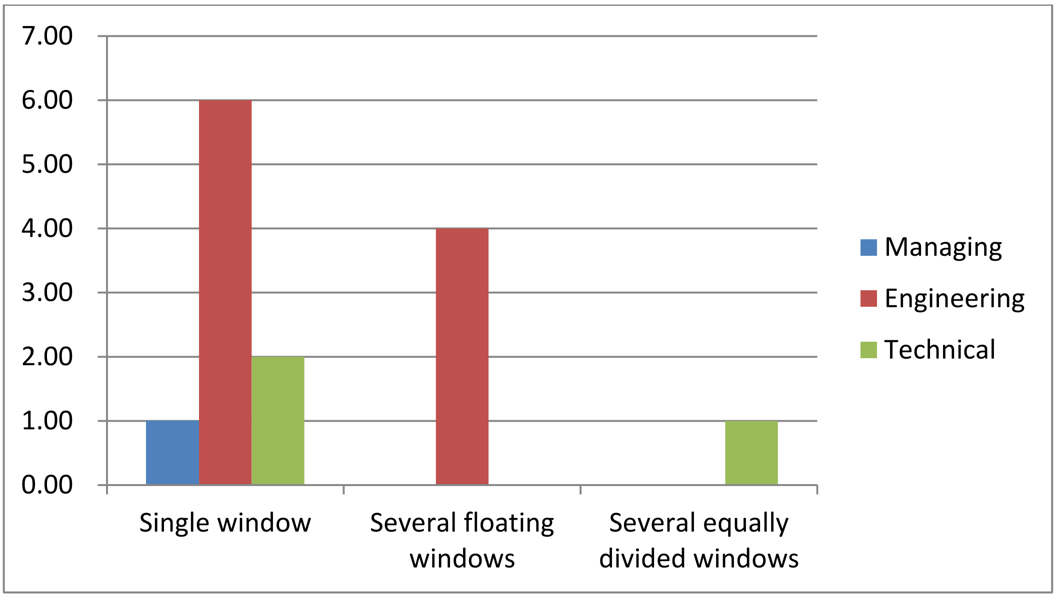


Chart E.12 Results Distribution of UI Preference

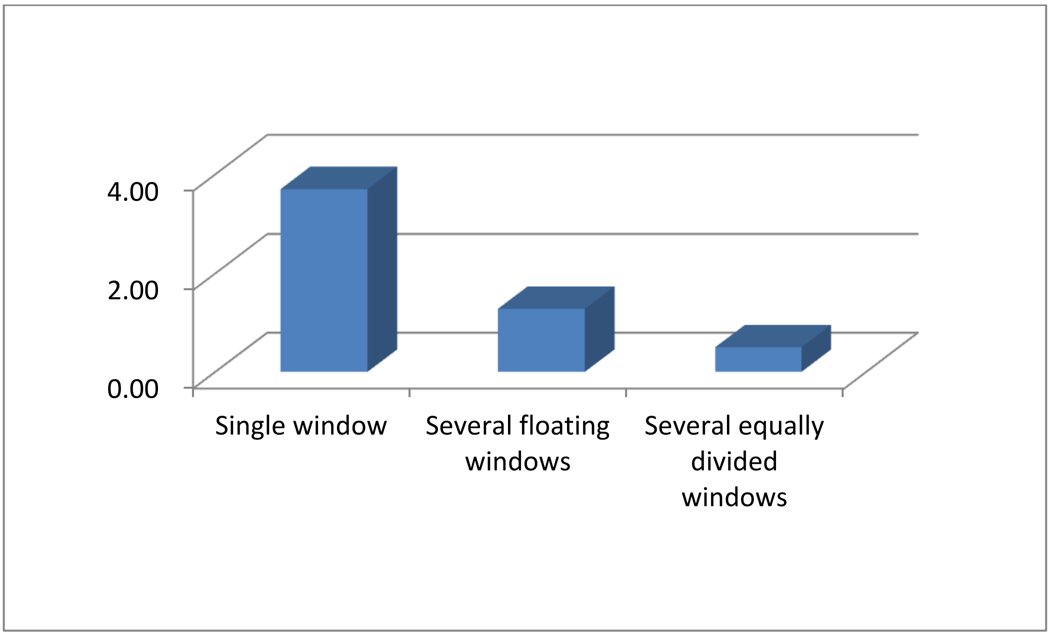


Chart E.13 Results Weighted Sum of UI Preference

Appendix F Example of Function Block Format

The following lines are a part of the process planing generated from fuction block system, in the format of the "function block format". They are tool path for the manufacturing the part "Iphone case" mentioned in the thesis.

```
Absolute
Feed F Max
Line to X NaN Y NaN Z NaN a NaN b NaN c NaN
Stop coolant
Tool change to 1
Incremental
Absolute
Line to X NaN Y NaN Z 150.0 a NaN b NaN c NaN
Spindle to 1691 CCW true
Line to X NaN Y NaN Z 150.0 a NaN b NaN c NaN
Line to X 65.0 Y 40.0 Z 150.0 a NaN b NaN c NaN
Line to X 142.0 Y 0.0 Z -4.0 a NaN b NaN c NaN
Line to X 142.0 Y 0.0 Z -6.0 a NaN b NaN c NaN
Feed F 457.0
Line to X -12.0 Y 0.0 Z -6.0 a NaN b NaN c NaN
Line to X -12.0 Y 8.0 Z -6.0 a NaN b NaN c NaN
Line to X 142.0 Y 8.0 Z -6.0 a NaN b NaN c NaN
Line to X 142.0 Y 16.0 Z -6.0 a NaN b NaN c NaN
Line to X -12.0 Y 16.0 Z -6.0 a NaN b NaN c NaN
Line to X -12.0 Y 24.0 Z -6.0 a NaN b NaN c NaN
Line to X 142.0 Y 24.0 Z -6.0 a NaN b NaN c NaN
Line to X 142.0 Y 32.0 Z -6.0 a NaN b NaN c NaN
Line to X -12.0 Y 32.0 Z -6.0 a NaN b NaN c NaN
Line to X -12.0 Y 40.0 Z -6.0 a NaN b NaN c NaN
Line to X 142.0 Y 40.0 Z -6.0 a NaN b NaN c NaN
Line to X 142.0 Y 48.0 Z -6.0 a NaN b NaN c NaN
Line to X -12.0 Y 48.0 Z -6.0 a NaN b NaN c NaN
Line to X -12.0 Y 56.0 Z -6.0 a NaN b NaN c NaN
Line to X 142.0 Y 56.0 Z -6.0 a NaN b NaN c NaN
Line to X 142.0 Y 64.0 Z -6.0 a NaN b NaN c NaN
Line to X -12.0 Y 64.0 Z -6.0 a NaN b NaN c NaN
Line to X -12.0 Y 72.0 Z -6.0 a NaN b NaN c NaN
Line to X 142.0 Y 72.0 Z -6.0 a NaN b NaN c NaN
Line to X 142.0 Y 80.0 Z -6.0 a NaN b NaN c NaN
Line to X -12.0 Y 80.0 Z -6.0 a NaN b NaN c NaN
Feed F Max
Line to X 65.0 Y 40.0 Z -4.0 a NaN b NaN c NaN
Line to X NaN Y NaN Z 150.0 a NaN b NaN c NaN
Stop coolant
Line to X NaN Y NaN Z 150.0 a NaN b NaN c NaN
Spindle to 1691 CCW true
Line to X NaN Y NaN Z 150.0 a NaN b NaN c NaN
Line to X 65.0 Y 40.0 Z NaN a NaN b NaN c NaN
Line to X NaN Y NaN Z -3.5 a NaN b NaN c NaN
Feed F 457.0
Line to X NaN Y NaN Z -5.5 a NaN b NaN c NaN
Line to X 69.0 Y 40.0 Z -5.5 a NaN b NaN c NaN
Incremental
Feed F 152.33
Helical to X 0.0 Y 0.0 Z -1.0 cX -4.0 cY 0.0 cZ NaN ccw true Plane XY
```

Helical to X 0.0 Y 0.0 Z -1.0 cX -4.0 cY 0.0 cZ NaN ccw true Plane XY
Helical to X 0.0 Y 0.0 Z -1.0 cX -4.0 cY 0.0 cZ NaN ccw true Plane XY
Helical to X 0.0 Y 0.0 Z -1.0 cX -4.0 cY 0.0 cZ NaN ccw true Plane XY
Helical to X 0.0 Y 0.0 Z -1.0 cX -4.0 cY 0.0 cZ NaN ccw true Plane XY
Helical to X 0.0 Y 0.0 Z -1.0 cX -4.0 cY 0.0 cZ NaN ccw true Plane XY
Helical to X 0.0 Y 0.0 Z -1.0 cX -4.0 cY 0.0 cZ NaN ccw true Plane XY
Helical to X 0.0 Y 0.0 Z -1.0 cX -4.0 cY 0.0 cZ NaN ccw true Plane XY
Helical to X 0.0 Y 0.0 Z -0.5 cX -4.0 cY 0.0 cZ NaN ccw true Plane XY
Helical to X 0.0 Y 0.0 Z 0.0 cX -4.0 cY 0.0 cZ NaN ccw true Plane XY
Feed F Max
Line to X -4.0 Y 0.0 Z 0.0 a NaN b NaN c NaN
Absolute
Line to X 65.0 Y 40.0 Z -12.0 a NaN b NaN c NaN
Line to X NaN Y NaN Z -3.5 a NaN b NaN c NaN
Stop coolant
Line to X NaN Y NaN Z 150.0 a NaN b NaN c NaN
Spindle to 1293 CCW true
Line to X NaN Y NaN Z 150.0 a NaN b NaN c NaN
Line to X 65.0 Y 40.0 Z NaN a NaN b NaN c NaN
Line to X 65.0 Y 40.0 Z -12.0 a NaN b NaN c NaN
Feed F 213.0
Line to X NaN Y NaN Z -14.0 a NaN b NaN c NaN
Line to X 62.0 Y 39.03747 Z -14.0 a NaN b NaN c NaN
Line to X 62.0 Y 40.96253 Z -14.0 a NaN b NaN c NaN
Line to X 68.0 Y 40.96253 Z -14.0 a NaN b NaN c NaN
Line to X 68.0 Y 39.03747 Z -14.0 a NaN b NaN c NaN
Line to X 62.0 Y 39.03747 Z -14.0 a NaN b NaN c NaN
Line to X 59.0 Y 38.074944 Z -14.0 a NaN b NaN c NaN
Line to X 59.0 Y 41.925056 Z -14.0 a NaN b NaN c NaN
Line to X 71.0 Y 41.925056 Z -14.0 a NaN b NaN c NaN
Line to X 71.0 Y 38.074944 Z -14.0 a NaN b NaN c NaN
Line to X 59.0 Y 38.074944 Z -14.0 a NaN b NaN c NaN
Line to X 56.0 Y 37.112415 Z -14.0 a NaN b NaN c NaN
Line to X 56.0 Y 42.887585 Z -14.0 a NaN b NaN c NaN
Line to X 74.0 Y 42.887585 Z -14.0 a NaN b NaN c NaN
Line to X 74.0 Y 37.112415 Z -14.0 a NaN b NaN c NaN
Line to X 56.0 Y 37.112415 Z -14.0 a NaN b NaN c NaN
Line to X 53.0 Y 36.149887 Z -14.0 a NaN b NaN c NaN
Line to X 53.0 Y 43.850113 Z -14.0 a NaN b NaN c NaN
Line to X 77.0 Y 43.850113 Z -14.0 a NaN b NaN c NaN
Line to X 77.0 Y 36.149887 Z -14.0 a NaN b NaN c NaN
Line to X 53.0 Y 36.149887 Z -14.0 a NaN b NaN c NaN
Line to X 50.0 Y 35.18736 Z -14.0 a NaN b NaN c NaN
Line to X 50.0 Y 44.81264 Z -14.0 a NaN b NaN c NaN
Line to X 80.0 Y 44.81264 Z -14.0 a NaN b NaN c NaN
Line to X 80.0 Y 35.18736 Z -14.0 a NaN b NaN c NaN
Line to X 50.0 Y 35.18736 Z -14.0 a NaN b NaN c NaN
Line to X 47.0 Y 34.22483 Z -14.0 a NaN b NaN c NaN
Line to X 47.0 Y 45.77517 Z -14.0 a NaN b NaN c NaN
Line to X 83.0 Y 45.77517 Z -14.0 a NaN b NaN c NaN
Line to X 83.0 Y 34.22483 Z -14.0 a NaN b NaN c NaN
Line to X 47.0 Y 34.22483 Z -14.0 a NaN b NaN c NaN
Line to X 44.0 Y 33.262302 Z -14.0 a NaN b NaN c NaN
Line to X 44.0 Y 46.737698 Z -14.0 a NaN b NaN c NaN
Line to X 86.0 Y 46.737698 Z -14.0 a NaN b NaN c NaN
Line to X 86.0 Y 33.262302 Z -14.0 a NaN b NaN c NaN
Line to X 44.0 Y 33.262302 Z -14.0 a NaN b NaN c NaN

Line to X 41.0 Y 32.299774 Z -14.0 a NaN b NaN c NaN
Line to X 41.0 Y 47.700226 Z -14.0 a NaN b NaN c NaN
Line to X 89.0 Y 47.700226 Z -14.0 a NaN b NaN c NaN
Line to X 89.0 Y 32.299774 Z -14.0 a NaN b NaN c NaN
Line to X 41.0 Y 32.299774 Z -14.0 a NaN b NaN c NaN
Line to X 38.0 Y 31.337244 Z -14.0 a NaN b NaN c NaN
Line to X 38.0 Y 48.662754 Z -14.0 a NaN b NaN c NaN
Line to X 92.0 Y 48.662754 Z -14.0 a NaN b NaN c NaN
Line to X 92.0 Y 31.337244 Z -14.0 a NaN b NaN c NaN
Line to X 38.0 Y 31.337244 Z -14.0 a NaN b NaN c NaN
Line to X 35.0 Y 30.374714 Z -14.0 a NaN b NaN c NaN
Line to X 35.0 Y 49.625282 Z -14.0 a NaN b NaN c NaN
Line to X 95.0 Y 49.625282 Z -14.0 a NaN b NaN c NaN
Line to X 95.0 Y 30.374714 Z -14.0 a NaN b NaN c NaN
Line to X 35.0 Y 30.374714 Z -14.0 a NaN b NaN c NaN
Line to X 32.0 Y 29.412184 Z -14.0 a NaN b NaN c NaN
Line to X 32.0 Y 50.58781 Z -14.0 a NaN b NaN c NaN
Line to X 98.0 Y 50.58781 Z -14.0 a NaN b NaN c NaN
Line to X 98.0 Y 29.412184 Z -14.0 a NaN b NaN c NaN
Line to X 32.0 Y 29.412184 Z -14.0 a NaN b NaN c NaN
Line to X 29.0 Y 28.449654 Z -14.0 a NaN b NaN c NaN
Line to X 29.0 Y 51.55034 Z -14.0 a NaN b NaN c NaN
Line to X 101.0 Y 51.55034 Z -14.0 a NaN b NaN c NaN
Line to X 101.0 Y 28.449654 Z -14.0 a NaN b NaN c NaN
Line to X 29.0 Y 28.449654 Z -14.0 a NaN b NaN c NaN
Line to X 26.0 Y 27.487123 Z -14.0 a NaN b NaN c NaN
Line to X 26.0 Y 52.512867 Z -14.0 a NaN b NaN c NaN
Line to X 104.0 Y 52.512867 Z -14.0 a NaN b NaN c NaN
Line to X 104.0 Y 27.487123 Z -14.0 a NaN b NaN c NaN
Line to X 26.0 Y 27.487123 Z -14.0 a NaN b NaN c NaN
Line to X 23.0 Y 26.524593 Z -14.0 a NaN b NaN c NaN
Line to X 23.0 Y 53.475395 Z -14.0 a NaN b NaN c NaN
Line to X 107.0 Y 53.475395 Z -14.0 a NaN b NaN c NaN
Line to X 107.0 Y 26.524593 Z -14.0 a NaN b NaN c NaN
Line to X 23.0 Y 26.524593 Z -14.0 a NaN b NaN c NaN
Line to X 22.3 Y 26.300003 Z -14.0 a NaN b NaN c NaN
Line to X 22.3 Y 53.699986 Z -14.0 a NaN b NaN c NaN
Line to X 107.7 Y 53.699986 Z -14.0 a NaN b NaN c NaN
Line to X 107.7 Y 26.300003 Z -14.0 a NaN b NaN c NaN
Line to X 22.3 Y 26.300003 Z -14.0 a NaN b NaN c NaN
Line to X 65.0 Y 40.0 Z -12.0 a NaN b NaN c NaN
Feed F Max
Line to X NaN Y NaN Z -3.0 a NaN b NaN c NaN
Stop coolant

Appendix G Output Command from Function Blocks

public boolean **isSynchronized**() {...}
public void **setIsSynchronized**(boolean value) {...}
public float **getFeedRate**() {...}
public void **setFeedRate**(float feedRate) {...}
public boolean **isDNCSessionOpen**() {...}
public int **getDNCStartTimeout**() {...}
public void **setDNCStartTimeout**(int timeOut) {...}
public CNCReturn **Connect**() {...}
public CNCReturn **Disconnect**() {...}
public CNCReturn **DNCStart**() {...}
public void **ClearNcCodeLog**() {...}
public String **GetNcCode**() {...}
public void **OnNcCodeSending**(String command) {...}
public void **DNCStop**() {...}
public CNCReturn **SendDNC**(String command) {...}
public CNCReturn **SendDNCAsync**(String command) {...}
public CNCReturn **SendDNCSync**(String command) {...}
public float **getSpindleSpeed**() {...}
public void **setSpindleSpeed**(float value) {...}
public void **ApplySpindleSpeed**() {...}
public void **SpindleStop**() {...}
public void **SpindleStop**(int spindleNumber) {...}
public void **SpindleStart**(boolean clockwise, int spindleNumber) {...}
public void **SpindleStart**(boolean value) {...}
public void **SpindleStart**() {...}
public void **CoolantStart**() {...}
public void **CoolantStop**() {...}
public void **CoolantInternalStart**() {...}
public void **CoolantInternalStop**() {...}
public void **ToolPrepare**(String toolNo) {...}
public void **ToolChange**(String toolNo) {...}
public void **GotoTarget**(Float x, Float y, Float z, Float a, Float b, Float c) {...}
public void **GotoTargetLinear**(Float x, Float y, Float z, Float a, Float b, Float c) {...}
public String **getTargetCoordsString**(Float x, Float y, Float z, Float a, Float b, Float c) {...}
public String **getCenterCoordsString**(Float cx, Float cy, Float cz, Float r) {...}
public void **ToolClamp**() {...}
public void **ToolUnclamp**() {...}
public void **DwellWait**(int value) {...}
public void **GoToHelical**(Float targetX, Float targetY, Float targetZ, Float centerX, Float centerY, Float centerZ, Float radius, boolean clockWise, CoordsPlain coordsPlain) {...}
public void **CoordinatesSystemDefine**(int coordinatesSystemNumber, Float originX, Float originY, Float originZ, Float originA, Float originB, Float originC) {...}
public void **setToolDiameterOffset**(int toolNumber, float toolRadius) {...}

public void **ToolDiameterOffsetEnable**(boolean shiftLeft) {...}
public void **ToolDiameterOffsetDisable**() {...}
public void **setToolLengthOffset**(String toolNumber, float toolLength) {...}
public void **ToolLengthOffsetEnable**(String toolNumber) {...}
public void **ToolLengthOffsetEnable**(String toolNumber, Float x, Float y, Float z, Float a, Float b, Float c) {...}
public void **ToolLengthOffsetDisable**() {...}
public void **ToolLengthOffsetAutoEnableOnToolChanges**(boolean enable) {...}
public boolean **isToolLengthOffsetAutoEnableOnToolChanges**() {...}
public void **Pause**() {...}
public LenghtMeasurementUnits **getLenghtMeasurementUnit**() {...}
public void **setLenghtMeasurementUnit**(LenghtMeasurementUnits lenghtMeasurementUnit) {...}
public void **ApplyMeasurementUnits**() {...}
public void **InterpolateCorner**(Float nextVertexX, Float nextVertexY) {...}
public CoordinatesMode **getCoordinatesMode**() {...}
public void **setCoordinatesMode**(CoordinatesMode coordinatesMode) {...}
public void **ApplyCoordinatesMode**() {...}
public String **getCurrrentToolNumber**() {...}
public void **CoordinateSystemActivate**(short coordinatesSystemNumber) {...}
public boolean **isCoordinatesSystemTransformActive**() {...}
public void **coordinatesSystemTransformActivate**() {...}
public void **coordinatesSystemTransformCancel**() {...}
public void **setAxisReverseStatus**(String axis, boolean toBeReveresed){...}
public boolean **getAxisReverseStatus**(String axis){...}
public boolean **isReverseAxesActive**(){...}
public void **reverseAxisActivate**(){...}
public void **reverseAxisCancel**(){...}
public void **limitSpindleSpeed**(int i, int i0) {...}
public void **constantSurfaceSpeedControlActivate**(float cuttingSpeed) {...}
public void **constantSurfaceSpeedControlCancel**() {...}
public void **synchronousFeedActivate**() {...}
public void **synchronousFeedCancel**() {...}
public void **lockAxis**(String axis) {...}
public void **unlockAxis**(String axis) {...}
public String **getTextSoFar**() {...}
public void **setTextSoFar**(String TextSoFar) {...}
public void **setCoordinatesSystemTransform**(javax.vecmath.Matrix4d transformationMatrix) {...}
public javax.vecmath.Matrix4d **getCoordinatesSystemTransform**() {...}
public void **initializeMachineMode**(wise.dpp.machinetools.MachineToolMode machineToolMode) {...}
public wise.dpp.machinetools.MachineToolMode **getMachineMode**() {...}
public void **AirBlowInternalStart**() {...}
public void **AirBlowStart**() {...}

Appendix H Computational Resource Consumption Test Result

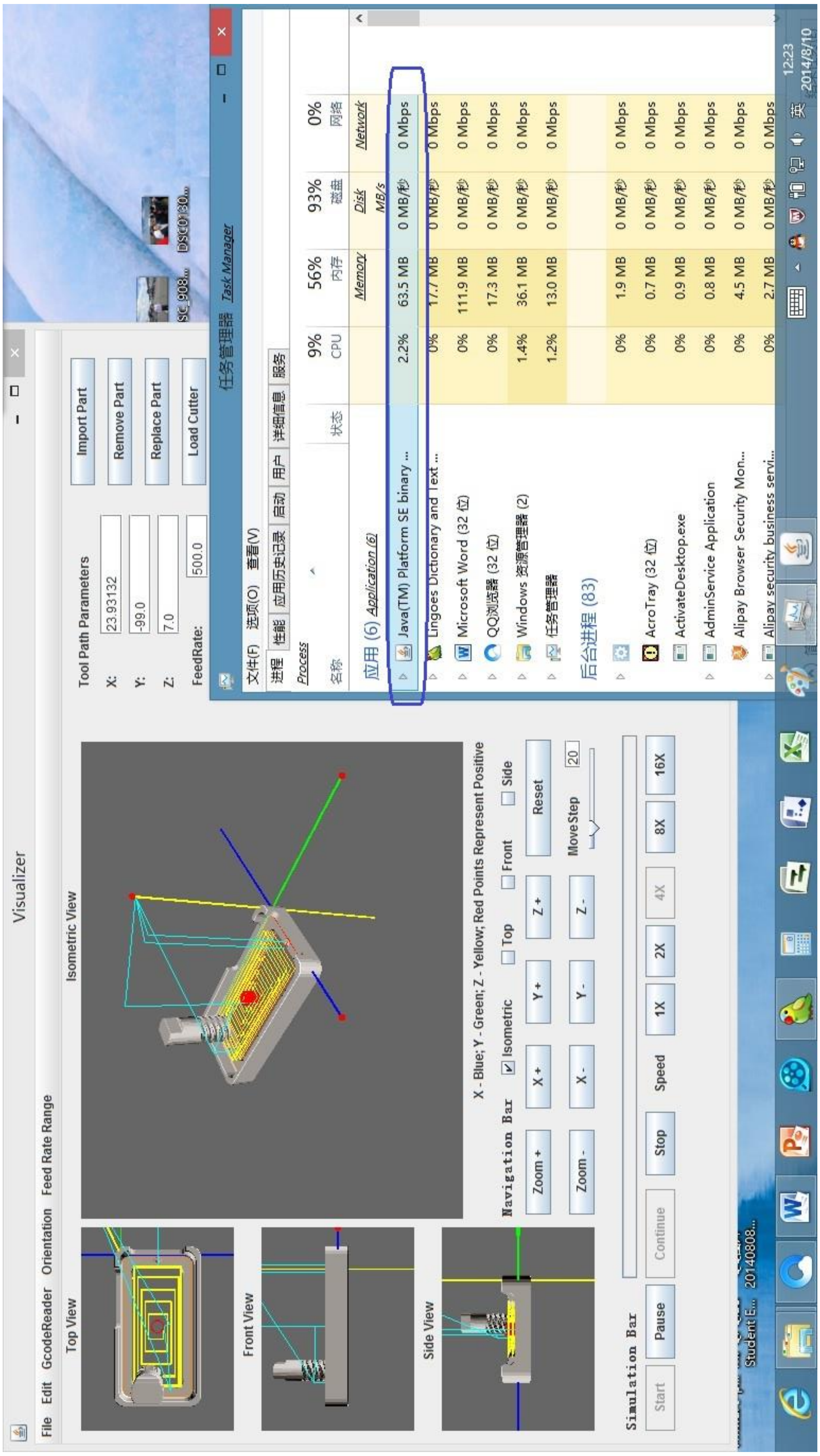


Figure H.1 Snapshot in computational resource consumption test

Appendix I Implementation Test Visit Plan

Visit Plan

Visitors: Dr Jörn Mehnen, Mr Qi Qiao

Time: 1.5 to 2 hours

Attendees: We sincerely invite you to attend this visiting, as well anyone in your company who is interested in this research. And it will be wonderful if there is an expert present, in case any technical details need to be discussed.

Introduction

The visualizer is programmed with Java language, aims to provide a light weight solution for function block behavior visualization. The size of the whole package is about 5 – 10 Mbs, and only a copy & paste operation is needed to install it. Currently, it can only work with 3D model in .obj format. The test part is an iphone case with the tool path for it.

Test Requirement

1. A normal desktop; 2. Internet connected or a trusted USB stick.

Visualizer Installation/Uninstallation procedures

This part is the procedures for the software package installation and uninstallation. An easy way to describe these is: first, copy the files on a desktop with windows; then register the software in the system; finally, set the java environment.

I will deal with the installation and uninstallation nicely and safely by myself. I'll try to make minimal changing to the computer and leave no trace after uninstallation. I'm happy to talk you through, explain every step in details to answer any concerns about the testing.

Following are the details, in case you want to know what will be done exactly on your machines.

1. A desktop with Windows OS is needed as testing platform. If there is a security concern, it can be disconnected from local network and internet after installation, as a sandbox for testing.
2. Copy the folder into the local hard drive. An email attachment will be the best way to do this, if the desktop is connected into internet. Otherwise, a trusted USB stick is needed to transform the file onto the desktop.
3. A Java Runtime Environment and Java3D interfaces are needed supporting the software. They can be downloaded from the official website of Oracle and then installed. After these two installations, there will be an environmental variable needs to be set up through the system setting of windows, which tells from where the software can find the library files.
4. Because of security rules of Oracle, an adjusting of the security level in Java control panel is needed to run self-signed java program. As the research is not finished, the visualizer is self-signed. But I can assure you that there is no malicious code in it.

Uninstallation: 1. Set the environment variable of the system as it was; 2. Uninstall Java Runtime Environment and Java3D Interface; 3.Delete the folder contains the software.

Appendix J Case Study Result

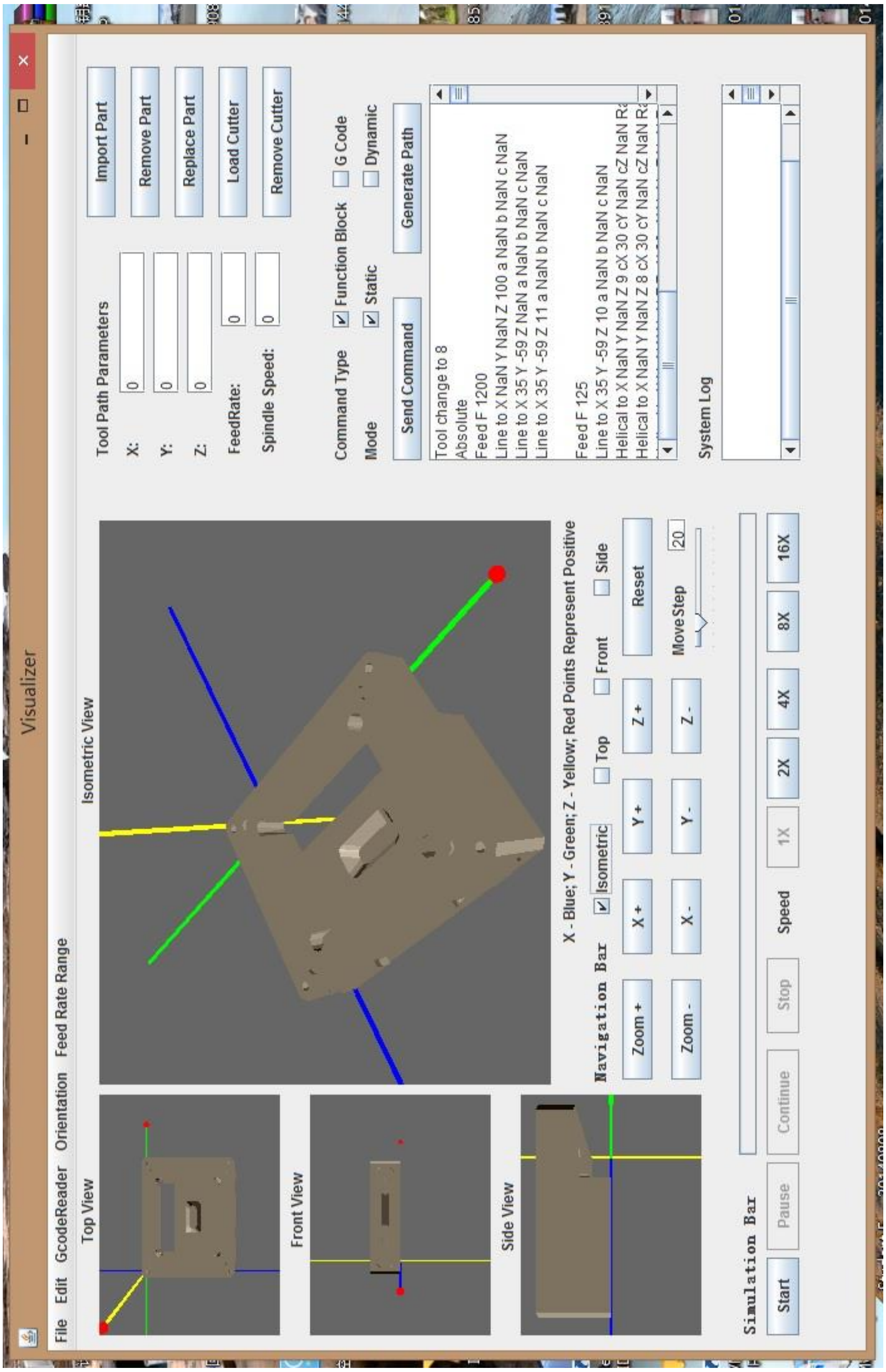


Figure J.1 Snapshot in Case 1

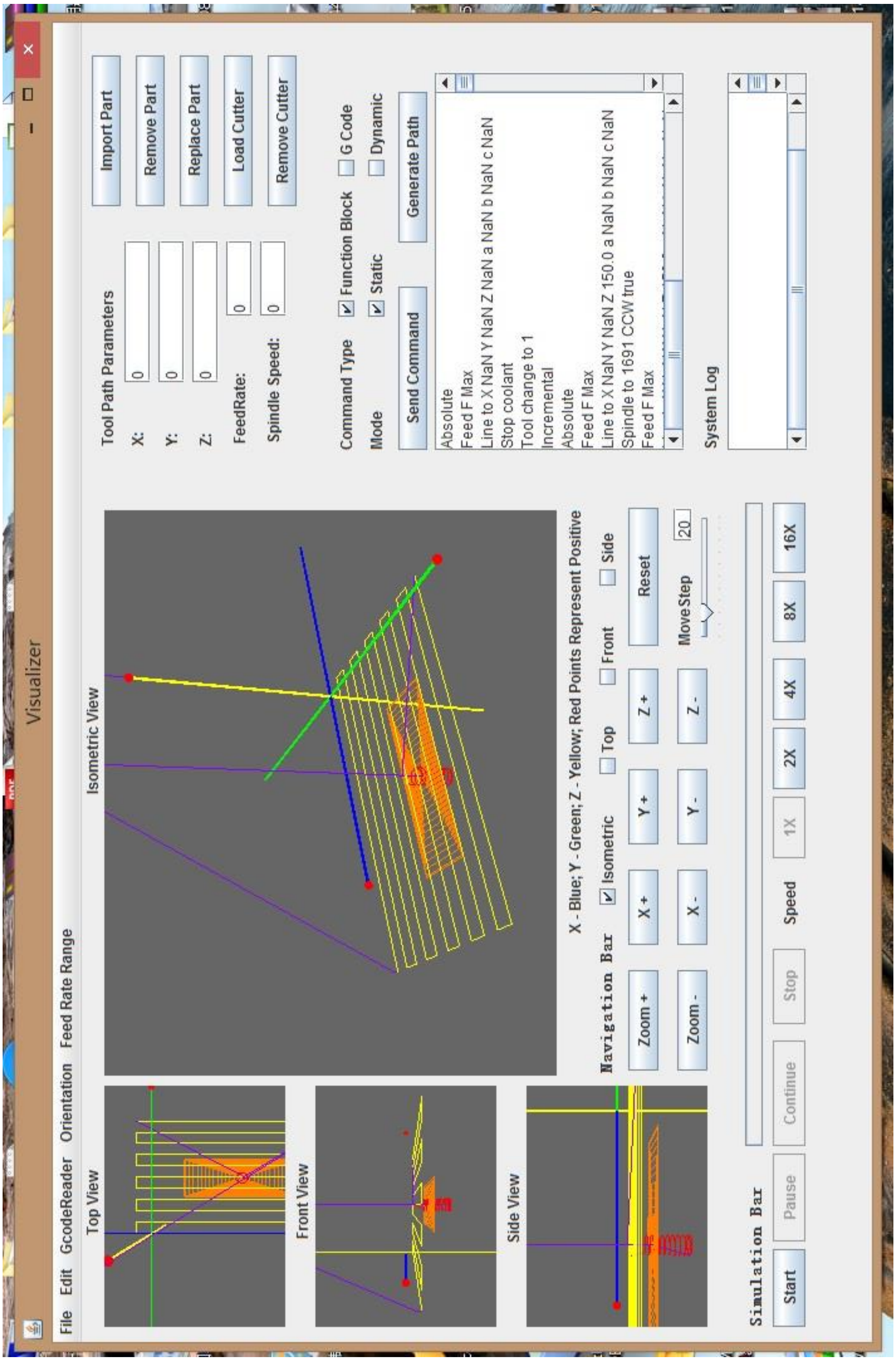


Figure J.2 Snapshot in Case 2

Tool path used in Case 2 is as the same as listed in Appendix F.

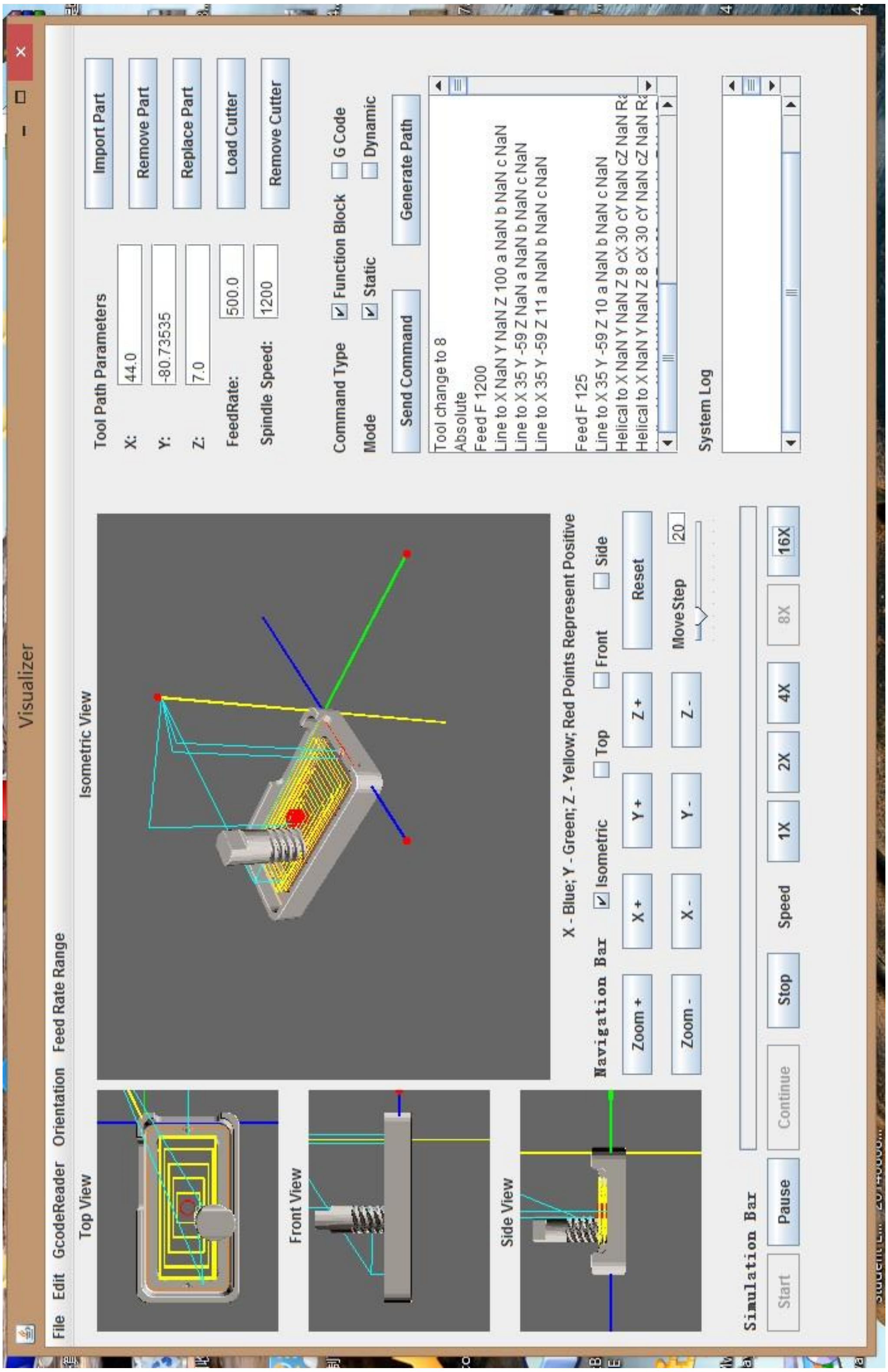


Figure J.3 Snapshot in Case 3

Appendix K Compatibility Test Result

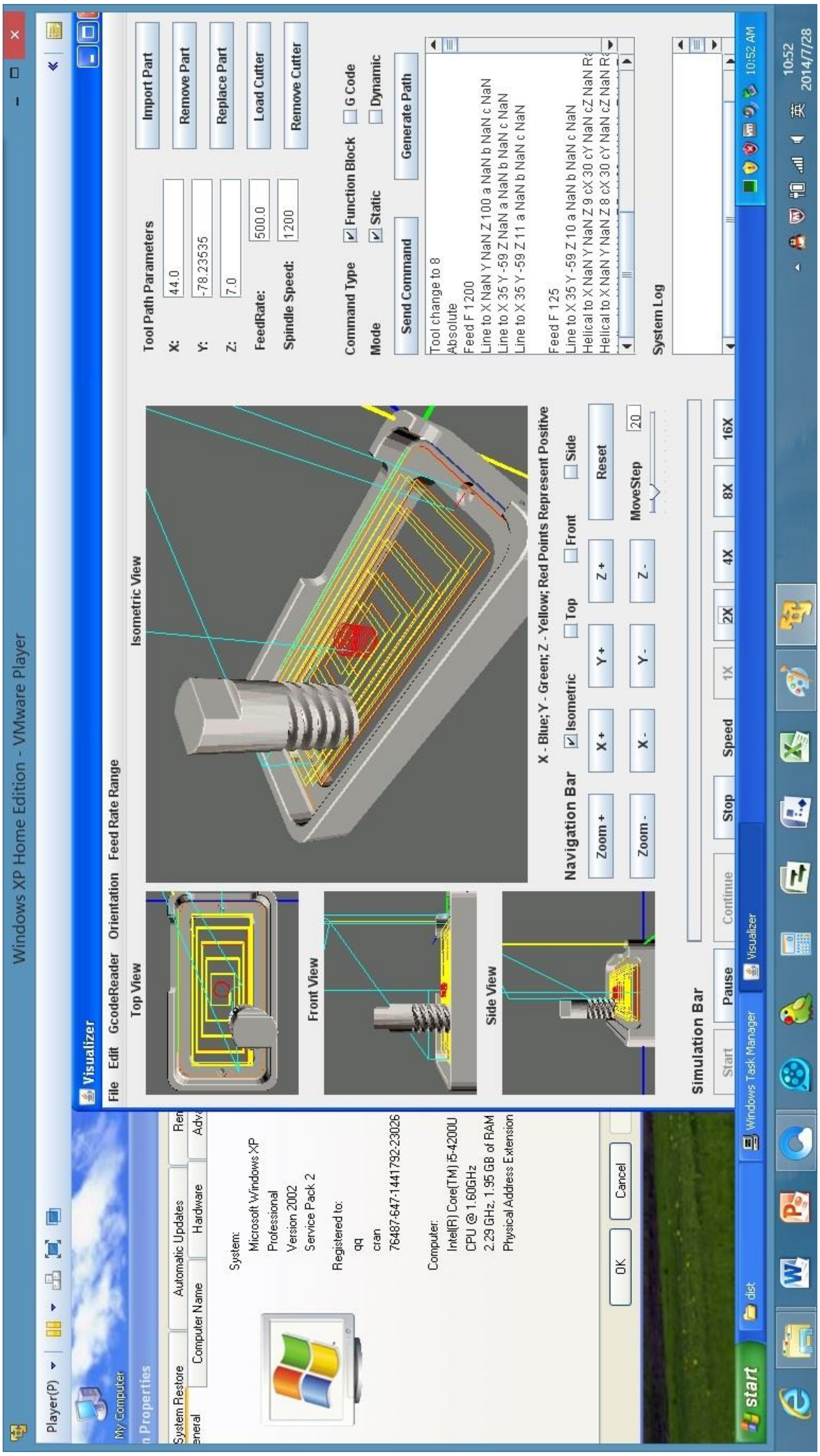


Figure K.1 Snapshot in capability test on Windows XP

Figure K.2 Snapshot in capability test on Windows 7

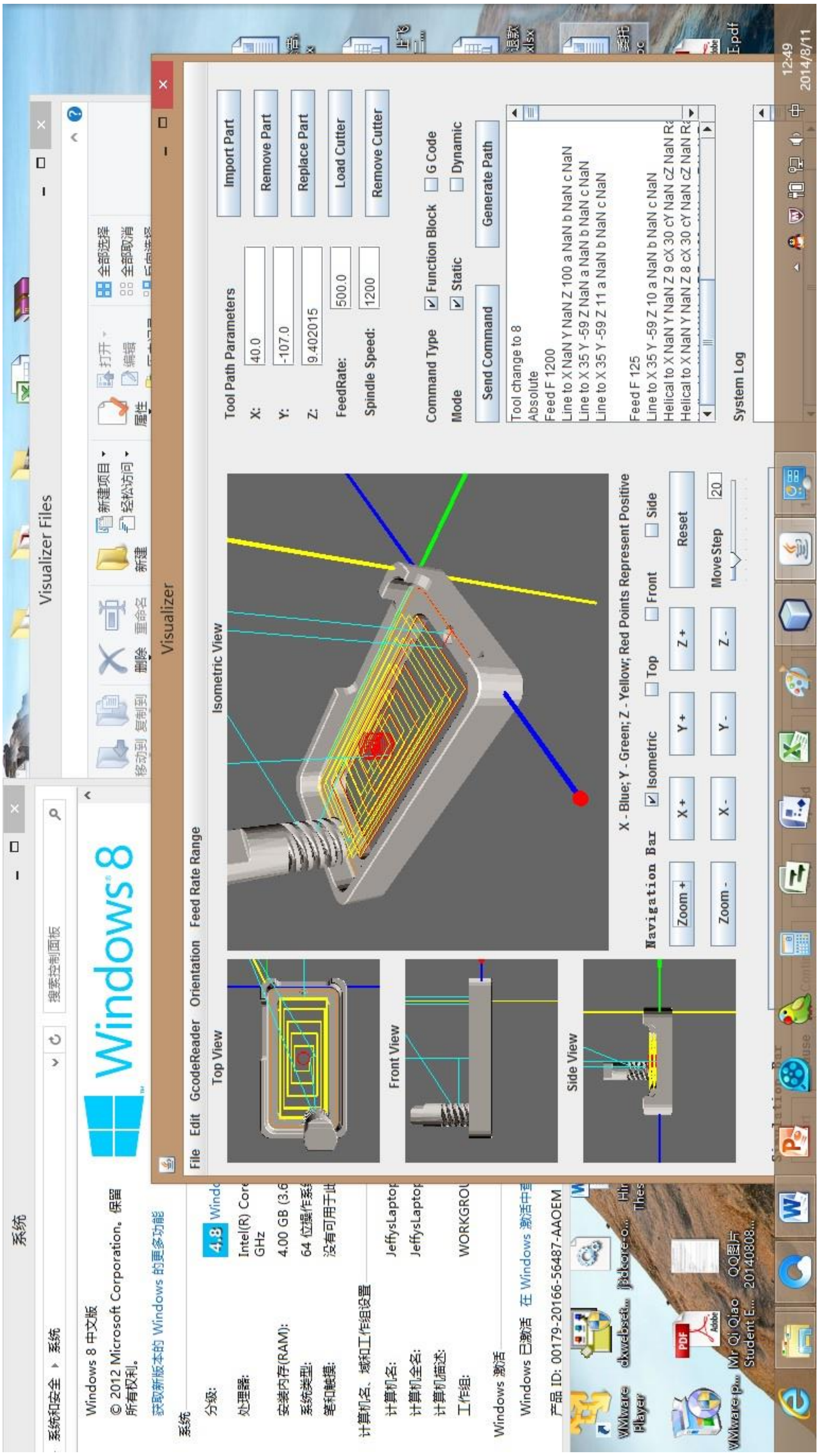


Figure K.3 Snapshot in capability test on Windows 8

Appendix L Validation Introduction

Introduction

The visualizer is programmed with Java language, aims to provide a light weight solution for function block behavior visualization. The size of the whole package is about 5 – 10 Mbs, and only a copy & paste operation is needed to install it. Currently, it can only work with 3D model in .obj format. The test part is an iphone case with the tool path for it.

Research Abstract

A solution for visualising the tool path generated from function block system is introduced in this research. It facilitates the monitoring and manipulating the behaviour of function block system.

In order to improve computer aided process planning for milling operations, a distributed function block system is introduced. This system is currently being developed through the EU project CAPP-4-SMEs (Collaborative and Adaptive Process Planning for Sustainable Manufacturing Environments). The function blocks are created in a Cloud environment and dispatched to CNC controllers to generate complex milling tool paths on-board. This approach is different to the conventional CAD-CAM G-code driven off-line approach. The ability of an on-board visualisation of the behaviour of function blocks is a very important process for the validation the function block behaviour. It makes the concept more practical and reliable by providing a real-time visualisation.

This research aims to find out suitable solutions to realise the visualisation of tool path generated from function block system. The existing visualisation methods are researched, compared and selected to fit the purpose. A number of aspects are focused on, such as program language, graphic user interface optimisation, cloud environment compatibility, and requirement from shop floor users. An Application with 3D graphic user interface is developed and tested. Functions for displaying and operating 3D CAD models and tool paths, animation of the milling process and process parameters monitoring are included in the software. The developed visualizer is a light-weight visualisation tool which is able to run directly on CNC controllers with Windows (or PC with Windows). It can be connected with a Cloud environment (work with servers located around Europe) for real-time tool path visualisation. Based on a requirement survey from industries, it is developed to fulfil the challenging practical needs of industrial shop floor users.

Presentation

Bullet points about the research are listed in the presentation file, which is also a review presentation for the research. The purpose, process and the result of the research is introduced in it.

Validation

Thanks to your contribution in the questionnaire survey, the visualisation tool has been developed based on that. I'd like to have your feedback after the experience of the application. It is very important for the validation of the research. How to operate the application is shown in the demonstration video. Please feel free to bring up any opinion and suggestion on the validation form provided, and send me a copy of it. Back side of the paper is also available for writing. It would be perfect that the application is installed and experienced by yourself. If anything fails the installation, please validate the application according to the video and write down the unexpected problem on the back of the form. Your contribution to this research is much appreciated.

Test Requirement

1. A normal desktop with Windows; 2. Internet connected or a trusted USB stick.

List of Files

1. A zip file contains the visualizer (the "dist" folder)
2. Two .obj file (3D model) of a part and a cutter
3. Introduction document
4. Demonstration video
5. A Piece of G-code generated from Function Block system
6. Presentation PowerPoint file
7. Validation form
8. Java Runtime setup files & Java3D setup files

Visualizer Installation/Uninstallation procedures

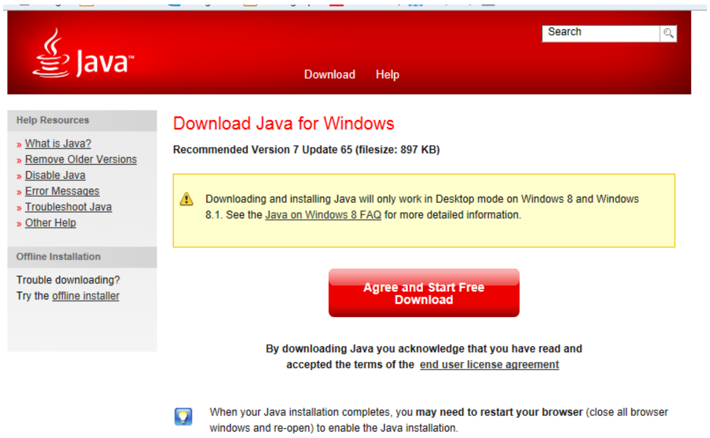
This part is the procedures for the software package installation and uninstallation. An easy way to describe these is: first, copy the files on a desktop with windows; then register the software in the system; finally, set the java environment.

I'm happy to explain every step in details to answer any concerns about the testing. Please don't hesitate to contact me when you need any information.

Following are the details, what need to be done exactly on your machines.

1. A desktop with Windows OS is needed as testing platform. I wrote it myself, so I can assure you no malicious virus contained in code of the visualizer. If there is a security concern, it is better that the computer is disconnected from local network and internet during the period, as a sandbox for testing.
2. Copy the folder into the local hard drive. An email attachment will be the best way to do this, if the desktop is connected into internet. Otherwise, a trusted USB stick is needed to transform the files onto the desktop.
3. A Java Runtime Environment and Java3D interfaces are needed supporting the

software. They can be downloaded from the official website of Oracle and then installed.



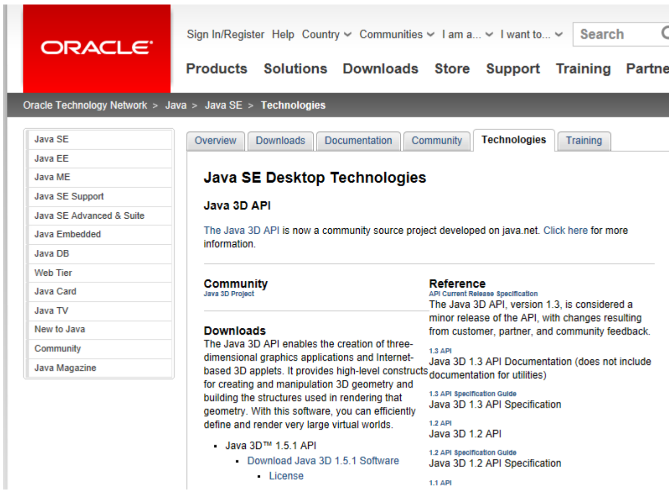
Java Runtime Environment Download is available at:

https://www.java.com

You can use the provided setup file as well.

jre-7u55-windows-i586.exe for 32-bit Windows;

jre-7u55-windows-x64.exe for 64-bit Windows.



Java3D download is available at:

http://www.oracle.com/technetwork/java/javase/tech/index-jsp-138252.html

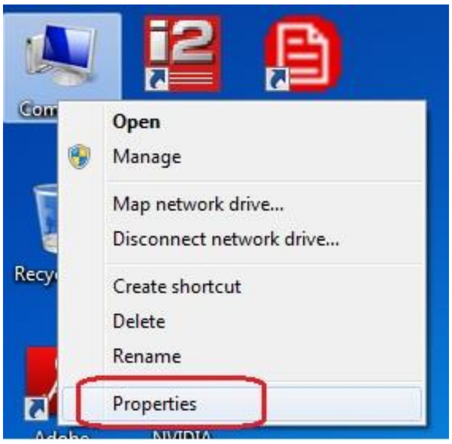
You can use the provided setup file as well.

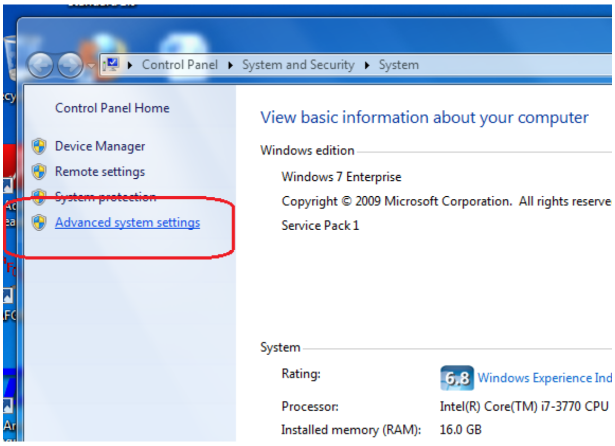
j3d-1_5_2-windows-i586_E.exe for 32-bit Windows;

j3d-1_5_2-windows-amd64_E.exe for 64-bit Windows.

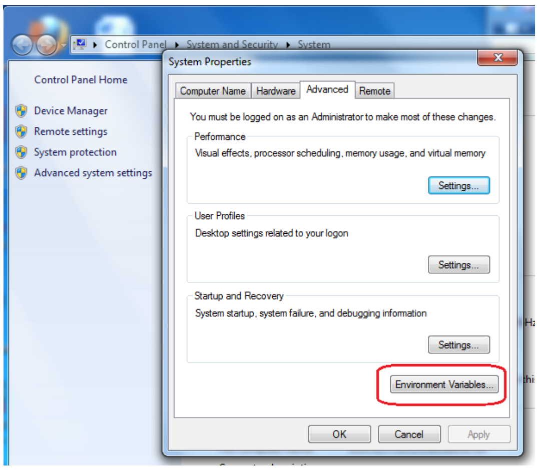
4. After these two installations, there will be an environmental variable needs to be set up through the system setting of windows, which tells from where the software can find the library files.

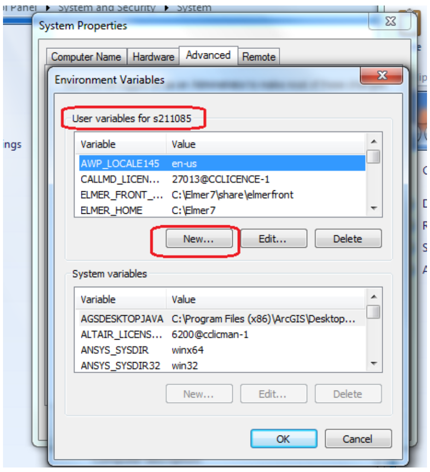
   First, open the properties of the computer. Select advanced system settings.





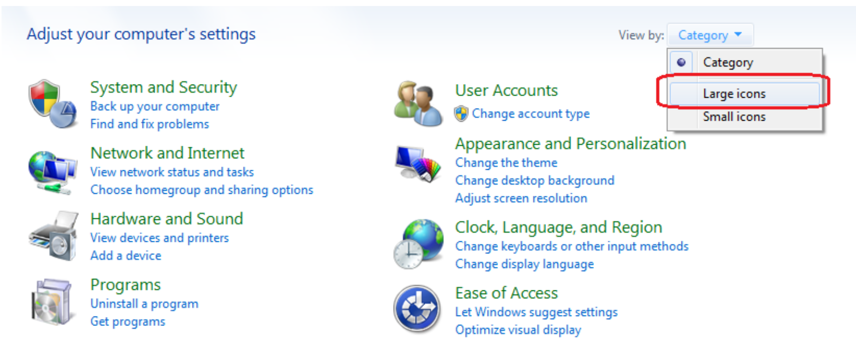
Then, open Environment Variables. Put a new User Variable called "Path" with the value of "X:\xxx\dist\lib". "X:\xxx\" means where you put the folder "dist" in the computer, which is provided in the files of the visualizer.



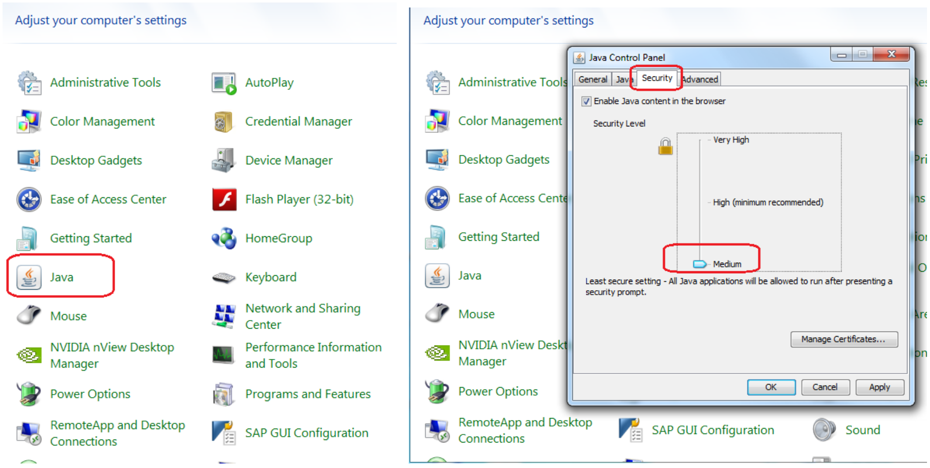


Because of security rules of Oracle, an adjusting of the security level in Java control panel is needed to run self-signed java program. As the research is not commercialized, the visualizer is self-signed.

First, open the control pad of the system. Select view by large icons.



Open the Java Icon.



Change the security level to medium.

Uninstallation:

1. Set the environment variable of the system as it was, delete the new user variable “Path” with caution and leave the system variable as it was; 2. Uninstall Java Runtime Environment and Java3D Interface; 3.Delete the folder contains the software.

Appendix M Expert Validation

Validation Sheet

Test Date:	**Test Platform:** MAZAK VTC 800/20SR / ON LAPTOP.		
Test Items	**Description**	**Yes / No**	**Grade (0-10)**
Model Import	Whether the model displayed correctly	~~NO SEE NOTE~~ YES	6
Suggestion	NEED TO LOOK AT WHAT TYPES OF FILE WILL RUN ON CONTROLLER		
Cutter Import	Whether the cutter imported correctly	NO - SEE NOTE	6
Suggestion	WORKED IN PLAN VIEWS BUT DID NOT DISPLAY ALWAYS ON 3D. VIEW		
Tool Path Generation	Please grade the speed of generation process		8
Suggestion			
	Whether the path meet the requirement for visualisation correctly	YES.	8
Suggestion	BASED ON FUNCTION INFORMATION SEEN.		
Navigation	Whether the navigation function is sufficient for use	YES.	8
Suggestion			
	Please grade the navigation function	GOOD.	8
Suggestion			
Cutting Process Simulation	Whether the basic function of animation provided	YES.	8
Suggestion			
	Please grade the simulation function	GOOD.	8
Suggestion			
Parameter Display	Whether all the parameters needed for tool path displayed	NO	6
Suggestion	TOOL HOLDING FOR CRASH DETECTION NEEDED.		
GUI (Graphic User Interface)	Does the GUI layout meet the practical requirement? Please grade the GUI.	YES	9
Suggestion			
Visualisation	Does the visualiser obtain the necessary functions for tool path generated from function blocks? Please grade the visualiser.	N/A.	
Suggestion			
	Do you think the visualiser can pass the validation case study for basic functions?	YES.	

Name: P. EVERITT Job Title: MANAGING DIRECTOR

By filling this sheet, you are consenting for your data (except personal information) to be used for internal MSc research only. Your answer will be treated confidential and all data will be anonymized.

Thank you for your participation in this research, your contribution is much appreciated.

Figure M.1 Expert validation form

Validation Sheet

Test Date: 8/1/2014 Test Platform ***: Video

Test Items	Description ***	Yes / No	Grade (0-10)
Model Import	Whether the model displayed correctly	Yes	10
Suggestion			
Cutter Import	Whether the cutter imported correctly	Yes	10
Suggestion			
Tool Path Generation	Please grade the speed of generation process	Yes	10
Suggestion			
	Whether different feedrates are represented by different colours correctly	Yes	10
Suggestion			
Navigation	Whether the navigation function is sufficient for use	Yes	10
Suggestion			
	Please grade the navigation function	Yes	10
Suggestion			
Cutting Process Simulation	Whether the basic function of animation provided	Yes	10
Suggestion			
	Please grade the simulation function	Yes	10
Suggestion			
Parameter Display	Whether all the parameters needed for tool path displayed	Yes	10
Suggestion			
GUI (Graphic User Interface)	Does the GUI layout meet the practical requirement? Please grade the GUI.	Yes	10
Suggestion			
Visualisation	Does the visualiser obtain the necessary functions for tool path generated from function blocks? Please grade the visualiser.	Yes	10
Suggestion			
	Do you think the visualiser can pass the validation case study for basic functions?	Yes	10

***: If the application doesn't work by any reason, please fill the test platform blank with "Video", and fill the sheet according to the demonstration video instead.

Name: Dennis Xu Job Title: Director

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Thank you for your participation in this research, your contributior is much appreciated.

Figure M.2 Expert validation form

Validation Sheet

Test Date: 2016.08.01	Test Platform ***: Video		
Test Items	**Description *** **	**Yes / No**	**Grade (0-10)**
Model Import	Whether the model displayed correctly	Yes	10
Suggestion			
Cutter Import	Whether the cutter imported correctly	Yes	10
Suggestion			
Tool Path Generation	Please grade the speed of generation process		10
Suggestion			
	Whether different feedrates are represented by different colours correctly	Yes	10
Suggestion			
Navigation	Whether the navigation function is sufficient for use	Yes	10
Suggestion			
	Please grade the navigation function		10
Suggestion			
Cutting Process Simulation	Whether the basic function of animation provided	Yes	10
Suggestion			
	Please grade the simulation function		10
Suggestion			
Parameter Display	Whether all the parameters needed for tool path displayed	Yes	9
Suggestion			
GUI (Graphic User Interface)	Does the GUI layout meet the practical requirement? Please grade the GUI.	Yes	9
Suggestion			
Visualisation	Does the visualiser obtain the necessary functions for tool path generated from function blocks? Please grade the visualiser.	Yes	10
Suggestion			
	Do you think the visualiser can pass the validation case study for basic functions?	Yes	10

*****:** If the application doesn't work by any reason, please fill the test platform blank with "Video", and fill the sheet according to the demonstration video instead.

Name: XU Min Job Title: Tooling Designer

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Thank you for your participation in this research, your contribution is much appreciated.

Figure M.3 Expert validation form

Validation Sheet

Test Date: 31st of July Test Platform ***: Windows Vista

Test Items	Description ***	Yes / No	Grade (0-10)
Model Import	Whether the model displayed correctly	YES	9
Suggestion	White screen after loading the model		
Cutter Import	Whether the cutter imported correctly	YES	10
Suggestion			
Tool Path Generation	Please grade the speed of generation process		10
Suggestion			
	Whether different feedrates are represented by different colours correctly	YES	10
Suggestion			
Navigation	Whether the navigation function is sufficient for use	YES	
Suggestion	Use of rotating wheel mouse for zoom in and zoom out.		
	Please grade the navigation function		8
Suggestion			
Cutting Process Simulation	Whether the basic function of animation provided	YES	
Suggestion			
	Please grade the simulation function		7
Suggestion	Fast machining simulation		
Parameter Display	Whether all the parameters needed for tool path displayed	YES	9
Suggestion	Axial depth of cut and radial depth of cut also could be interesting parameter.		
GUI (Graphic User Interface)	Does the GUI layout meet the practical requirement? Please grade the GUI.	YES	8
Suggestion			
Visualisation	Does the visualiser obtain the necessary functions for tool path generated from function blocks? Please grade the visualiser.	YES	8
Suggestion			
	Do you think the visualiser can pass the validation case study for basic functions?	YES	9

***: If the application doesn't work by any reason, please fill the test platform blank with "Video", and fill the sheet according to the demonstration video instead.

Name: Alejandro Muñoz España Job Title: Manufacturing Engineer

By filling this sheet, you are consenting for your data (except personal information) to be used for internal MSc research only. Your answer will be treated confidential and all data will be anonymized.

Thank you for your participation in this research, your contribution is much appreciated.

Figure M.4 Expert validation form

Validation Sheet

Test Date: 20th July   Test Platform ***: video

Test Items	Description ***	Yes / No	Grade (0-10)
Model Import	Whether the model displayed correctly	Yes	10
Suggestion			
Cutter Import	Whether the cutter imported correctly	Yes	10
Suggestion			
Tool Path Generation	Please grade the speed of generation process	Yes	10
Suggestion			
	Whether different feedrates are represented by different colours correctly	Yes	10
Suggestion			
Navigation	Whether the navigation function is sufficient for use	Yes	
Suggestion			
	Please grade the navigation function		10
Suggestion			
Cutting Process Simulation	Whether the basic function of animation provided		
Suggestion	Backward replay, forward replay. animation speed can be changed in any number from 1X to 16X		
	Please grade the simulation function		8
Suggestion			
Parameter Display	Whether all the parameters needed for tool path displayed	Yes	
Suggestion			
GUI (Graphic User Interface)	Does the GUI layout meet the practical requirement? Please grade the GUI.		
Suggestion	the step which is running should be visible.		
Visualisation	Does the visualiser obtain the necessary functions for tool path generated from function blocks? Please grade the visualiser.	Yes	10
Suggestion			
	Do you think the visualiser can pass the validation case study for basic functions?	Yes	

***: If the application doesn't work by any reason, please fill the test platform blank with "Video", and fill the sheet according to the demonstration video instead.

Name: Lijuan Sun   Job Title: Tooling Designer

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Thank you for your participation in this research, your contribution is much appreciated.

Figure M.5 Expert validation form