Coordinate Measuring Machine (CMM) Inspection Planning and Knowledge Capture – Formalising a Black Art

Dimitrios Anagnostakis

Submitted for the degree of Doctor of Philosophy

Heriot-Watt University

School of Engineering and Physical Sciences

2020

Supervisors:

Professor James Ritchie

Dr. Theodore Lim

Abstract

In manufacturing, the automated elicitation of engineering knowledge is a major challenge due to the increasing knowledge-intensive processes and systems used in industry. Capturing and formalizing engineering knowledge is a highly costly and time-consuming task. The existing literature covers little in this field, leaving unanswered the technical difficulties of capturing and representing knowledge in Coordinate Measuring Machine (CMM) inspection planning applications.

This work presents the Inspection Planning and Capturing Knowledge (IPaCK) system, a novel paradigm for the automated capturing and formalising of human centred expertise in the field of CMM planning. The proposed solution is an innovative physical setup using a simple tracked hand-held probe that facilitates intuitive planning of a CMM measurement strategy as a user interacts with a real component. As the sequence is generated, in real time a motion tracking-based digital tool logs user activity throughout the task. A post processor then converts log file data into multiple formalised outputs representing the knowledge created and utilised during the CMM inspection planning task.

Experienced CMM inspection planners validated IPaCK's potential to produce knowledge representations of CMM planning strategies that were useful, relevant and accurate. A comparison of planning strategies resulted in the detection of measurement patterns; embedding both inspection planning knowledge and experience, constituting the first known implementation of automatically capturing best practice and defining benchmarks to evaluate future planning strategies. A task completion time (TCT) comparison against a conventional CMM showed that IPaCK facilitates faster measurement planning and part programming.

On using the system, novice planners rated IPaCK and its knowledge representations to provide significant metacognition support to CMM planning and training. Experienced planners confirmed IPaCK's knowledge capture capability and that the formats were industry acceptable, relevant and beneficial in inspection planning tasks.

IPaCK could be at the heart of the next generation of CMM inspection planning systems; one that automatically captures and formalises inspection planning knowledge and experience in multiple outputs. This thesis presents the underpinning science and technology to realise the implementation.

Dedication

In dedication to my beloved daughter, Angelina.

Acknowledgments

Many thanks to my academic supervisors Prof. James Ritchie and Dr Theodore Lim for their kind support and guidance throughout this study. Also, to Dr Richard Dewar and Dr Raymond Sung as partners from the sponsor company of this project, Renishaw plc. Additionally, to Dr Aparajithan Sivanathan for his kind help and contribution to this research.

I am particularly indebted to all the participants who generously gave their time and knowledge to help in the experimentation and case studies, without which much of this work would not have been possible.

Special thanks to my parents, Vassiliki and Ioanni, and my sister, Lea, for their encouragement and spending a lot of their life and earnings to support my studies.

Finally, I would like to thank my wife, Elina, for her patience, support and encouragement.

Research Thesis Submission

Please note this form should be bound into the submitted thesis.

Name:	Dimitrios Anagnostakis		
School:	EPS		
Version: *(i.e. First, Resubmission, Final)*	Final	Degree Sought:	Doctor of Philosophy

Declaration

In accordance with the appropriate regulations I hereby submit my thesis and I declare that:

1. The thesis embodies the results of my own work and has been composed by myself
2. Where appropriate, I have made acknowledgement of the work of others
3. The thesis is the correct version for submission and is the same version as any electronic versions submitted*.
4. My thesis for the award referred to, deposited in the Heriot-Watt University Library, should be made available for loan or photocopying and be available via the Institutional Repository, subject to such conditions as the Librarian may require
5. I understand that as a student of the University I am required to abide by the Regulations of the University and to conform to its discipline.
6. I confirm that the thesis has been verified against plagiarism via an approved plagiarism detection application e.g. Turnitin.

ONLY for submissions including published works

Please note you are only required to complete the Inclusion of Published Works Form (page 2) if your thesis contains published works)

7. Where the thesis contains published outputs under Regulation 6 (9.1.2) or Regulation 43 (9) these are accompanied by a critical review which accurately describes my contribution to the research and, for multi-author outputs, a signed declaration indicating the contribution of each author (complete)
8. Inclusion of published outputs under Regulation 6 (9.1.2) or Regulation 43 (9) shall not constitute plagiarism.

* *Please note that it is the responsibility of the candidate to ensure that the correct version of the thesis is submitted.*

Signature of Candidate:		Date:	30/04/2020

Submission

Submitted By *(name in capitals):*	DIMITRIOS ANAGNOSTAKIS
Signature of Individual Submitting:	
Date Submitted:	04/05/2020

For Completion in the Student Service Centre (SSC)

Limited Access	Requested	Yes		No		Approved	Yes		No
E-thesis Submitted (***mandatory for final theses***)									
Received in the SSC by *(name in capitals):*					Date:				

Table of Contents

ABSTRACT .... **II**

DEDICATION .... **III**

ACKNOWLEDGMENTS .... **IV**

LIST OF FIGURES .... **IX**

LIST OF TABLES .... **XV**

LIST OF ABBREVIATIONS .... **XVIII**

LIST OF PUBLICATIONS .... **XIX**

CHAPTER 1 INTRODUCTION **1**

1.1 FIELD OF RESEARCH 1
1.2 MOTIVATION 3
1.3 RESEARCH HYPOTHESIS, QUESTIONS AND OBJECTIVES 4
1.3.1 Research questions 4
1.3.2 Research objectives 5
1.4 STRUCTURE OF THESIS 5

CHAPTER 2 CAIP REVIEW **7**

2.1 INTRODUCTION 7
2.2 INSPECTION PLANNING TASKS 7
2.2.1 Part setup and orientation 8
2.2.2 Accessibility analysis 10
2.2.3 Sampling strategy 12
2.2.4 Inspection path planning 15
2.3 COMPUTER AIDED INSPECTION PLANNING SYSTEMS 17
2.3.1 Expert systems 18
2.3.2 Other CAIP systems 23
2.3.3 Commercial CAIP packages 24
2.4 SUMMARY 25

CHAPTER 3 REVIEW OF ENGINEERING KNOWLEDGE CAPTURE AND FORMALISATION **28**

3.1 INTRODUCTION 28
3.2 DEFINITION OF KNOWLEDGE 28
3.3 AUTOMATED ENGINEERING KNOWLEDGE CAPTURE 30
3.3.1 Automated knowledge capture in design 30
3.3.2 Automated knowledge capture in planning tasks 32

3.4 ENGINEERING KNOWLEDGE FORMALISATION 33
3.5 KNOWLEDGE CAPTURE AND FORMALISATION IN CAIP 38
3.6 SUMMARY 41

CHAPTER 4 IPACK FRAMEWORK AND PILOT STUDY 42

4.1 INTRODUCTION 42
4.2 METHODOLOGY AND INITIAL IPACK PROTOTYPE DEVELOPMENT 43
4.2.1 Apparatus and user activity logging 45
4.2.2 Knowledge representation formats 49
4.3 PILOT STUDY - KNOWLEDGE REPRESENTATIONS EVALUATION 58
4.3.1 Pilot study results 61
4.3.2 Lessons learnt 63
4.4 FINAL PROTOTYPE 64
4.4.1 Updated apparatus and user activity logging 65
4.4.2 Final knowledge representations 70
4.4.3 Other knowledge representations 78
4.5 SUMMARY 80

CHAPTER 5 EXPERIMENTAL RESULTS AND ANALYSIS 1 - CMM INSPECTION PLANNING STRATEGY CAPTURE 82

5.1 INTRODUCTION 82
5.2 EXPERIMENTAL METHODOLOGY AND TESTS 82
5.3 IPACK USABILITY TESTING 85
5.4 COMPARISON AND EVALUATION OF STRATEGIC PLANNING APPROACHES 89
5.4.1 Common activity and patterns detection 89
5.4.2 Evaluating the quality of strategic planning 101
5.5 CMM PART PROGRAMMING 104
5.6 SUMMARY 108

CHAPTER 6 EXPERIMENTAL RESULTS AND ANALYSIS 2 – THE EVALUATION AND VALIDATION OF CMM INSPECTION PLANNING KNOWLEDGE REPRESENTATIONS 110

6.1 INTRODUCTION 110
6.2 EXPERIMENTAL METHODOLOGY 110
6.3 KNOWLEDGE REPRESENTATIONS EVALUATION AND STATISTICAL ANALYSIS 113
6.3.1 Main groups comparison and statistical analysis 113
6.3.2 Sub-groups' comparison and statistical analyses 118
6.4 SUMMARY 128

CHAPTER 7 DISCUSSION 130

CHAPTER 8 CONCLUSIONS AND FUTURE WORK **136**

8.1 MAIN CONCLUSION 136

8.2 LIMITATIONS OF RESEARCH AND FUTURE DIRECTIONS 137

REFERENCES **141**

APPENDIX A **159**

APPENDIX A.1 EARLY STAGE IPACK – DEMO VIDEO 159

APPENDIX A.2 RAY TRACING ALGORITHM FOR INSPECTION PATH 160

APPENDIX A.3 CODE FOR CMM PART PROGRAM GENERATION 162

APPENDIX A.4 VBA MACRO CODE FOR IDEF0 GENERATION 165

APPENDIX A.5 VBA MACRO CODE FOR SUBTITLES GENERATION 174

APPENDIX A.6 VBA MACRO CODE FOR TEXT INSTRUCTIONS GENERATION 176

APPENDIX A.7 EXAMPLE OF ANNOTATED VIDEO-CLIP – PILOT STUDY 178

APPENDIX A.8 FINAL IPACK – DEMO VIDEO 178

APPENDIX A.9 EXAMPLE OF ANNOTATED VIDEO-CLIP – MAIN EXPERIMENTAL STUDY 178

APPENDIX B **179**

APPENDIX B.1 KNOWLEDGE REPRESENTATIONS EVALUATION – PILOT STUDY QUESTIONNAIRE 179

APPENDIX B.2 INSPECTION PLANNING STRATEGIES QUESTIONNAIRE 188

APPENDIX B.3 PATTERN DETECTION TOOL (PADET) ALGORITHM 191

APPENDIX B.4 STRATEGIES COMPARISON ALGORITHM 193

APPENDIX C **194**

APPENDIX C.1 KNOWLEDGE REPRESENTATIONS PILOT STUDY RESULTS - RAW DATA 194

APPENDIX C.2 USABILITY STUDY AND SUS RATINGS AVERAGE AND STANDARD DEVIATION 196

APPENDIX C.3 PART 1 – PART PROGRAMS (PLAN 7) 197

APPENDIX C.4 PART 2 – PART PROGRAMS (PLAN 8) 199

APPENDIX D KNOWLEDGE REPRESENTATIONS AND QUESTIONNAIRE – MAIN STUDY **201**

APPENDIX D.1 KNOWLEDGE REPRESENTATIONS – PART 1 201

APPENDIX D.2 KNOWLEDGE REPRESENTATIONS – PART 2 210

APPENDIX D.3 KNOWLEDGE REPRESENTATIONS – MAIN EXPERIMENTAL STUDY QUESTIONNAIRE 219

APPENDIX E RAW DATA **230**

List of Figures

Figure 1.1 Computer Aided Inspection & Planning within Computer Integrated Manufacturing [1] 2

Figure 2.1 Strategic and Tactical inspection planning tasks 7

Figure 2.2 Example of tolerancing information on a 2D drawing 8

Figure 2.3 Example of tolerancing information CAD model 8

Figure 2.4 Example of uniform sampling points distribution on measuring a plane 13

Figure 3.1 Relationships among data, information and knowledge concepts [121,122] 29

Figure 3.2 Example of an XML based log file [131] 31

Figure 3.3 IDEF0 and schematics of its functional components [145] 34

Figure 3.4 Example of IDEF0 representation of machining process planning [146] 35

Figure 3.5 Example of DRed diagram for a generic problem diagnosing task [147] 35

Figure 3.6 PSL and plain English syntax instructions for a VR based cable harness assembly planning task [134] 36

Figure 3.7 Example of an ontology model in the form of flow chart for sampling points 37

Figure 3.8 Therblig symbols and definitions [142] 37

Figure 3.9 Example of a Therbligs sequence for a cable assembly drag and drop task [142]. 38

Figure 3.10 Example of an IDEF0 diagram in inspection planning[149] 38

Figure 3.11 Example of IDEF extended ontology model for inspection planning tasks [154,155] 40

Figure 4.1 Schematic representation of experimental workflow 43

Figure 4.2 Initial technical framework of IPaCK and the proposed methodology 45

Figure 4.3 Experimental setup and motion capture volume for the current work 45

Figure 4.4 Hand-held Inspection stylus and tablet analogue input devices 46

Figure 4.5 Motion capture operating software 47

Figure 4.6 Procedure to follow in the experimental trial planning session 48

Figure 4.7 Example of the strategic planning sequence representation generated by IPaCK 51

Figure 4.8 Example of the tactical planning motion trajectory generated by IPaCK 51

Figure 4.9 Example of the representation groups of planning activities generated by IPaCK 53

Figure 4.10 Example of the collision free inspection path generated by IPaCK...................... 54

Figure 4.11 Example of a CMM part program generated by IPaCK 55

Figure 4.12 Examples of IDEF0 diagrams of planning strategy for part alignment (top) and true position inspection (bottom) generated by IPaCK 56

Figure 4.13 Example of plain text representation format generated by IPaCK 57

Figure 4.14 Screenshots of annotate video clip with embedded subtitles generated by IPaCK 57

Figure 4.15 Storyboard knowledge representation generated by IPaCK................................ 58

Figure 4.16 Participants per experience grop of knowledge representations evaluation pilot study 59

Figure 4.17 Example section of the questionnaire used in the pilot study............................. 61

Figure 4.18 Pilot study results - Average ratings of representation formats in the aspects: easure of understanding, usefulness, overall performance.. 62

Figure 4.19 Pilot study results – Number of appearances of chosen combinations............... 62

Figure 4.20 Pilot study results - Number of appearances of each format in chosen combinations 63

Figure 4.21 Final technical framework of IPaCK and proposed methodology 65

Figure 4.22 Updated IPaCK's user input devices: Hand-held stylus (left) – tablet analogue (right) 66

Figure 4.23 Graphical user interface and display of logged activity and steps. 67

Figure 4.24 Procedure to follow during the experimental measurement planning session (Appendix A). 68

Figure 4.25 Example of updated tactical planning trajectory representation generated by IPaCK.. 72

Figure 4.26, Example of Strategic planning activity representation generated by IPaCK....... 73

Figure 4.27 Example of Strategic planning activity representation generated by IPaCK – different angle view... 73

Figure 4.28 Example of IDEF0 diagrams representation generated by IPaCK........................ 74

Figure 4.29 Example of subtitles file in contrast with the inspection plan generated by IPaCK 75

Figure 4.30 Example of annotated video clip screenshots generated by IPaCK 76

Figure 4.31 Example of storyboard knowledge representation generated by IPaCK 77

Figure 4.32 Exmaple of th inspection path representation generated by IPaCK 78

Figure 4.33 Example of the plain text instructions representation generated by IPaCK 79

Figure 4.34 Example of the CMM part program generated by IPaCK.................................... 80

Figure 5.1 Part 1 used in experimental trials 82

Figure 5.2 Part 2 used in experimental trials 82

Figure 5.3 Example of the SUS questionnaire used in the usability evaluation of IPaCK........ 83

Figure 5.4 Adjective rating scale for classifying a system's usability and acceptability [185]. 84

Figure 5.5 Overview of design of experiments for the main experimental stage.................. 85

Figure 5.6 IPaCK's usability study – distribution of participants per group of CMM experience 86

Figure 5.7 IPaCK usability study results - Average ratings for novice, experienced and all participants (Set 1) 86

Figure 5.8 IPaCK's usability study results - Average ratings per participants' group of experience (Set 2)... 87

Figure 5.9 Part 1 tolerance specifications and feature indices for trial task 1........................ 90

Figure 5.10 Part 2 tolerance specifications and feature indices for trial task 2...................... 90

Figure 5.11 Strategic planning trajectory for Part 1 91

Figure 5.12 Strategic planning trajectory for Part 2 91

Figure 5.13 Novice planners, Part 1 - Patterns with at least 3 features length and 3 appearances 93

Figure 5.14 Novice planners, Part 1 - Patterns with at least 3 features length and 4 appearances 93

Figure 5.15 Novice planners, Part 1 - Patterns with at least 4 features length and 3 appearances 94

Figure 5.16 Novice planners, Part 1 - Patterns with at least 4 features length and 4 appearances 94

Figure 5.17 Experienced planners, Part 1 - Patterns with at least 3 features length and 3 appearances 94

Figure 5.18 Experienced planners, Part 1 - Patterns with at least 3 features length and 4 appearances 94

Figure 5.19 Experienced planners, Part 1 - Patterns with at least 4 features length and 3 appearances 95

Figure 5.20 Experienced planners, Part 1 - Patterns with at least 4 features length and 4 appearances 95

Figure 5.21 Novice planners, Part 2 - Patterns with at least 3 features length and 3 appearances 97

Figure 5.22 Novice planners, Part 2 - Patterns with at least 4 features length and 3 appearances 97

Figure 5.23 Novice planners, Part 2 - Patterns with at least 3 features length and 4 appearances 98

Figure 5.24 Novice planners, Part 2 - Patterns with at least 4 features length and 4 appearances 98

Figure 5.25 Experienced planners, Part 2 - Patterns with at least 3 features length and 3 appearances (experienced) 99

Figure 5.26 Experienced planners, Part 2 - Patterns with at least 3 features length and 4 appearances (experienced) 99

Figure 5.27 Experienced planners, Part 2 - Patterns with at least 4 features length and 3 appearances (experienced) 99

Figure 5.28 Experienced planners, Part 2 - Patterns with at least 4 features length and 4 appearances (experienced) 99

Figure 5.29 CE Johansson CMM available in the Metrology lab of Heriot-Watt University . 106

Figure 5.30 Modus environment for programming a CMM 106

Figure 6.1 Sample of questionnaire on final knowledge representations evaluation 111

Figure 6.2 Sample of questionnaire on final knowledge representations evaluation (continued from Figure 6.1) 112

Figure 6.3 Ease of understanding average ratings - novice, experienced and all participants (Set 1) 113

Figure 6.4 Usefulness average ratings - novice, experienced and all participants (Set 1) 114

Figure 6.5 Overall performance average ratings - novice, experienced and all participants (Set 1) 115

Figure 6.6 All aspects' median values of novice and experienced groups responses for all the knowledge formats 117

Figure 6.7 Average ratings of all sub-groups responses for inspection plan + tactical planning trajectory combined format 119

Figure 6.8 Median values of all sub-group's responses for the inspection plan + tactical planning trajectory combined format 120

Figure 6.9 Average ratings of all sub-groups responses for inspection plan + strategic planning trajectory format 121

Figure 6.10 Median values of all sub-group's responses for Inspection Plan + Strategic Planning Trajectory 122

Figure 6.11 Average ratings of all sub-groups responses for inspection plan + IDEF0 diagram format 122

Figure 6.12 Median values of all sub-group's responses for inspection plan + IDEF0 diagram combined format 123

Figure 6.13 Average ratings of all sub-groups responses for Annotated Video clip format . 124

Figure 6.14 Median values of all sub-group's responses for Annotated Video-clip 125

Figure 6.15 Average ratings of all sub-groups responses for storyboard format 126

Figure 6.16 Median values of all sub-group's responses for storyboard representation 127

Figure 7.1, Integrated knowledge capture and dissemination cycle followed within the thesis [118] 130

Figure C2. 1 Part programs – Part 1, Plan 7 198

Figure C2. 2 Part programs – Part 2, Plan 8 200

List of Tables

Table 2.1 Minimum points required for substitute geometry construction according to BS [8] 12

Table 2.2 Summary of papers in sampling methodologies 14

Table 2.3 Summary of papers in path generation methodologies 16

Table 3.1 Groups of product design and process knowledge representations [144] 34

Table 4.1 Motion capture log file 48

Table 4.2 Initial inspection plan format generated by IPaCK 50

Table 4.3 IPaCK's user logging output data file 69

Table 4.4 Example of updated inspection plan generated by IPaCK 71

Table 5.1 Classification of participants in IPaCK's usability study in CMM experience groups 85

Table 5.2 IPaCK's usability study - Results of normality tests per group of experience (Set 2) 88

Table 5.3 Statistical testing results for each experience group of participants (Set 2) 88

Table 5.4 Set 1 planning strategies for Part 1 92

Table 5.5 Set 1 planning strategies for Part 2 92

Table 5.6 Detected patterns from all participants' planning strategies for Part 1 96

Table 5.7 Detected patterns with at least four appearances from all participants' planning strategies for Part 2 100

Table 5.8 Patterns considered from experienced strategies and benchmark sequences for Part 1 and Part 2 102

Table 5.9 Comparison of novice and experienced strategies against benchmark for Part 1 103

Table 5.10 Comparison of novice and experienced strategies against benchmark for Part 2 103

Table 5.11 Individual task completion times and average values in each trial test using IPaCK 105

Table 5.12 Task completion times for Part 1 and Part 2 planning using a CMM 106

Table 6.1 Classification of participants based on level of experience (Set 2) 113

Table 6.2 Summary of statistical testing results for the two main groups' responses (Set 1) for all knowledge formats 117

Table 6.3 Statistical testing results (Kruskal-Wallis test) of all sub-groups responses for the inspection plan + tactical planning trajectory combined format 120

Table 6.4 Statistical testing results of all sub-groups responses for the inspection plan + strategic planning trajectory combined format 122

Table 6.5 Statistical testing results of all sub-groups responses for inspection plan + IDEF0 diagram combined format... 123

Table 6.6 Statistical testing results of all sub-groups responses for annotated video clip format 125

Table 6.7 Statistical testing results of all sub-groups responses for annotated storyboard format.. 127

Table E. 1 Raw data for SUS questionnaire – usability study (Trial Novice planners - Set 1) 230

Table E. 2 Raw data for SUS questionnaire – usability study (Online Experienced planners - Set 1)... 231

Table E. 3 Raw data for SUS questionnaire – usability study (Online junior planners - Set 2) 232

Table E. 4 Raw data for SUS questionnaire – usability study (Online Intermediate planners - Set 2)... 232

Table E. 5 Raw data for SUS questionnaire – usability study (Online Senior planners - Set 2) 233

Table E. 6 Raw data for SUS questionnaire – usability study (Online Expert planners - Set 2) 233

Table E. 7 Raw data for Knowledge representations evaluation – Trial Novice planners - Set 1 234

Table E. 8 Raw data for Knowledge representations evaluation – Online Experienced planners - Set 1 235

Table E. 9 Raw data for Knowledge representations evaluation – Online junior planners - Set 2 237

Table E. 10 Raw data for Knowledge representations evaluation – Online intermediate planners - Set 2 238

Table E. 11 Raw data for Knowledge representations evaluation – Online senior planners - Set 2 239

Table E. 12 Raw data for Knowledge representations evaluation – Online expert planners - Set 2 240

Table E. 13 Raw data for Inspection Plan + Tactical Planning Trajectory evaluation – All subgroups - Set 2 241

Table E. 14 Raw data for Inspection Plan + Strategic Planning Trajectory evaluation – All subgroups - Set 2 242

Table E. 15 Raw data for Inspection Plan + IDEF0 diagram evaluation – All subgroups - Set 2 243

Table E. 16 Raw data Annotated Video-clip evaluation – All subgroups - Set 2 244

Table E. 17 Raw data Storyboard evaluation – All subgroups - Set 2........ 245

List of Abbreviations

AFEM	Automatic Features Extraction Module
AI	Artificial Intelligence
AIPM	Automatic Inspection Planning Module
AR	Augmented Reality
ASME	American Society of Mechanical Engineers
BS	British Standards
CAD	Computer Aided Design
CADIP	Computer-Aided Design and Inspection Planning
CAI	Computer Aided Inspection
CAIP	Computer Aided Inspection Planning
CAM	Computer Aided Manufacturing
CATIP	Computer-Aided Tactile Inspection Planning system
CIM	Computer Integrated Manufacturing
CMM	Coordinate Measuring Machine
CMMM	Coordinate Measuring Machine Module
CNC	Computer Numerical Control
DAKA	Design Activity Knowledge Acquisition
DMIS	Dimensional Measuring Interface Standard
DRED	Design Rationale Editor
GA	Genetic Algorithm
GAC	Global Accessibility Cone
GD&T	Geometric Dimensioning and Tolerancing
HAMMS	Haptic, Assembly, Manufacturing and Machining System
IDEF	Integrated Definition
IGES	Initial Graphics Exchange Specification
ISO	International Organization for Standardization
LAC	Local Accessibility Cone
MOKA	Methodology and tools Oriented to Knowledge based engineering Applications
MR	Mixed Reality
NN	Neural Network
NURBS	Non-uniform rational basis spline
OOIP	Object-Oriented Inspection Planner
OOPIPP	Object Oriented Planner for Inspection of Prismatic Parts
PLM	Product Life-Cycle Management
PSL	Process Specification Language
STEP	Standard for the Exchange of Product model data
STEP-NC	Standard for the Exchange of Product model data for Numerical Control
STL	Stereo-Lithography
TCT	Task Completion Time
TSP	Traveling Salesman Problem
VR	Virtual Reality
VRML	Virtual Reality Modelling Language
XML	Extensible Mark-up Language

List of Publications

Anagnostakis, D., Ritchie, J., Lim, T., Sivanathan, A., Dewar, R., Sung, R., Bosche, F. and Carozza, L., 2016. "Knowledge capture in CMM inspection planning: barriers and challenges." *Procedia CIRP*, 52, pp.216-221.

Anagnostakis, D., Ritchie, J., Lim, T., Sung, R. and Dewar, R., 2016. "Towards the automated capturing of CMM inspection strategies." *Bulletin of the Transilvania University of Brasov, Series I: Engineering Sciences*, 9.

Anagnostakis, D., Ritchie, J., Lim, T., Sung, R. and Dewar, R., 2017, August. "A virtual CMM inspection tool for capturing planning strategies." In *ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (pp. V001T02A090-V001T02A090)*. American Society of Mechanical Engineers.

Anagnostakis, D., Ritchie, J., Lim, T., Sung, R. and Dewar, R., 2018. "Automated coordinate measuring machine inspection planning knowledge capture and formalization." *Journal of Computing and Information Science in Engineering*, 18(3), p.031005.

Chapter 1 Introduction

The ever-increasing market competition and customers demand for high quality products have put a great deal of pressure into manufacturers to improve their production processes. Thus, a great need for better product verification and inspection practices has emerged. By enhancing measuring technologies not only can products' quality be assured but also significant feedback can be provided to manufacturing processes upstream so that problems can be identified, and improvements can be achieved, towards enhanced production throughput. This chapter presents the general field of research and motivation of the reported work, the major aims, questions and objectives as well as the structure of the thesis.

1.1 Field of research

Automation in modern manufacturing has been fundamental over the last three decades. Computer Integrated Manufacturing framework (CIM)[1] offers the integration of computer based technologies and automation into the product life-cycle for manufacturing companies to cope with a highly competitive environment and need for continuous improvement. Computing systems and information technologies have been employed to support production under the prism of Computer Aided Manufacturing (CAM) offering a wide set of methods, technologies and developments for supporting flexible and automated manufacturing.

In any well-performing production system, inspection plays a key role [2]. Primarily, it focuses on a product's conformance to initial design intent, specifications, standards and, more importantly, to customer requirements. When a product is characterised as not conforming, inspection feedback can inform upstream stages to identify the causes of non-compliance with the original design. By enhancing inspection knowledge, companies can improve their design and manufacturing processes to reduce the amount of scrap and rework, resulting in higher production rates and money savings. Figure 1 below illustrates this loop, highlighting the connections of Computer Aided Inspection (CAI) to other steps of product's life cycle and thus the requirement for continuous improvement in quality check and verification processes.

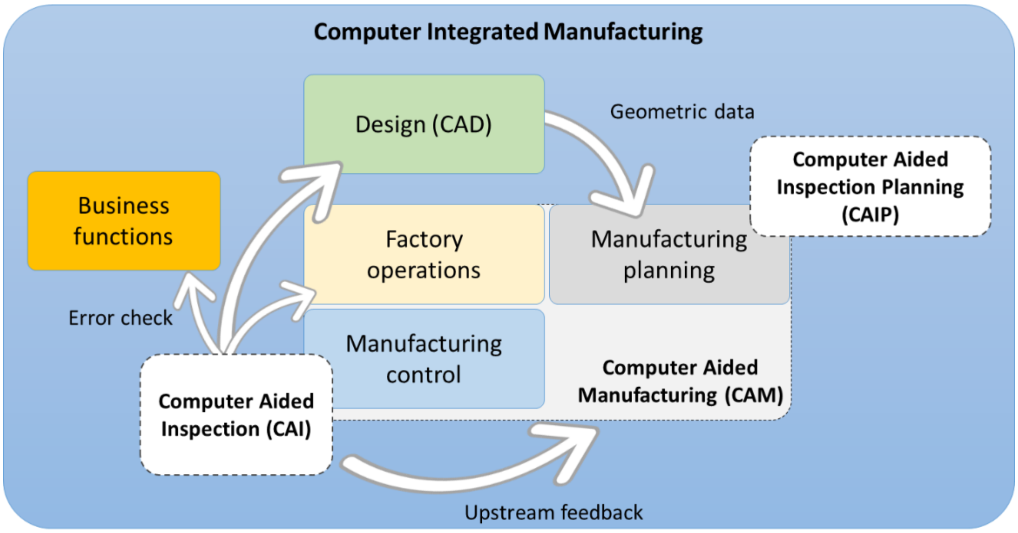


Figure 1.1 Computer Aided Inspection & Planning within Computer Integrated Manufacturing [1]

The automation of inspection process has been implemented by the concept of Computer Aided Inspection (CAI) providing firms with an advanced quality control tool contributing to production of high-quality products. A key technological application of CAI is the Coordinate Measuring Machine (CMM). The preparation stage for programming a CMM is stated as Computer Aided Inspection Planning (CAIP) (Figure 1). The inspection routine is generated using CAIP systems by experienced metrology engineers and CMM programmers, and it is translated into a part program which drives the CMM to perform the dimensional and tolerancing measurements. However, available CAIP packages generally do not provide standardised methods and strategies for creating a measurement plan. Therefore, the effectiveness of such methods and strategies affects repeatability. This is because, ultimately, a part program's quality depends on the CMM programmer's expertise and knowledge.

The inspection results, coming from a strategy include geometrical dimensions, form and positional accuracy and are used as the basis for quality analysis, upstream processes feedback and decision making support throughout the whole product life-cycle [3]. This data is crucial for the product life cycle, affecting all stages from product design to manufacturing processes and quality testing. Therefore, it is necessary to ascertain that the best of knowledge and expertise are engaged in generating an inspection plan and part program. Without standardised planning practices the quality of a plan is questionable leading eventually to uncertain and possibly faulty results of the product verification process.

Moreover, with the absence of formalised knowledge and standardised planning methods, the generation of new inspection plans, can cause bottlenecks, lengthening the product's manufacturing cycle. To address these challenges, it is required to obtain a deeper understanding and insight of how an inspection plan is created, what parameters and considerations are involved, and what the decision making and thinking behind a generated strategy are. By fulfilling this requirement, standardised practices and best rules for inspection planning can by structured as well as training procedures, assuring that products are tested and validated sufficiently as well as proper feedback informs upstream operations. Then, the standardisation of CMM inspection planning strategies will be feasible as well as the development of each new measurement plan required will be faster and the measurement results precise and certain.

1.2 Motivation

In the last three decades, a wide variety of computer aided inspection planning (CAIP) tools and systems were developed to facilitate the preparation of measurement strategies. However, there are still open questions in understanding how a CMM programmer generates and plans an inspection.

Although significant work has been conducted in the past to propose rules, practices and methodologies, the lack of a methodology for capturing and formalising explicit knowledge on how experts prepare and carry out CMM measurements constitutes a bottleneck in the product quality testing stage that has led to a repetitive generation of new inspection plans. Creating CMM part programs is a time-consuming task, even for experienced programmers, and the lack of appropriate knowledge formalization tools prevents engineers from automating or even semi-automating the task, causing the eventual loss of this expertise in the long term. Therefore, a key motivation of this research is to enable and enhance the deeper understanding of thought processes and decision making behind the planning and generation of inspection strategies for CMM measurements.

Another driver for this work results from a key concern regarding knowledge storing and reuse in industry. That is, when experienced personnel are about to leave from a company or retire, then valuable knowledge is lost potentially affecting future product development [4]. To deal with this issue, companies have tried to take some measures in order to mitigate the consequences. For example, in some cases engineers who are going to leave their position were asked to record and document their rationale and expertise in performing a task. However, this is a highly time-consuming activity, especially in the field of CMM inspection. Planning an inspection routine and documenting its rationale could take a huge amount of time and could also lead to the distraction of the planner and potential inefficiencies or severe in the measurement strategy. Thus, an advanced approach and tool are necessary to be developed aiming to quick, automated knowledge capture and formalization so that implicit knowledge and expertise can be extracted, formalised, stored and reused easily in future tasks.

One outcome of this work is to support training procedures of entry level and inexperienced CMM programmers. By making explicit and formalising the knowledge generated by experts, novice engineers in the field will be able to study already developed measurement plans and get familiarised more quickly in planning their own strategies. To achieve this an understanding on how to set-up and manage a successful workflow from capture to distribution will be carried out.

By curating different inspection strategies for the same or similar components, common patterns of activity will be observable. These can potentially lead to identifying rules and best practices resulting from hands-on experience. Then, standardised inspection planning will become available to the CMM planners and programmers for reuse and further improvement.

Finally, this research aims to develop an interface for planning CMM measurements and logging user activity. Such a system will not only allow capturing of a strategy but also provide a risk-free environment where novices and inexperienced users can learn and practice in planning CMM inspections.

1.3 Research hypothesis, questions and objectives

Considering the industrial and research needs, the hypothesis of this work is:

"A novel CMM inspection planning prototype using a combination of user logging and motion tracking tools will enable implicit engineering knowledge to be made explicit and reusable."

1.3.1 Research questions

Considering the motivating drivers of the current study several research questions have been raised:

1. Can human centred inspection planning knowledge be captured non-invasively? **(RQ1)**
2. Can human centred inspection planning knowledge be formalised and represented in multiple outputs? **(RQ2)**
3. Can formalised human centred knowledge be validated by experienced CMM programmers? **(RQ3)**
4. Can patterns of activity be detected using the proposed formalisations? **(RQ4)**
5. Can inspection planning most preferred sequences be structured and used for the evaluation of planning strategies? **(RQ5)**

1.3.2 Research objectives

To address the identified gaps and answer the research questions, a set of objectives has been defined:

- To design and develop a novel prototype for planning and capturing CMM inspection planning strategies by logging user activity. **(RO1)**
- To design knowledge representation structures and build a tool for generating these automatically. **(RO2)**
- To test and evaluate the planning prototype's usability and compare it against a conventional CMM in terms of task completion time (TCT). **(RO3)**
- To test and validate the generated knowledge outputs and representations. **(RO4)**
- To compare planning strategies, detect most common patterns of activity and suggest the most preferred strategic sequences. **(RO5)**
- To evaluate strategic planning approaches using the most preferred sequences as a benchmark. **(RO6)**

1.4 Structure of thesis

CHAPTER 2 explores the state of the art of Computer Aided Inspection Planning techniques and systems. This chapter critically reviews the current techniques and tools in addressing each of the steps of planning a CMM inspection strategy. Moreover, the range of existing automated inspection planning systems is studied, highlighting key limitations with regards to human knowledge capture and integration.

CHAPTER 3 reviews current engineering knowledge capture and formalisation approaches and tools in various engineering tasks. Key research gaps within previous works are described highlighting the needs of the conducted research. Additionally, past scientific paradigms of engineering knowledge capture and representation that influenced the proposed methodology are presented.

CHAPTER 4 outlines the two-stage designed methodology and how this will enable meeting the derived objectives. First, the components of the prototype IPaCK system are presented as well as the logic behind its function with a view to knowledge and human expertise capture. Then the proposed knowledge representations are tested and evaluated through a pilot study. Finally, key updates in the final versions of the prototype system and recommended knowledge formats are described considering the feedback from the pilot study.

CHAPTER 5 presents the first part of the main experimental study (stage 1) and results with regards to IPaCK's usability evaluation by novice and experienced planners. Then a comparison of planning strategies between the two groups of participants is conducted and a methodical approach for structuring the most preferred sequences reusing the captured strategies is suggested. In addition, a practical time comparison of the IPaCK system against a real CMM is performed with regards to part programming.

CHAPTER 6 expounds the results from the second stage of the main experimentation; the knowledge representation formats evaluation study. A statistical analysis performed highlights similarities and differences between novice and experienced planners as well as among the different subgroups depending on their level of exposure in CMM inspection planning.

CHAPTER 7 discusses the main findings and comments how the results serve meeting the defined objectives. Moreover, it is shown how the key outcomes answer the research questions and eventually address the identified knowledge gaps in the existing literature.

CHAPTER 8 concludes with the confirmation of research hypothesis and key contributions to the scientific community and associated engineering areas. Critical limitations of the carried-out research are reported. In addition, directions for future work and development are suggested, illustrating the potential extends and scalability of the technological solutions presented in the thesis.

Chapter 2 CAIP review

2.1 Introduction

Computer Aided Inspection planning (CAIP) has evolved considerably as a support to metrology and quality engineers in planning component measurement using a coordinate measuring machine (CMM). The inspection planning process can be divided into two levels: Strategic and tactical as illustrated in Figure 2.1 [5]. Strategic level tasks include component setup, accessibility analysis and probe and orientation selection while tactical level planning typically concerns distribution and quantity of measurement points and path generation. A similar classification in global and local inspection planning tasks was proposed by Cho et al. [6]

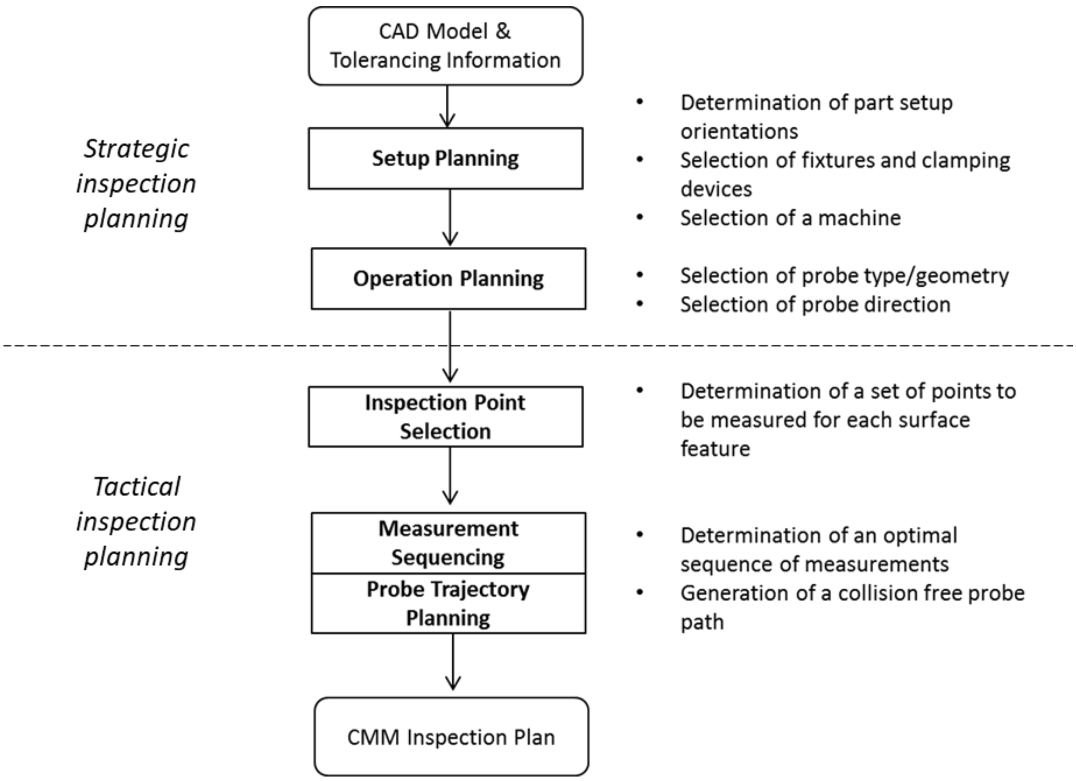


Figure 2.1 Strategic and Tactical inspection planning tasks

2.2 Inspection planning tasks

Prior to planning a measurement strategy for a component, the first step is to study and review the design drawing. Dimensional and tolerancing annotations called Geometric Dimensioning and Tolerancing (GD&T) are stated on a drawing; these provide inspection engineers with the necessary information for preparing a measurement plan. This information is documented by different standards institutions such as International Organization for Standardization (ISO) [7], British Standards (BS) [8] , American Society of Mechanical Engineers

(ASME) [9]. These standards provide a guide to metrology and quality engineers in order to test a product's quality. This critical stage affects the whole product lifecycle and determines if the component is characterised as conforming or not. In the latter case either rework will be required, or the component will be scrapped leading to significant time and money losses.

Every production drawing, either paper-printed (Figure 2.2) or in the electronic format of a CAD model (Figure 2.3), includes GD&T information, indicating which features of the component require inspection. These features typically are critical in the function of the component and usually have small tolerance dimensions. Depending on the purpose of measurement, a component might be tested for acceptance or not, by inspecting only those critical features.

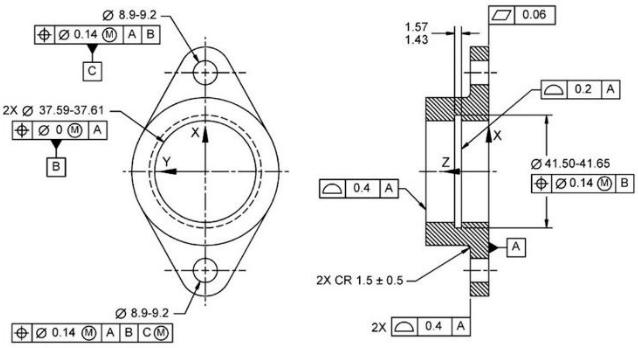


Figure 2.2 Example of tolerancing information on a 2D drawing

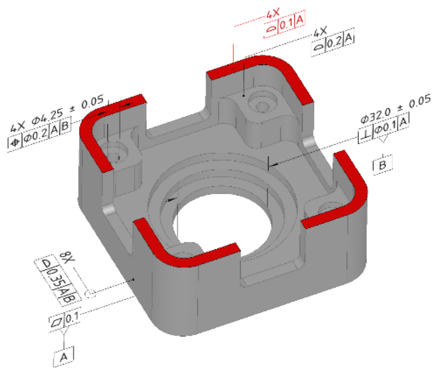


Figure 2.3 Example of tolerancing information CAD model

An inspection engineer, by studying the GD&T information will have to make a series of decisions related to part setup and orientation, inspection stylus selection, probe head orientations, order and group of features to inspect, size and distribution of point sets for each geometrical feature for creating an efficient measurement plan.

2.2.1 Part setup and orientation

Setting up and orienting a part on CMM table is the first step to achieving appropriate accessibility of features and repeatable inspection planning. As a generic rule, a single setup should be used for measuring a component as changing location and orientation will cause significant time delays [10]. When changes of part orientation occur, further errors may be introduced resulting in lower accuracy of results due to misalignments. However, there might be cases where reorienting a part is necessary, establishing thus a higher level of accessibility and finally improving the accuracy compared to using a complicated stylus configuration for accessing all required geometrical features in a single part orientation.

Several tools have been proposed throughout the literature for selecting proper part setup and orientation. Corrigall and Bell [11] developed a tool which produces a list with all possible part orientations and the number of accessible toleranced features on each face. This work cites the importance of selecting suitable part and probe orientations in order to reduce the setup time on a CMM. The assumption is that any feature of the component can be accessed in at least one of the six approach directions along the component's axis system. The orientation with the greatest number of accessible entities is selected and the process is repeated until all the features have been allocated. This assumption constitutes a limitation of the approach, as there might be features that are not accessible by any approach direction.

Ziemian and Medeiros [12] addresses the challenges of part setup perceived as a time consuming and costly process. They introduced a technique using static equilibriums to calculate work piece stable orientations. A minimum required percentage of accessibility for each inspection item was input by the user, considering the type of tolerance and function of the part. If the value calculated by the algorithm was lower than the minimum set, then the region was characterised as inaccessible in this orientation. If no single setup satisfies the requirements, then the minimum number of work piece orientations necessary for inspection is calculated, based on the accessibility analysis results and the previously calculated stable part orientations.

Kweon and Medeiros [5] methodology for determining part orientations for CMM inspection used visibility maps (VMaps) based on Gaussian Maps to calculate accessible directions for inspecting a geometrical feature. According to the authors, defining a set of part orientations so that all required features are accessible is an important step within a planning strategy necessitating significant efforts. Their heuristic algorithm grouped features accessible in the same direction together and a respective part orientation was determined for each cluster. The final output is a list of tolerances to be inspected in each orientation, without however suggesting an optimal sequence for these.

Beg and Shunmugam [13] implemented fuzzy logic to select stable part orientations and inspection probe orientations. Part orientation criteria considered were base surface should have a maximum contact surface area and minimum number of features to inspect while not having any protrusions. Probe orientation criteria were probe orientation for inspecting datum face and target feature, probe orientation for inspecting a datum face and probe orientation for accessing a face not accessible by any other probe orientation. Each of the above criteria are assigned a weight for which the fuzzy logic selected the optimal part orientation and created a sequencing order for probe orientations. Their use of criteria tries to replicate the thought process of a human expert planner; however, it was not explicitly mentioned how the utilised rules to optimise part's and probe's orientations and implied knowledge were extracted.

Within this section, part setup and orientation have been identified as key steps within a planning strategy. This work will consider this in the development of the required tools and will aim to capture these key elements as well as formalise and represent any associated user activity within meaningful and accurate knowledge formats.

2.2.2 Accessibility analysis

As can be seen from the previous section there is a strong correlation between a component's setup and inspection probe orientations. Accessibility analysis is the step of planning an inspection where a CMM operator has to decide which probe angles are necessary for a particular part orientation in order to inspect a feature or a group of them. This requirement has led to the development of a series of accessibility analysis techniques.

Spyridi and Requicha [14] introduced the novel concept of local and global accessibility cones (LAC and GAC) to characterize how accessible a feature is. The former considers obstacles close to the testing area while the latter takes the entire component into account. A clustering algorithm then creates the set of minimum probe orientations for inspecting all the required features. Major limitations are the modelling of a probe as a half-line, considering only straight configurations as well as features of low geometric complexity.

Based on the previous concept Lim and Menq [15] built a heuristics algorithm for optimal angle search considering all the possible combinations of probe orientations to approach the required features. Criteria employed in the algorithm were the number of points which the probe could inspect in one orientation, grouping of inspection points and number of points per group. Additional rules for modifying and optimising the solution were introduced in the algorithm, by considering replacement of two or more angles with another one. A key gap in this research is that no explanation was provided on how the criteria and rules were structured and what the related sources of knowledge were.

Ziemian and Medeiros [16] proposed a feature accessibility algorithm to generate an collision-free sequence of probe orientations. This methodology takes into account the global accessibility of inspection points and a volumetric approximation of probing system: probe stylus as a vector, touch probe as a cylinder and probe head – mounting arm as a rectangular block. The algorithm calculates a percentage of accessibility for a feature and determines a set of feasible probe orientations. The current system does not provide any means of optimal probe orientations and focuses mainly in addressing the issue of features accessibility.

Spitz et al. [17] suggested a tool for accessibility analysis for inspection of mechanical components based on the theory of global and local accessibility cones. As reported by the authors, due to high complexity of spatial and geometrical analyses, approximations were made such as: consideration of only straight probes, abstraction of a CMM body structure as a ram-probe assembly modelled as semi-finite lines and ignoring any possible collision with the component and limited sampling points on features' surfaces. Considering these, it is apparent that the challenges of accessibility on a component are difficult to overcome and require high complexity algorithms. That is, human reasoning and decision making cannot be replicated easily for this scope.

Wu et al. [18] overcame the limitation of modelling a probe as an infinite half-line. They considered the influence of a probe's actual length, volume and configuration in their accessibility analysis for features such as slots and holes. Using the projection lengths of probe stylus and body improved accessibility analysis and avoided the inaccuracies caused by previously suggested over-simplified models of a probing system.

Similarly to previous studies, Alvarez et al. [19] approached accessibility analysis in two stages: locally and globally. The novel contribution of this work were the ray-tracing algorithms developed to identify intersections between the tessellated component model and the probe model considering the actual probing system's dimensions and volume.

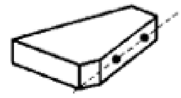
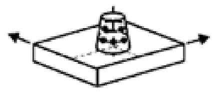
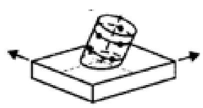
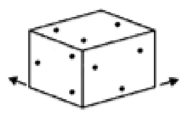
Accessibility was analysed by Wang et al. [20] using a haptic virtual environment. Their collision response analysis was able to distinguish a contact as a collision or measurement by using different force feedback models. This methodology is extended further in [21] including STL representation of the part and CMM probe unit and resulting in a more sophisticated accessibility analysis. Although these works provided a close-to-reality CMM planning task, they lacked storing or documenting the conducted plan and validation.

Accessibility analysis mainly refers to the features and how these can be accessed using the inspection tools. In terms of this key aspect of inspection planning, the research will focus on capturing and representing how each feature and respective inspection points are taken in terms of approach and retract directions and suitably recorded for representation in the various knowledge formats.

2.2.3 *Sampling strategy*

The core of inspection planning is the selection of a proper size and distribution of measurement points. The point set will form the actual shape of a feature or the whole geometry of a workpiece which will be compared against its nominal values. The measurement points selection must be made in a way that the component's digital equivalent will be as close as possible to the real geometry. Standards and practical guides [22] [23] have made some recommendations for the minimum amount of points to reconstruct the part digitally. Table 2.1 shows the minimum number of points recommended by British Standards [8].

Table 2.1 Minimum points required for substitute geometry construction according to BS [8]

Geometric feature	Minimum points	Schematic representation	Geometric feature	Minimum points	Schematic representation
Straight line	2		Cone	6	
Plane	3		Ellipse	4	
Circle	4		Cylinder	5	
Sphere	5		Cube	6	

Probing a feature using as many points as possible could lead to a representation very close to the actual geometry, however this would add significantly costs in terms of time. Therefore, a balance should be maintained between the number of measurement points and the total time for inspection. To deal with this issue, a range of different methodologies and techniques have been proposed towards optimising the amount of probing points and proper distribution.

A study [24] on the measurement of surface roughness and flatness, compared three sampling schemes: uniform, Hammersley and Halton-Zaremba sequences, taking into account the number of measurement points, their distribution and the resulting error. Uniform sampling requires dividing a plane into equal rectangular blocks and taking a random point in each one (Figure 2.4).

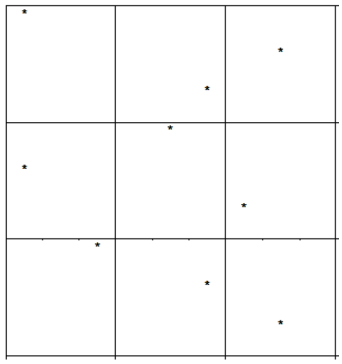


Figure 2.4 Example of uniform sampling points distribution on measuring a plane

The comparison was made for three different sampling sizes: 16, 64, and 256. The results from the comparison have shown that Hammersley was the best method with the least error for all the sample sizes compared to the other sequences; although close enough was Halton-Zaremba with 7% more error while uniform was the worst performing approach.

A study [25] on measuring circular features focuses on deviations of circularity and true position using a calibrated ring gauge with known dimensions, tolerances and maximum allowed error. The results showed that as the number of points increased, the diameter deviations were smaller tending to a fixed value. Although the results are of very high confidence, an influential factor on the measurements is the kinematics of the probing system which may affect the measurement error.

Hammersley sequence was employed in [26] and compared against the uniform and random sampling approaches for measuring the form errors in cylindrical, conical and hemispherical features. Based on the results, modified Hammersley method needs about four times fewer sampling points than the other two patterns. Moreover, the proposed approach appears to be more accurate when it is compared with uniform and random sampling under the same number of measurement points.

Kim and Raman [27] tested Hammersley, Halton-Zaremba, aligned systematic sampling and systematic random sampling to measure the flatness of 30 plates using different sample sizes. In terms of point distribution and total mean accuracy of flatness, Halton-Zaremba sequence sampling method was the most accurate. From sample size viewpoint, the systematic random sampling showed the highest accuracy at the sample size of 32 and 64.

A summary of all reviewed research papers is provided in Table 2.2 including the type of characteristic as studied by the authors and what techniques have been tested in the scope of sampling process. The variety of approaches dealing with the selection and generation of distribution and size of probing point sets, reveals the significance of this step in planning a measurement strategy. Also, the study reveals research mainly focused on the tactical level of a measurement strategy without considering the strategic planning aspects. All the methods reported relied on rules based on previously generated knowledge and expertise. However, none of the research studied report how this knowledge was extracted and processed to acquire the reported practices and rules. Also, the original sources of knowledge are not known. This thesis will therefore address the identified knowledge gaps.

Table 2.2 Summary of papers in sampling methodologies

Paper	***Characteristic***	***Sampling method tested***	***Knowledge/rule-based method***	***Source of knowledge***	***Knowledge capture***
[28]	*Profile, form*	*Iterative-adaptive algorithm*	✓	✗	✗
[29]		*Heuristic algorithms (Equal-parametric, Patch Size Based, Curvature Based, Hybrid)*	✓	✗	✗
[30]		*Hybrid/curvature based*	✓	✗	✗
[31]		*Hammersley-Gaussian curvature*	✓	✗	✗
[32]		*Adaptive/heuristic algorithms*	✓	✗	✗
[33]		*Adaptive algorithm*	✓	✗	✗
[34]		*Hybrid-Particle Swarm Optimization*	✓	✗	✗
[35]		*Hammersley-machining error model*	✓	✗	✗
[36]	*Flatness*	*Predictive grey theory*	✓	✗	✗
[37]		*Random uniform*	✓	✗	✗
[38]		*Hammersley*	✓	✗	✗
[39]		*Prussian blue technique*	✓	✗	✗
[40]	*Flatness, straightness*	*Regression model*	✓	✗	✗
[41]		*Iterative search-based sampling (region-elimination, tabular search, hybrid of the two)*	✓	✗	✗
[42]		*Search based heuristics*	✓	✗	✗
[43]	*Circularity, cylindricity*	*Statistical/iterative*	✓	✗	✗
[44]		*Uniform with random starting point*	✓	✗	✗
[45]		*Regression model*	✓	✗	✗
[46]		*Circumferential, helix, axis parallel-across height rays*	✓	✗	✗
[47]		*Iterative-adaptive algorithm*	✓	✗	✗
[48]	*Any*	*Iterative method*	✓	✗	✗
[49]		*Curvature dependent algorithm*	✓	✗	✗

As highlighted through this section, sample size and points distribution both play key roles in a measurement planning strategy. Thus, the consideration of capturing these elements will be central to the design and development of a knowledge capture methodology. In this vein, the tools will log user activity and represent the embedded knowledge so that it the inspection points and their distribution across the surfaces involved in the planning strategy are clear.

2.2.4 Inspection path planning

The last step of planning a measurement is the generation of an efficient and collision-free path for inspecting all the required features of a component. An extended variety of algorithms and techniques have been suggested throughout the literature, aiming to calculate optimal solutions for dealing with inspection path generation.

According to Lim and Menq [15] an inspection path is created based on the results from accessibility analysis module by a heuristics algorithm. The novelty added by this research is that each probing step of the total path is divided into: approach-retract point, approach-retract path and inspection point; therefore, possible collisions are checked at every step. By introducing pre-approach and post-retract positions, the probe is free to rotate and move safely depending on the previous or next operation.

Yau and Menq [50] proposed one of the first tools for path planning simulation in a computerised environment capable of detecting collisions between a part and the probing system. The path is consisted of sub-segments between two probing points. If collisions are detected, the path or probe orientation is modified by a heuristic algorithm. The advantage of this work was the run-time modification of the planned measurement path when a collision of probe’s tip and stylus or CMM column is detected. A significant omission concerns where and how knowledge was embedded in the heuristic algorithm was acquired.

Qu et al. [51] suggested the use of Genetic Algorithms (GA) to generate an optimal inspection path. Based on the Traveling Salesperson Problem, the example presented was to measure a cylindrical feature. They achieved a reduction of the total measuring time by one third compared to traditional operation of a CMM. While the GA obtained a shortest path, GA has weak local optimisation and low robustness in the effort to reach the optimal global path [52]. However, the main critique here was that the proof-of-concept was on a rather simplistic feature.

Table 2.3 summarizes the path planning techniques and part/geometry inspected in the reviewed studies. Common aim of these works was the generation of an optimal collision-free inspection path by minimising the travelling distance of the probing system. In this scope, the main methods used are heuristic algorithms, Ant Colony Optimisation, Genetic algorithms.

Path generation is a complex process which requires consideration of many parameters such as the geometry of the test-piece and accessibility to each required feature and neighbour-features. That is, the strategic thinking of planning the whole measurement path. The reviewed works employed a series of algorithms which imply utilisation of knowledge and strategic thinking expressed in the form of rules or weights for statistical and probabilistic algorithms. However, no descriptions were provided on how such knowledge was captured and formalised or the form of rules or what its sources were. With such an extensive use of knowledge related systems and techniques, it is apparent there is a need for developing a methodology and suitable tools for capturing and documenting human expertise and decision making in inspection planning. This thesis aims to make a major contribution that will facilitate the rapid development and evolution of future knowledge-based systems.

Table 2.3 Summary of papers in path generation methodologies

Paper	***Method***	***Work piece geometry***	***Knowledge/rule -based method***	***Source of knowledge***	***Knowledge capture***
[15]	Heuristic algorithm	Prismatic with slots, pocket, holes, free form	✓	✗	✗
[48]		Prismatic with slots, pocket, holes	✓	✗	✗
[50]		Free-form, complex features	✓	✗	✗
[53]		Complex with free-form features	✓	✗	✗
[54]		Any geometry	✓	✗	✗
[55]		Any geometry	✓	✗	✗
[56]		Any geometry	✓	✗	✗
[57]		Prismatic, spherical, conical	✓	✗	✗
[52]	Ant Colony Optimisation algorithm	Any geometry	✓	✗	✗
[58]		Any geometry	✓	✗	✗
[59]		Any geometry	✓	✗	✗
[60]		Any geometry	✓	✗	✗
[51]	Genetic algorithm	Prismatic, free form	✓	✗	✗
[61]		Any geometry	✓	✗	✗
[62]		Multi-component	✓	✗	✗

[63]	Neural network	Multi-component	✓	✗	✗
[64]	Ray-tracing algorithm	Prismatic	✓	✗	✗
[65]	NURBS-based algorithm	Free-form surfaces	✓	✗	✗
[66]	B-rep & ray tracing algorithm	Prismatic with slots	✓	✗	✗
[67]	TSP algorithm	Any geometry	✓	✗	✗
[68]	NURBS parametric algorithm	Free-form, curved features	✓	✗	✗
[69]	Triangulation-bounding box algorithm	Complex, curved features	✓	✗	✗

The final core element of an inspection planning strategy, as dictated by the current review sections, is path planning. That is, the movement of the inspection tool from point-to-point and from a feature's last point to next feature's first point. When combined in order, these ultimately form the final inspection planning path and are key data are required when logging and capturing user planning activity and representing it in the various knowledge formats.

2.3 Computer Aided Inspection Planning systems

A variety of techniques reviewed in the previous sections has been employed to address and support engineers focusing only on specific aspects of a CMM inspection planning task, i.e. probe configuration and accessibility analysis, part setup and orientation, sampling and path generation. An extended range of Computer Aided Inspection Planning (CAIP) systems have been proposed for generating a complete measurement strategy and part program covering all the required key steps.

ElMaraghy and ElMaraghy [70] reviewed CAIP and point out that intelligent inspection planning systems should be extendable and adaptable, providing suitable user interfaces as a support decision making tool to CMM inspection planners. As it will become clearer from the literature reviewed in the following sections, this is still an issue with limitations with regard to the capture and formalisation of expert knowledge and rationale.

Li and Gu reviewed [71] inspection planning techniques for free-form geometries dividing methods in contact and non-contact inspection. Also, they identified differences when planning inspections for tolerances with datums and tolerances without a datum. Thus, the order of probing each feature was different, depending on what was required. Hence, a key parameter influencing strategic planning was detected.

Zhao et al. [72] classified systems in tolerance-driven and geometry-based CAIP systems. The former involves a selection process of features with the tighter tolerances by engineers, while the latter requires inspection of the entire component and comparison of the results against the design model; a process that takes a lot of time to complete. Furthermore, the authors highlighted the significance of the inspection results as a feedback to inform and update the manufacturing stage.

Stojadinovic and Majstorovic [73] reviewed an extended variety of CAIP tools developed to date, from the scope of intelligent systems and solutions for planning inspections on prismatic parts. Key industrial issue highlighted through this work is the need for reducing the time required to plan an inspection for a component as this affects the whole manufacturing cycle.

The following sections critique existing CAIP systems depending on the technology employed with regard to CMM inspection planning knowledge elicitation and reuse as suggested by Anagnostakis et al. [74]. These highlight how expert knowledge and decision making are formalised, processed and embedded in such systems, as well as possible knowledge capture techniques present in this area of the literature. The following sections are structured as follows:

- Expert systems
    - Knowledge based systems
    - Neural Networks & Genetic Algorithms
    - Other expert systems
- Other CAIP systems

2.3.1 Expert systems

An expert or intelligent system is a computer program capable of utilising domain specific knowledge to solve a problem [75]. In the field of Computer Aided Inspection Planning, many systems employ Artificial Intelligence (AI) technologies to support planning for CMM inspection such as knowledge-based systems, neural networks, fuzzy theory techniques and others.

2.3.1.1 Knowledge based CAIP systems

Knowledge-based systems are usually algorithms which utilise knowledge from past recorded cases in the form of “if-then” rules to solve challenging tasks and problems with heavy computational load. Considering that inspection planning for CMMs is a complex process, a variety of knowledge-based systems has been developed.

ElMaraghy and Gu [76] developed one of the first expert inspection planning systems implemented in PROLOG. The novelty was its feature clustering and sequencing based on datums. More importantly the system attempted to capture and follow the rationale of human inspection planners using expert rules; however, there is no description of a capturing method for the knowledge associated with these.

In **[81, 82]** a knowledge-based Object-Oriented Inspection Planner (OOIP) integrated with a STEP-based product modelling environment is presented, capable of feature selection for manual and machine inspection, accessibility analysis, selection of probe and probing points and total path inspection generation. Each module operates using a separate knowledge base and rules. However, it is not explicitly reported how utilised knowledge was captured and where it comes from to optimise plans.

Gu [79] suggested an expert inspection planning system consisting of a feature database and a planning knowledge base. The system relies on a data list and retrieves geometrical information related to each tolerance and feature to inspect e.g. dimension, tolerance, location, orientation after which a heuristic algorithm generates the planning strategy. The knowledge is structured as “if-then” rules. This work lacks an automated method or approach for capturing and introducing any form of new knowledge and rules.

CADIP [80] is a knowledge based system with three main components: design by feature, feature recognition and inspection planning. The inspection planning module consists of a listing with knowledge related to the hierarchy and geometrical attributes of features, directions and locations, probe approach directions and other inspection planning parameters. Knowledge representation is in the form of a subclass-superclass structure of geometrical features and measurement requirements relationships. Process Capability indices (PCIs) characterise and assign a value to features based on their upper and lower tolerance limits. Ketan et al. [81] also developed a knowledge based system using PCIs to determine the critical functional features required to inspect and create a proper inspection strategy. The knowledge capturing process used to formalise these rules is not explained, while the sources of this knowledge are not discussed.

An expert system for CMM inspection planning is produced by Pei and Ma [82]. Inspection elements are divided into basic categories associated with geometric and dimensional tolerances. For each element the knowledge base, containing math fitting and tolerance evaluation algorithms, provides alternative inspection sequences. The inference engine uses rules in the format of “if-then” and according to inspection requirements selects the proper sequence. In this research the sources of knowledge and how it is captured are not described; neither how this was introduced in the knowledge base.

Nasr [83] proposed a CAD integrated inspection planning system structured in three modules: Automatic Features Extraction Module (AFEM), Automatic Inspection Planning Module (AIPM), Coordinate Measuring Machine Module (CMMM). The AIPM develops an inspection plan based on the inspection knowledge and rules stored in the system. No explicit description was provided on how the utilised knowledge was extracted or where it came from to build and structure the proposed knowledge-based system.

Messina et al. [84] described a knowledge based inspection system capable of analysing manufacturing features (slots, holes, etc.), suggesting part orientations and measuring features. Although the authors have identified and utilised specific types of necessary inspection planning knowledge such as procedural, in situ and externally received (or a-priori), they have not explained how knowledge is captured and classified.

Stojadinovic et al. [85,86] developed an intelligent approach for planning CMM inspection using CMMs for prismatic parts. The system integrates a knowledge base which extracts and utilises information from the IGES CAD model of the component. Then a set of rule-based algorithms creates the measurement point set distribution and size, determines proper probe orientations and finally produces a collision free inspection path. How the knowledge acquired was elicited and what were the associated sources are not defined.

The current state of the art as it stands still shows the lack of a methodology for capturing knowledge and decision making in CMM inspection planning tasks.

2.3.1.2 Neural Networks (NN) and Genetic Algorithms (GA) in CAIP systems

Neural Networks is another technology employed for dealing with complex problem solving in engineering applications such CMM inspection planning. In inspection planning NN have been used in order to tackle some of the key stages of a strategy as sampling point set size [87], distribution and path generation [63],probe and part orientations selection and feature sequence optimisation to generate an efficient plan [88]. Kamrani et al. [89] proposed a CAD-integrated tool for generating inspection plans. The core of the system is a set of neural networks for clustering features considering the probe's orientation and feature's accessibility. Several rules are proposed however it is not described how associated knowledge was captured and formalised.

Since NNs work mainly by learning from and processing previous data, central to their build and development is to capture existing knowledge and formalise it in the form of rules and statistical weights for the future decisions to make. However, there is no previous work regarding any method for extracting knowledge and input it in a NN-based inspection planning system. Moreover, previous research has been focused on minimising the probe's travelling distance, neglecting strategic thinking and planning constraints for example tolerances that require specific datum features involved in inspection of other tolerances. Such considerations are difficult to capture and integrate in an expert system as it is required to interview or observe and shadow an expert while planning a strategy; a time-consuming and expensive process.

Commonly used to solve optimisation problems, in inspection planning GA have been used mostly for generating efficient inspection paths [51]. Lu et al. [62] proposed a GA to solve the problem of multi-component inspection path planning. Kovacic and Brezocnik [90] presented a GA based system taking into account the part geometry, the probing system and measuring machine attributes. Main drawback of GA is the slow searching of optimal solution as well as the risk of premature convergence leading to a not optimised solution. More importantly, the basic function of a GA is to search for the optimal solution based on an initial plan that is introduced manually. How existing knowledge has been captured and processed to structure a GA and integrate its associated parameters were not reported.

2.3.1.3 Other Expert CAIP systems

Hybrid neuro-fuzzy approaches have been proposed in [6] [91] [92] for addressing key steps of inspection planning or generating a complete measurement strategy. A fuzzy inference mechanism with rules and functions utilises past data and structured knowledge. However, in these works it is not known how previous knowledge was captured and embedded in the presented systems.

The Computer-Aided Tactile Inspection Planning system (CATIP) [93] offers efficient inspection plan by minimising probe changes and reorientations, features clustering and optimised sequencing of measurement points. Although collision-free paths are generated automatically, the user may select the inspection points manually or modify the generated plan. The developed tools, as stated by the authors, arose from expert knowledge of inspection planners among other sources. The capturing process of the involved knowledge is not explicitly described.

Zhang et al. [94] proposed an intelligent inspection planner. By extracting functional and tolerancing information from a CAD model, the measuring plan module produces efficient inspection sequences. According to the authors various data and metrology knowledge provided by CMM experts are processed and integrated in the module. They do not report how these were captured and formalised to be embedded in their system.

Zhou et al. [95] designed and implemented an automated inspection planning system for parts with freeform features using the CAD model. A search-based planning algorithm generates an optimal sampling point set by using curvature of features and geometric information from the CAD file. Then the sampling points are transformed, and the final inspection path is generated. No reference to a knowledge capture methodology or how utilised rules were structured is provided.

Hussien et al.'s [96] automatic inspection planning system incorporates a rule based feature recognition module, sampling strategy module, accessibility analysis module and a probe orientations clustering module. No use of previous strategic inspection planning knowledge is reported. Thus, it is not clear how the rules utilised were formed and the rationale behind the generated plans acquired.

A computer aided inspection model by Stojadinovic et al. [97] employed a Hammersly based algorithm for sampling size and distribution for creating a collision free measurement path. Although it is mentioned the integration of a digital model for transferring geometrical and tolerancing information, strategic thinking is not involved on generating a features probing sequence. The system is limited to calculate the shortest inspection path.

Polini and Moroni [98] presented a complete frame for a computer aided inspection planning system using the geometric model of a work-piece and rule-based optimisation algorithms. In this work the authors stated that "analysis of the human based inspection process was carried out to acquire domain knowledge and integrate it in the developed system." However, the methodology applied to achieve this is not outlined. Moreover, no testing and validation of the system and its generated outputs is reported.

Khan et al. [99] demonstrated an integrated object oriented system for process planning, fixture design and inspection planning of prismatic parts. The inspection planning module can determine part set-up, probe path creation, and generate an entire inspection plan. The novelty of this system is the integration of inspection planning and information flow from the process planning and fixture design modules downstream. They do not discuss how the rules in the inspection planning sub-system were captured, developed and embedded in the proposed solution.

Mohib et al. [100] developed a hybrid inspection planner combining a knowledge base and optimisation techniques. Knowledge codified as rules selected the proper inspection probe configuration. Geometric data extracted from the STEP file of the testing component are input and analysed for inspection planning and sequencing optimisation module. The authors stated that they analysed inspection plans created by human planners and specific inspection procedures were detected so as a list of knowledge rules and adjustable parameters is generated. However, it is not explicitly described how these plans were analysed and compared to produce the resulted rules nor they mention any methods to capture the human expert knowledge embedded in the proposed system.

A CAD-integrated system proposed by Fan and Leu [101] considers rules based on the minimum number of required inspection points and their even distribution for probing basic geometrical features. Additionally, a module for setting measuring points manually is available. As the authors state, any CMM planner might end up with a different point-set size and distribution within their strategy; a critical decision which depends on their experiences. No module was included in this approach to capture the decision making of the process or the selection of inspection points and strategy.

Zhang et al. [102] suggested a prototype for CMM inspection planning which consists of five modules: tolerancing information input, accessibility analysis, features clustering, path generation and process simulation. While the user selects the probing system, collision-free probe orientations are calculated using a Gauss mapping algorithm. Finally, a knowledge base supports the clustering module. No description was provided on how knowledge was captured and used in structuring the knowledge base.

A common limitation of the above body of work is a lack of a methodology for capturing CMM inspection planning expertise and knowledge and a standardised approach for formalising and structuring required inspection rules. Therefore, the need for a robust knowledge capture and formalisation technique is a key issue in the development of an expert inspection planning system.

2.3.2 Other CAIP systems

Virtual Reality technologies have been successfully used in product design and manufacture and are now seeing applications in product quality verification processes to support and improve further measurement techniques. Stouffer and Horst [103] used the Virtual Reality Modelling Language (VRML) to develop a web-based environment and interface for simulating a CMM in real time while interacting with this using a real world controller; this is similar mode of operation to most commercial CAIP packages.

Calonego et al. [104] implemented a virtual environment to teach CMM use and operating procedures; it can be controlled using different user interfaces, textual, graphical or optical tracking devices. Zhao and Peng's [105] VR-based CMM for training purposes allows users to navigate within the environment and control the virtual machine as in the real world by using 3D digital display of the component. Hu et al. [106] developed a virtual CMM for testing and simulation of CMM operations. Using this system, the user can plan a measurement strategy and evaluate the results without using a real machine. An "augmented virtuality" integrated CMM was proposed by Wang et al. [107], which is operated either by a marker-less gesture recognition algorithm or using two joysticks.

Chen et al. [108–110] implemented a novel CMM inspection planning environment with the use of haptic modelling. This replicates the operation of a real CMM using a hand-held stylus adding the haptic perception as well. In this way the operator can feel the collision between the part and the probing system digital equivalent. This force feedback combined with a visual interface allows a CMM user to create collision free inspection paths easily and quickly.

The proposed systems highlighted previously do not provide any means of user activity logging and neither a knowledge elicitation methodology nor the generation of formalised outputs that illustrate the planning strategy performed. Moreover, there is no testing or feedback from inspection planners of any kind to evaluate and validate system functionality.

2.3.3 Commercial CAIP packages

Apart from the academic research, various commercially software packages are available for creating CMM measurement plans and part programs. Some of the most popular packages are reviewed below.

Zeiss Calypso [111] provides another solution for measuring standard geometries. The required characteristics are necessary input by a CMM programmer for generating the inspection plan. A lot of automation is also offered with regards to travel path and generation of inspection plans using product and manufacturing information from a CAD model. All geometric features associated to a characteristic are considered in the measuring program. A measurement plan can be edited, and the sequence of steps can be changed by the programmer. The capabilities offered indicate how much a CMM measurement plan depends on the programmers' expertise. This software does not provide any means of capturing the generated and utilised knowledge during the measurement planning task.

Key characteristics of the Hexagon PC-DMIS [112] CMM programming software are: the use of CAD models, an integration interface, linking the measurement software to any

CAD systems, digital simulation of the measurement plan for validation before the actual execution and part alignment assistance routines. An additional capability offered is a range of power wizards that guide a programmer through planning process. In the viewpoint of this research the previously mentioned feature constitutes a drawback as it does not allow a programmer to think and intuitively prepare the measurement plan rather than leading them to select predetermined settings and options in order to build the part program.

Wenzel OpenDMIS [113] is a CMM programming software offering various CAD related capabilities such as importing multiple CAD formats, geometry recognition and layering and colouring modes. A range of virtual programming modules enable inspection planning simulation, verification and optimisation including part setup, inspection tools and probes selection, motion path generation and collision avoidance. In addition, automatic routines are available for feature inspection planning. The disadvantage of the package is that it guides the programmer through a series of functionalities instead of enabling intuitive measurement planning and strategic and tactical thinking.

Mitutoyo MCOSMOS [114] software through its different modules allows measurement of complex components such as gears, aerofoils and other components. The package offers an easy, user-friendly graphical interface with a range of tools and wizards for automatic inspection path generation, part alignment, tool setup and collision avoidance.

Polyworks Inspector [115] is another commercially available solution for CMM inspection planning. The toolset provides part alignment techniques, geometrical analysis and best-fit algorithms, offline simulation of the measurement plan and motion of the CMM probing system.

Renishaw MODUS [116] offers CAD-driven offline programming, full motion simulation and collision detection and mathematical algorithms selection. As with the previous packages, the main drawback of these is that they prompt the operator through the automatic functionalities to plan a CMM measurement, preventing the generation and capture of implicit knowledge through an intuitive planning process.

2.4 Summary

In this chapter, existing research work was studied aiming to identify the major principles and steps of computer aided inspection planning. As indicated by most of the related works, such a strategy consists of part setup and orientation, accessibility analysis, inspection point set size and distribution and measurement path generation. A great amount of different techniques and methodologies were employed aiming to automate and support CMM operators to make proper decisions for each step. Central to most of the proposed approaches is utilisation of knowledge, especially in intelligent algorithms such as heuristic algorithms and neural networks. A key limitation of the solutions presented is the lack of a knowledge capture technique to reuse it and structure it in rules for developing an intelligent planning system.

In the perspective of capturing CMM inspection planning knowledge and formalising it in human and machine-readable formats, this thesis will focus on all the aspects of carrying out an inspection planning task but will only consider contact and point-to-point CMM measurements. Out of the scope of this work will be non-contact or scanning inspection methods. In addition, this research aims to capture human centred knowledge and represent it in visual outputs; the inspection planning techniques involved will be evaluated at a strategic level.

Also out of the scope of this thesis will be the evaluation of the CMM part programming methods and relevant outputs. The methodology and tools developed will aim to capture and represent the knowledge generated employing the proposed formalisations for the following inspection planning activities:

Part setup: how a component is located and oriented on a CMM table. To address this step, proper visualisations will be used with the aid of a 3-axis coordinate system indication of the part orientation.

Accessibility: how each feature is accessed in order to be inspected using an inspection tool. This activity will be captured by displaying the approach directions visually for all the measurement points on each feature of the component.

Sampling strategy: the number of points and their distribution over a measured feature's surface will be captured and shown visually in the representation formats.

Path planning: the strategic (feature-to-feature sequence) and tactical (point-to-point sequence on a feature) inspection paths will be captured and represented aiming to capture the strategic thinking and planning processes.

Central to the research presented is the capture of CMM inspection planning knowledge and strategies. All of the above key elements of a measurement planning strategy will be captured by logging the user activity. Various representation formats will be developed and evaluated using specific metrics with regards to ease of understanding, usefulness and overall performance.

In the second section of the chapter, the current state of literature is reviewed in the perspective of automated inspection planning systems for CMM measurements. A wide variety of different technologies was employed regarding expert systems. Although these were built upon human expertise and knowledge, there were no descriptions or evidence of a methodology to robustly capture the knowledge and strategic thinking in order to formalise and make it easily accessible for reuse.

In addition, there were no systems which attempted to log, in real time, the whole inspection planning activity or any human centred expertise and knowledge that could be embedded into expert systems. Moreover, some of the most popular commercially available CMM measurement planning packages were reviewed. Although they provide a wide range of features and capabilities for quick and easy generation of CMM part programs, they tend to replace programmer's strategic and tactical thinking and decision making. Due to the various automated options and functionalities the CMM programmer is limited to selection of settings of options and prevented from creating an inspection plan intuitively. Furthermore, no capabilities for implicit knowledge capturing were found available in the reviewed packages. These limitations leave unanswered the question if human knowledge can be captured in the field of CMM inspection planning. The next chapter will attempt to identify any available solutions to this issue and paradigms from other engineering areas.

Chapter 3 Review of engineering knowledge capture and formalisation

3.1 Introduction

The ever-increasing complexity in manufacturing and customer demands for higher quality products with shorter production times has forced industry to develop more advanced processes which are more knowledge intensive [117]. To achieve improved processes and better products requires utilisation of high-quality knowledge and skills. However, previously generated knowledge and experience in CMM planning is seldom stored and available for future reuse. Therefore, there is a need for designing a methodology and developing suitable tools that will enable human expertise and domain knowledge to be captured, stored and accessible for reuse. This is the primary purpose of this research.

3.2 Definition of knowledge

Knowledge management [118] is the field of science that facilitates capturing, storing, sharing and effectively using knowledge. To delve into the concept of Knowledge Management a definition of the term knowledge should be provided. Many perspectives have been proposed in the literature aiming to define and explain "knowledge". Dalkir [118] states that "knowledge is information translated, processed by experts and applied on a case." According to Sainter et al. [119] "knowledge is the combination of experiences, concepts, values, beliefs and ways of working that can be interpreted and communicated." Moreover, the authors in [120] argue that "knowledge is evaluated information that can be used in a problem solving process." In these definitions, knowledge is linked to the term "information", thus it is necessary to clarify their meanings and relationship between them.

A graphical representation [121,122] in Figure 3.1 shows how each definition is developed based on the others and the relationships and boundaries amongst data, information and knowledge. According to this, "information is defined as the processed and contextualised data resulting from real facts" and "knowledge is the interpreted and applied information." That is, one has to understand the meaning of data, put them into the domain context to convert into information and then reflect on the information to understand and acquire the inferred knowledge.

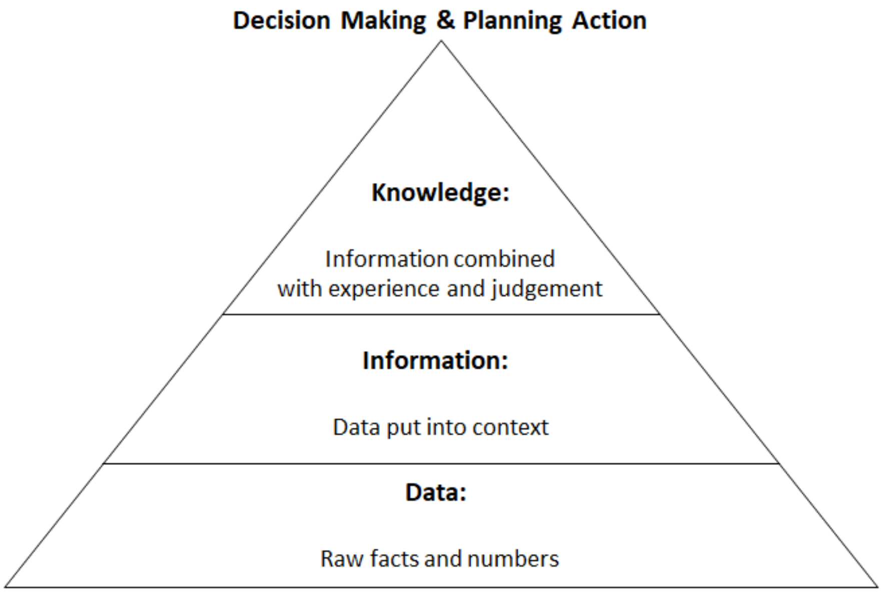


Figure 3.1 Relationships among data, information and knowledge concepts [121,122]

Du and Liu [123] classified knowledge into two categories: explicit and tacit. Explicit is the knowledge that can be directly codified. It is more formal and systematic and often exists in books, manuals, databases and computer programs. Tacit knowledge is unclear, difficult to express and comes primarily from personal experience influenced by the organisation and working nature of the company. In an effort to understand the different natures of knowledge, a taxonomy recommended by Lundvall and Johnson [124] proposes four categories: know-what, know-why, know-how and know-who. Shadbolt and Milton [125] described pairs of opposite knowledge types for understanding and dealing with those more effectively as:

- Declarative or static (know-what) & procedural or dynamic (know-how).
- Tacit (cannot be articulated easily) & explicit (can be articulated easily).
- Abstract (applies in many cases) & specific (applies in one or few cases).

For the research presented in this thesis, the definition suggested by Davenport and Prusak [126] is applied:

> *"Knowledge is information with the most value and is consequently the hardest form to manage. It is valuable precisely because somebody has given the information context, meaning, a particular interpretation; somebody has reflected on the knowledge, added their own wisdom to it, and considered its larger implications."*

This definition was chosen as it highlights the need for expert CMM planners to reflect on and interpret the generated knowledge formats and validate them by providing feedback. This is central to this research because the knowledge will be captured through logging user (or human centred) inspection planning activities. The focus of the current work is on the tacit type of knowledge which is undocumented, resides in a human's mind and results from their personal experience, according to Du and Liu [123], and therefore difficult, expensive and time-consuming to capture with the existing traditional methodologies [127].

3.3 Automated engineering knowledge capture

Knowledge capture is the process of extracting knowledge and expertise for structuring a knowledge-based system [128]. Acquiring high quality knowledge to develop a reliable and effective system is a highly time-consuming task causing a bottleneck in building an expert system [129]. Hence knowledge capture has become a major research field within knowledge engineering aimed at developing methods and tools to facilitate the task of knowledge extraction from an expert and its subsequent integration into a knowledge-based system.

To perform knowledge acquisition from a human expert a variety of tools and techniques have been developed from manual to fully automated processes. Traditional knowledge capture includes interviewing an expert, observation, task interruption and discussion, structured questionnaires and audio and video recording. However, manual methods are very time consuming, usually not effective enough to capture high quality tacit knowledge and experts could be distracted from following the usual process. Therefore, researchers have focused on proposing automated knowledge capture techniques that keep interruptions to a minimum.

3.3.1 Automated knowledge capture in design

Engineering design is an area that has attracted the most attention for developing knowledge acquisition methodologies. In [130] DAKA tool is proposed, capable of capturing design activity and knowledge through mining and monitoring CAD events in real time. Key components of the proposed system include a product model roadmap, representing the sequence followed by the designer as a list of actions and a design operation-mining algorithm for recognising design patterns and sequences as operations. The knowledge obtained represents the followed rationale to reach a final design model and identifies key decisions for specific tasks. Contributory to the current thesis is the use of a real-time user activity monitoring system for capturing knowledge and expertise in CAD design.

Rea et al. [131] proposed an experimental setup for the automated capture of design knowledge. It emphasises actions and changes made by the designer to achieve a goal. The system was tested using software developed for studying the mechanical performance and behaviour of virtual creatures. The results after each design and test are recorded in the form of an Extensible Mark-up Language (XML) [132] (Figure 3.2) and post processed for analysis and improvement. XML is a simple and flexible text format designed to facilitate large-scale electronic publishing and web-based data exchange. Its advantage is that it is both human and machine-readable. This work highlighted the capability to capture a sequence of actions in a data log-file and by post-processing it to generate other formats, easily readable and understandable, for studying the performed activity.

```
<logfile >
    <header >
        <session_id text = "20070310_120934_11" >
        </session_id>
        <session_start hour = "12" minutes = "09" seconds = "34" seconds_milli = "921" >
        </session_start>
        <session_control filename = "Apprentice.xml" >
        </session_control>
        <baseline_zook filename = "Test Zook" >
        </baseline_zook>
        <copy_to_log_header copy_att = "an attribute" >
            <copy_element value = "test" >
            </copy_element>
        </copy_to_log_header>
```

Figure 3.2 Example of an XML based log file [131]

The use of a VR cable harness design system was demonstrated [133] via a novel non-intrusive method for knowledge and information capture by user logging. The captured expertise was formalized in multiple representations such as Integrated DEFinition Methods (IDEF) diagrams, Design Rationale Editor (DRed) graphs, Process Specification Language (PSL), Extensible Markup Language (XML), annotated movie clips and storyboard representations. These representations are explained in detail in Section 3.4. This work has particularly influenced the current research by pointing out the capabilities of user logging in real time that facilitates expression of human centred knowledge and expertise through performing a task in a virtual environment. A key contributing factor is the generation of multiple formats by post-processing one log-file containing the captured data.

Sung et al. [134] proposed a system that unobtrusively captures design process and knowledge by logging a designer's activity and interactions while using CAD system for a design task. Various CAD system-independent representations were produced to give a visual and formal representation of the user's decision making and rationale during the task. This work constitutes a novel paradigm for automated knowledge capture and formalization within a CAD environment. In this work, the benefits of unobtrusive user activity monitoring are once again emphasized in the effort to capture decision making and key steps of thought process.

A biometric-based system was suggested [135] capable of capturing knowledge combined with psychological data recording in order to extract expertise in the design process. User logging modalities include, time-stamped keyboard/mouse user input, facial expressions, pupil dilations and brain signal inputs. The novelty added relates engineer's cognitive affective status with conventional decision making in the process of designing. The knowledge captured is represented in formats that can make it available for reuse in optimising a product's design process.

Sivanathan et al. [136] demonstrated a novel engineering knowledge capture and reuse prototype for team-based design 'reviews'. The prototype includes a VR-based 3D model display as a multi-user interactive environment and a web interface for simultaneous access during review activity. Tests and feedback from engineers using the system showed that this system can enhance their engineering task knowledge capture, and reuse capabilities. More importantly, this illustrates how a multi-modal data capturing system can contribute to user activity logging and knowledge capture as well as the significance of evaluating such a system by obtaining feedback from experienced engineers.

3.3.2 Automated knowledge capture in planning tasks

Other engineering areas that have attracted the interest of researchers for developing knowledge capture techniques and tools are machining process planning and assembly planning. Park's [137] three-phase modelling approach for knowledge extraction from process planning of machining holes uses three categories: facts (geometry, machining process, cutting tools), constraints (capability of machining, processes sequence) and rules (key parameters) for mimicking the rationale followed by human experts. The current system is limited only to process planning for machining a hole, thus it was suggested to extend the methodology in other feature geometries and engineering tasks.

Sung et al. [138] developed a haptic soldering environment for simulating the process and logging the motions of a haptic pen user logging, aiming to capture and investigate the activity during the task. A log-file is generated automatically containing the forces, velocity and motion of user's hand. By parsing the log-files, different knowledge representation formats (codified, textual, graphical, etc.) are produced, illustrating critical user actions of the soldering session. Their pilot study found that users preferred the representations with more visual outputs such as storyboards and annotated video clips.

Zhang et al.'s [139] Universal Process Comprehension interface (UPCi) was developed aiming to capture and reuse shop-floor and machining process knowledge. By post-processing low level G and M code programmes written for CNC machines, domain knowledge is represented in a standardised STEP-NC format. In this approach an XML-based meta-model was built and utilised for translating and reusing the developed process plan in new manufacturing resources.

In [140] the authors developed a haptics-based virtual environment for capturing human expertise in planning machining operations. The proposed system allows the real-time simulation of drilling, turning and milling processes for planning purposes generating feasible process plans. These plans contain all the necessary knowledge for part setting up and cutting processes sequencing. The current system was tested on the production of three work-pieces validating the efficiency. Moreover, functionality of the haptic-virtual process planning environment was assessed and validated through a usability study engaging experienced and novice planners.

Ritchie et al. [141] developed a mixed haptic VR environment called Haptic, Assembly, Manufacturing and Machining System (HAMMS) for user logging in assembly planning tasks. Main formalisation outputs consist of assembly plans, chronocyclegraphs (motion trajectories) and Therbligs (symbolic language for activities). This work has successfully shown that by capturing and utilising the generated outputs, user activity can be analysed so as manufacturing methods and associated decision making can be improved. Extending this work [142] with a time comparison of the system's use against traditional assembly planning, it was found that HAMMS is approximately five times faster in generating an assembly sequence.

Read et al. [143] developed a sketch-based haptic virtual environment for capturing assembly planning sequences. The system consists of an overview where the user can see the assembly and receive feedback on the design and compare design changes; an assembly environment to capture the assembly sequence and a modelling environment to edit the geometry of the parts.

3.4 Engineering knowledge formalisation

As it has been highlighted in the previous section, knowledge representation is closely associated with knowledge capture as a means of making the knowledge explicit and understandable either by (usually experienced) humans or a machine and available for direct or indirect reuse. A classification of knowledge representations related to product design knowledge is proposed by Owen and Horvath [144] forming five groups: pictorial, symbolic, linguistic, virtual, and algorithmic. The Table 3.1 below shows some of the various representation types related to product design and process knowledge.

Table 3.1 Groups of product design and process knowledge representations [144]

Pictorial	Symbolic	Linguistic	Virtual	Algorithmic
Sketches	Decision tables	Design rules Constraints	CAD models	Mathematical equations
Drawings	Production rules	Analogies	Animations	Parameterisation
Charts	Flow charts	Verbal communication	Multimedia	Computer algorithms
Photographs	Assembly tree			Design/operational procedures
CAD model	Fishbone diagram			
	Ontology			

IDEF diagrams are commonly used in representing knowledge related to engineering tasks. A number following the initials IDEF indicates the level of the function and details to describe it. IDEF0 (Figure 3.3) is a graphical representation used to model decisions, actions and activities of an organisation or system [145].

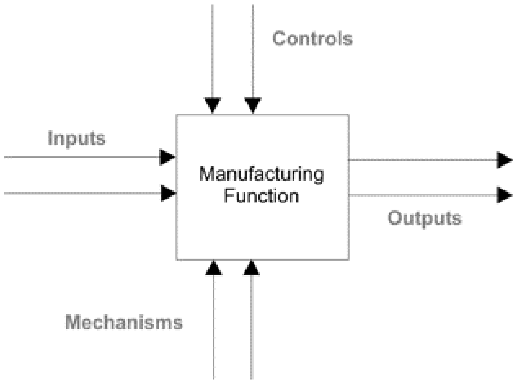


Figure 3.3 IDEF0 and schematics of its functional components [145]

Feng [146] presented an activity model for machining process planning by using IDEF diagrams. Major activities included in the approach are selection of machining centres, specification of setups and tool assemblies and fixtures. The activity model was developed for integration with automated machining process using numerical controllers. Figure 3.4 illustrates the IDEF diagrams that capture the functional components of process planning and data requirements.

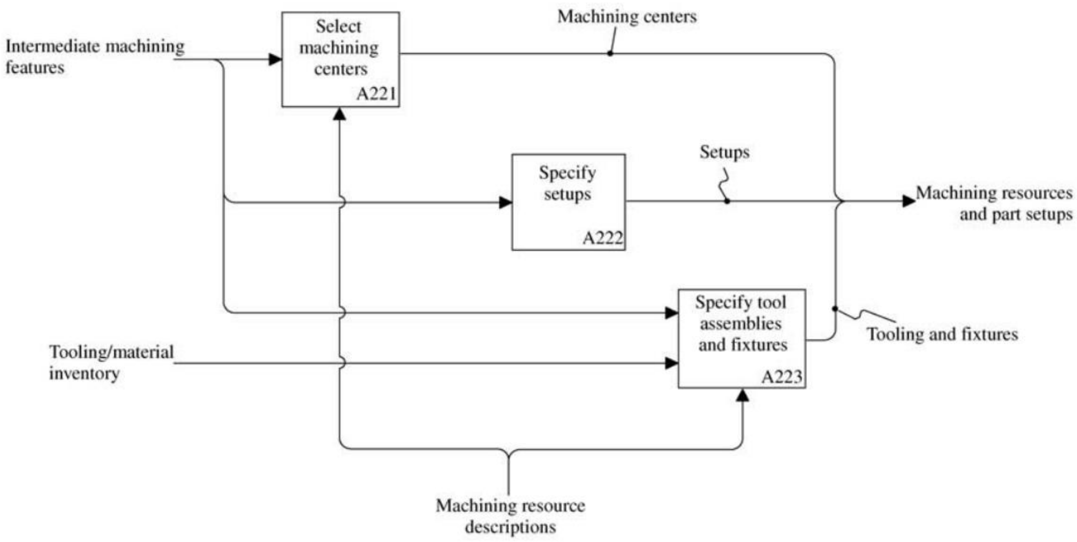


Figure 3.4 Example of IDEF0 representation of machining process planning [146]

DRed (Design Rationale Editor) is a simple and unobtrusive software tool that allows engineering designers to record their rationale as the design proceeds [147]. A DRed diagram is structured by coloured symbols describing acceptable, possible or rejected answers and solutions in different stages of an operation. Practical benefits for designers include: easy and clear structuring of thought process, simple and flexible way of managing designs, reduced need for written reports. Figure 3.5 below shows an example of a DRed diagram for a generic problem diagnosing task.

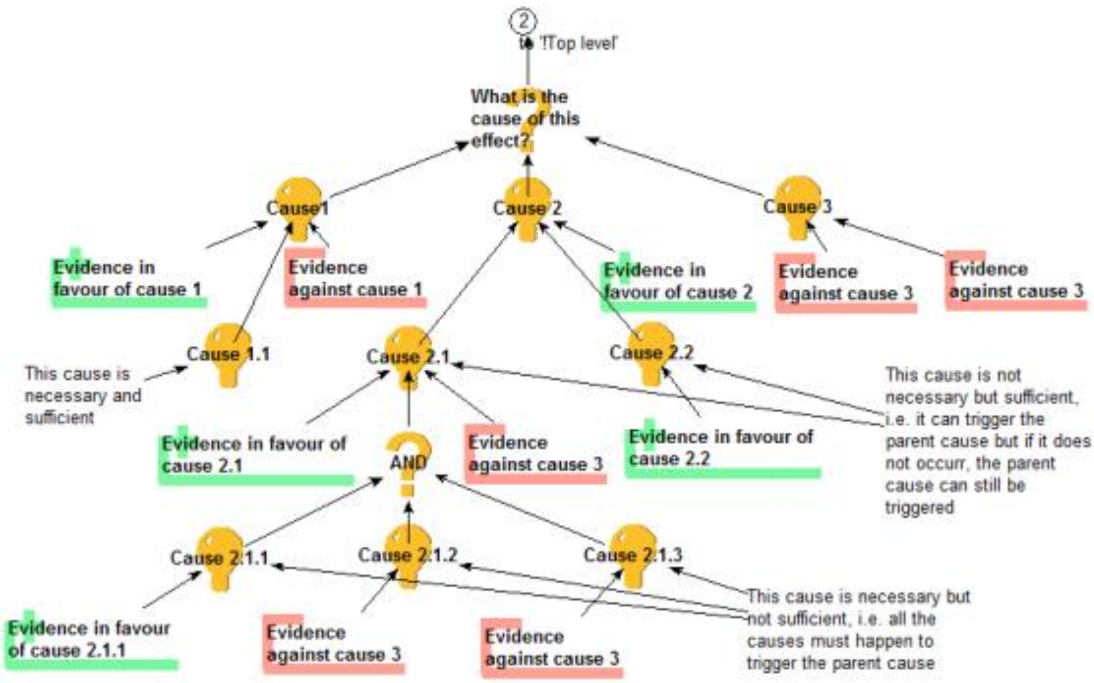


Figure 3.5 Example of DRed diagram for a generic problem diagnosing task [147]

In addition to DRed, Sung et al. [134] suggested PSL format for coding representations of a VR cable harness assembly planning process. PSL is a widely acceptable format in industry and it is used to model manufacturing and production processes. It consists of constants, functions and variables for describing a process and can be easily converted into human readable instructions. To this extent, plain English-syntax instructions were employed in this work to describe the key decisions made during the planning process. The simplified representation produced in English-syntax instructions can be used as a direct support for new users of a system or it can be stored in the database of a PLM system. Figure 3.6 illustrates the PSL and plain English syntax representations of this work.

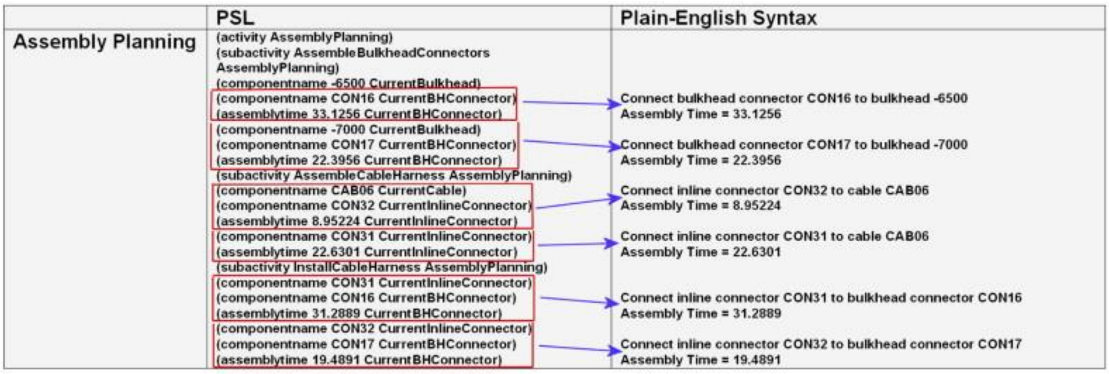


Figure 3.6 PSL and plain English syntax instructions for a VR based cable harness assembly planning task [134]

Flow charts were employed by Barreiro et al. [148] to structure an informal model, as shown in Figure 3.7, containing knowledge for the purpose of building an ontology in the domain of measurement with a manual portable coordinate measuring arm. Based on recommended rules this model informed a knowledge-based system for improving measurement reliability taking into accounting both inspection strategy and operator factors. The knowledge involved is acquired from suggestions in manuals and standards and not directly from captured human expertise.

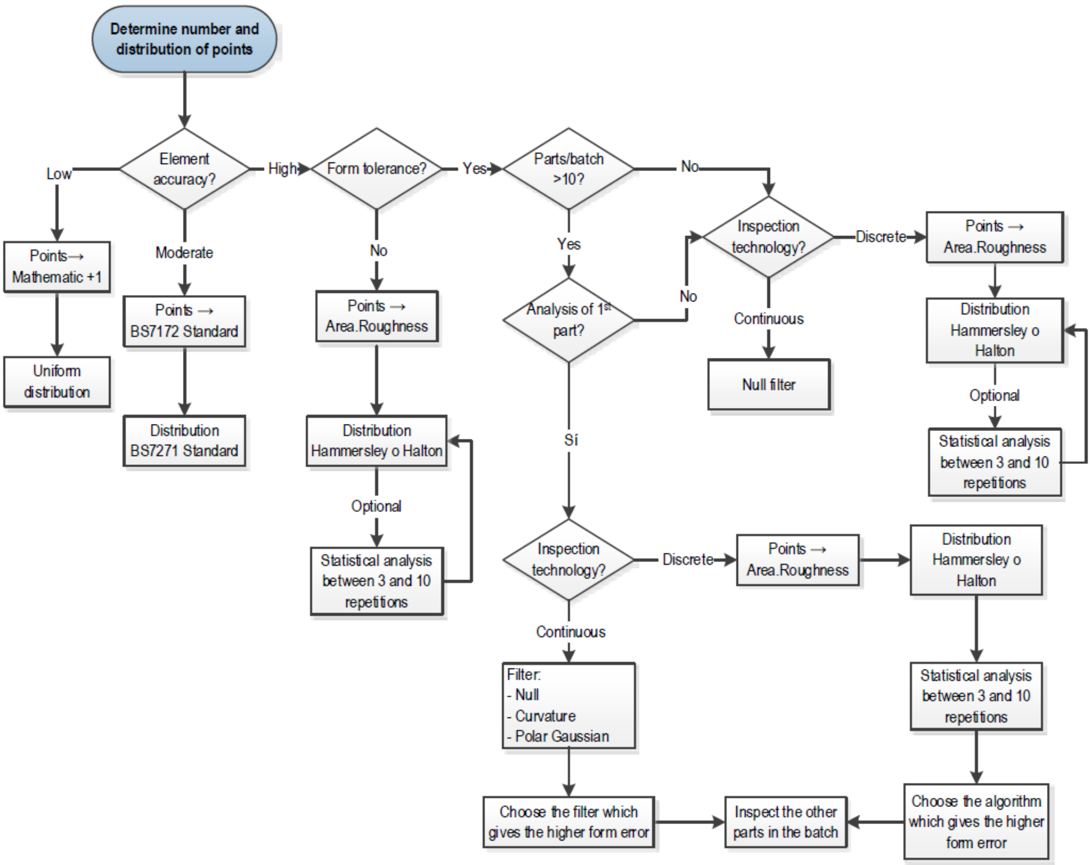


Figure 3.7 Example of an ontology model in the form of flow chart for sampling points

In [142] Gilbreth's Therblig symbols (Figure 3.8) were utilised to represent a sequence of user actions in assembly. In this work user's motions are studied while performing an assembly planning task in a virtual environment. The benefits offered by such a method is the quick and easy identification of inefficiencies during an operation as well as comparison of different strategies and detection of repeated activity patterns. Therblig symbols and related descriptions along with an example (Figure 3.9) of a sequence showing user motion logging during cable drag and drop are shown below.

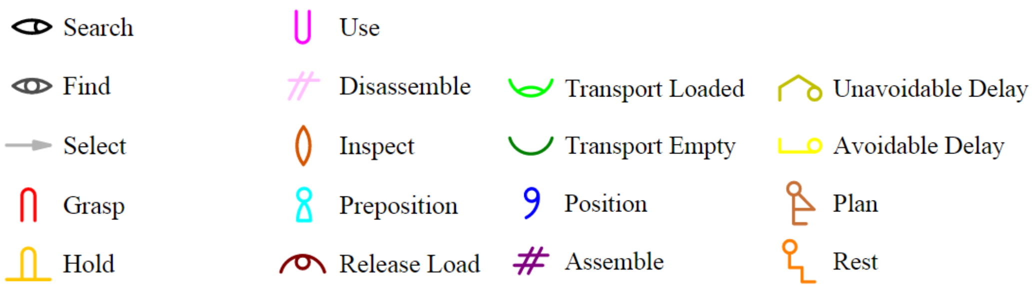


Figure 3.8 Therblig symbols and definitions [142]

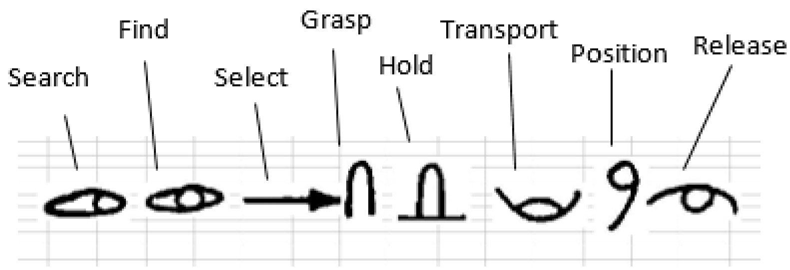


Figure 3.9 Example of a Therbligs sequence for a cable assembly drag and drop task [142]

3.5 Knowledge capture and formalisation in CAIP

Barreiro et al. [149] developed a functional model of inspection planning activities using IDEF diagrams for the purpose of integrating dimensional inspection with manufacturing and design stages within product's life-cycle. In Figure 3.10an IDEF0 based generic model for an inspection planning activity is shown. Each activity is decomposed into sub-elements providing further details. Unfortunately, the work has not mentioned how inferred knowledge was captured in order to formalise it in IDEF formats.

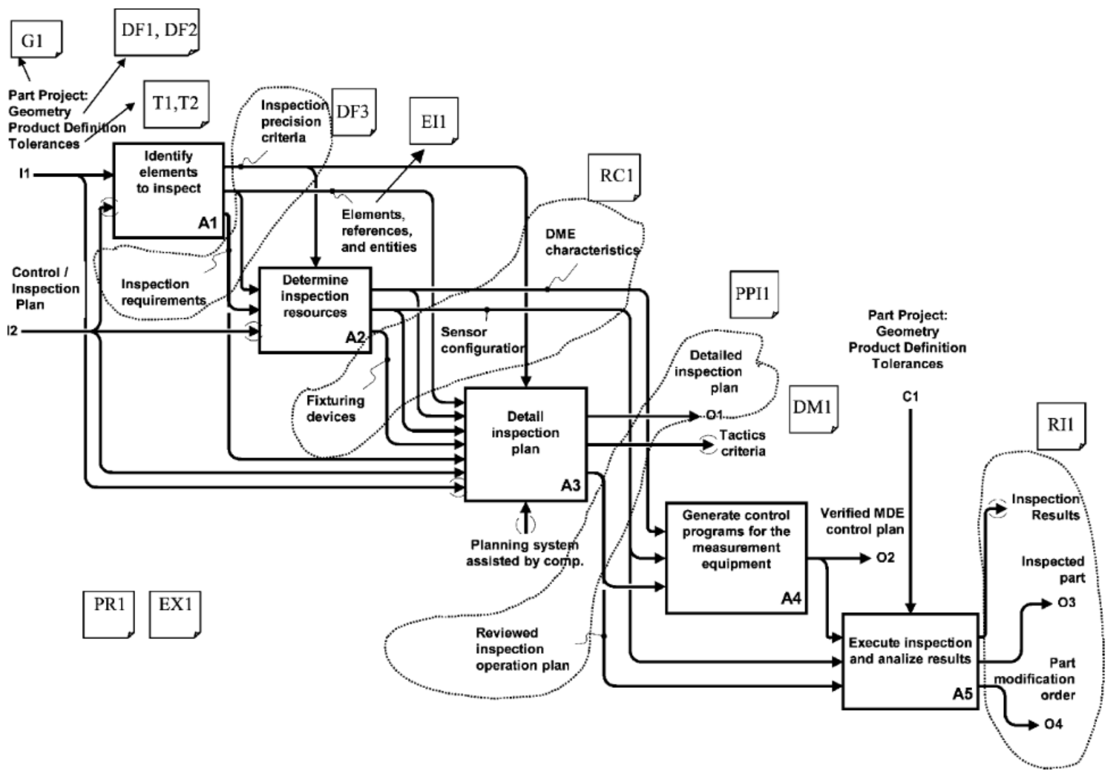


Figure 3.10 Example of an IDEF0 diagram in inspection planning[149]

Martinez et al. [150] presented a methodology for representing knowledge in CMM inspection planning in the form of ontology. Major focus of this work was to provide an easily interpretable knowledge format for non-specialists in CMM programming languages as well as develop an ontology that would work as the informal model for building a knowledge-based system for inspection planning. A drawback of the presented approach is the application of manual methods for extracting domain knowledge such as interviewing CMM experts and technical documentation (handbooks, manuals, etc.). As the authors stated, if the knowledge capture stage is not conducted properly, formalisation of knowledge will be inefficient.

In their research Barreiro et al. [151] suggested a method to elicit knowledge in inspection planning from manuals, standards and documents using a data mining application (PC-PACK) in order to structure a knowledge base. According to the authors the most common technique for knowledge elicitation is interviewing experts; a costly and time-consuming process. Thus, their research is focused on explicit forms of knowledge documented in technical reports and handbooks. This work was further extended [152] and applied [153] on a case study for identifying and representing knowledge and rules in selecting CMM inspection equipment. However, the work lacked an evaluation study and validation of the generated outputs and inferred knowledge by experienced CMM planners.

IDEF and ontologies have been combined by Barreiro et al. [154] and Barreiro et al. [155] to produce a more complete knowledge representation. Having extracted knowledge from documents and using the MOKA methodology the authors identified activities, rules, resources, constraints and entities to form an IDEF-based ontology representation (Figure 3.11) for the task of inspection planning. No forms of evaluating and validating the detected knowledge and formalised outputs were found.

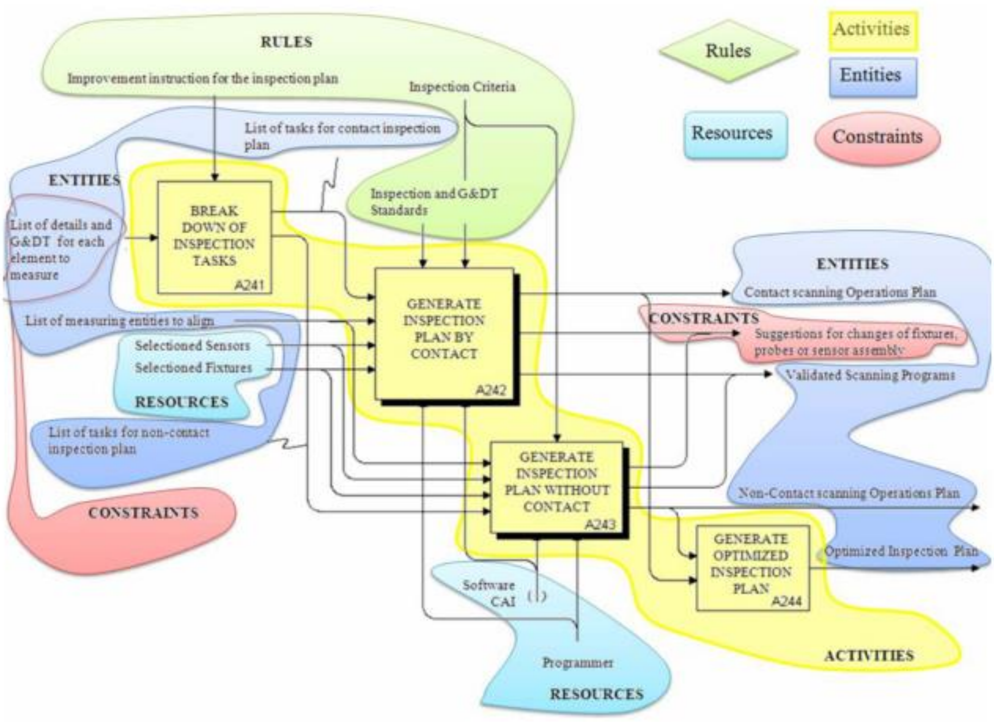


Figure 3.11 Example of IDEF extended ontology model for inspection planning tasks [154,155]

Majstorovic et al.[156,157] presented a knowledge-base model to develop an expert system for inspection planning. Knowledge is represented by an ontology expressing the relationships between tolerances and entities of a measuring part such as geometric features, metrological features, probe configuration and inspection sequence. This research is limited from a testing and knowledge validation point of view. Also, it does not explain where the underpinning knowledge base came from.

Similarly, Stojadinovic and Majstorovic [158] applied an engineering ontology to develop an intelligent inspection planning system. Graph theory was used to decompose a component and related tolerances, into metrological and geometric features. This work was further extended in [159] to share and reuse domain knowledge. No information was provided with regards to the knowledge capture method or sources.

Martinez et al. [160] described a knowledge model to automate inspection probe configuration, selection and orientation. In this work the knowledge engaged comes from reports, guides, handbooks and interviews with experts. Although the origin of the utilised knowledge is known, it is not explicitly reported how it was elicited and processed to result in the rules of the knowledge-based system.

3.6 Summary

From this review of past research, it can be shown that there are no available real-time knowledge capture methods for CMM inspection planning applications, which in other engineering tasks have been proven beneficial in understanding of highly complex problems. Many attempts have been made to develop tools utilising knowledge for automating some steps or a complete strategy for inspection planning with CMMs, indicating a great need for more contemporary knowledge capture techniques in this engineering field.

Existing work on capturing and utilising human centred knowledge relies on manual, time-consuming methods such as document analysis and interviews with experts which add overheads to the whole process. Most of the work dealing with knowledge-based systems is focused on the development of algorithms and systems without paying attention in capturing domain specific knowledge and its representation in the perspective of human understanding which can aid the decision making and thought process for planning a CMM inspection and potentially training novice operators more effectively and quickly.

Moreover, the knowledge models and formalisations used in past research have not been tested and validated by experienced CMM programmers. Finally, no previous work was detected dealing with comparison and evaluation of planning strategies so that repeated patterns are observed, captured and analysed to help create and identify best practice throughout the whole CMM inspection planning process.

Therefore, key research gaps in the CMM inspection planning knowledge domain are:

- Lack of an automated human centred real-time knowledge capture method or tool for planning CMM measurements.
- No existing tools for the automated generation of human centred knowledge representations.
- No validation method of captured knowledge or any evaluation and validation of the associated representations.
- No methodology for comparing and evaluating strategies and detecting repeated patterns of activity.

These emerging insights and key findings from the literature review helped frame this research's associated hypothesis, research questions and research objectives as outlined in Chapter 1. They also subsequently informed the definition and development of the experimental methodology, analyses and outputs detailed in the following chapters.

Chapter 4 IPaCK Framework and Pilot study

4.1 Introduction

This Chapter presents the Inspection Planning and Capturing Knowledge (IPaCK) framework to address the identified knowledge gaps and outlines solutions to meet the associated objectives. Major considerations taken into account were the logging of user activity, post-processing the data, and to automatically generate multiple representations of the planned strategy and logged user activity. To meet these requirements, motion tracking was used to capture strategic planning thinking and decision making while moving a handheld inspection tool. Key decisions and actions are input through an analogue tablet with inspection planning options. The primary goal was the formulation of a prototype design that would enable an intuitive setup to allow easy and quick planning of a CMM inspection and avoidance of too much user interaction with a software environment, as most of the available CMM software packages.

As illustrated in Figure 4.1, central to the methodology developed was the testing and validation of the tools developed and the outputs generated by both experienced CMM planners and novice users. Thus, it was necessary to include a two-stage experimentation; firstly, on inspection planning and the user logging tool's usability (Stage 1) and secondly on the generated knowledge format representation suitability, knowledge validation and reuse (Stage 2).

Prior to the main experimentation stages, a pilot study was carried out aiming to an initial evaluation of the suggested representation formats and personal preferences. The following sections detail the initial IPaCK prototype and its outputs, the pilot study results and the feedback acquired as well as how these informed the refinement and enhancement of the IPaCK tools.

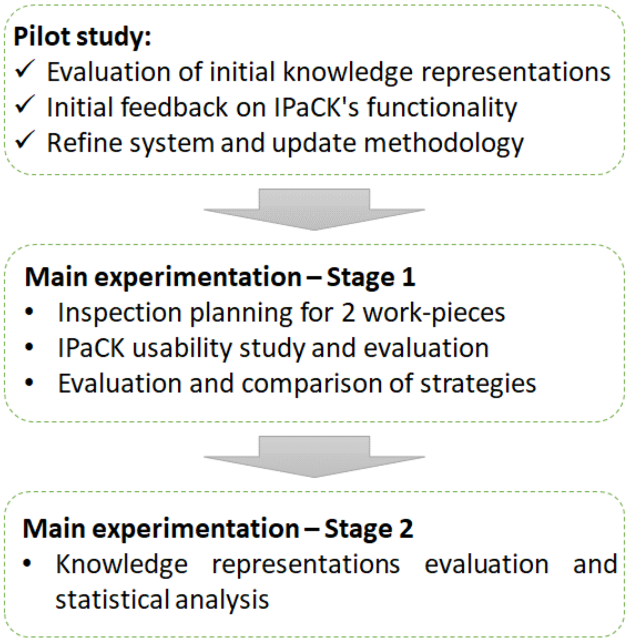


Figure 4.1 Schematic representation of experimental workflow

4.2 Methodology and initial IPaCK prototype development

Aiming to address the requirements of the defined research objectives, a CMM inspection planning environment was created, called the Inspection Planning and Capturing Knowledge (IPaCK) system, focusing on capturing the user's strategy and knowledge when planning a measurement of mechanical parts. IPaCK aims to emulate the activity of an operator while planning a measurement strategy for a CMM by digitizing it so that it can be captured and analysed more quickly and effectively.

A well-established method of tracking humans and objects with a view to recording motion activity is motion capture technology (MoCap) [161]. The main reason for using this technique is to gain a greater visibility and better understanding of human activity and behaviour while modelling and simulating a performed task. MoCap technology has been used for surveillance, control and analysis applications [162]. Surveillance applications are related to monitoring multiple subjects, i.e. vehicle counting, crowd flux and congestion analysis. Control applications involve the generation of an interface for controlling a model or object; this usually applies to human-computer interaction case studies. MoCap for analysis covers diagnostics and optimisation studies such as clinical and orthopaedic patients and athletes' performance.

Previous research has employed MoCap technology for investigating and analysing engineering and manufacturing tasks. Qiu et al. [163] proposed a MoCap based methodology for modelling human performance in assembly and disassembly of a car engine's connecting rod caps within a virtual reality environment. An optical motion tracking system was proposed [164] for data capture and evaluation of a ladder climbing task. The setup as part of a cyber-physical system can provide opportunities for capturing expertise from experienced operators and facilitate training of workers in building and construction activities. A multi-depth camera motion tracking tool [165] was developed for tracking and observing workers' activity within a production environment aiming to optimise processes and ergonomics of a workplace. Therefore, motion capture and tracking techniques can effectively be used for logging user activity effectively in real world environments. The captured data can enable the modelling and simulation of real-world environments to be digitised with a view to capturing and formalising human centred knowledge in engineering tasks.

The recommended solution was developed based on a physical setup combined with an optical motion tracking system. A hand-held stylus moved by a user is tracked and the motion data are logged and codified in a data file. The stylus moves imitate the function of a CMM probing system. The log file generated is then post-processed and multiple visual outputs are produced showing the planned measurement strategy for the component. Each output focuses on various elements of the planning strategy and therefore a range of different representations were proposed. A schematic diagram of technical framework is shown in Figure 4.2 while the functionality of IPaCK is illustrated in a demo video (Appendix A.1).

The selected knowledge representations are: user activity motion trajectories, IDEF0 diagram, text instructions, annotated video clip, and storyboard. Past works [4,134–136,166] have successfully employed these outputs to represent knowledge in tasks such as engineering design, process and assembly planning. In addition, IPACK generates a part program for driving a CMM and performing the planned inspection routine.

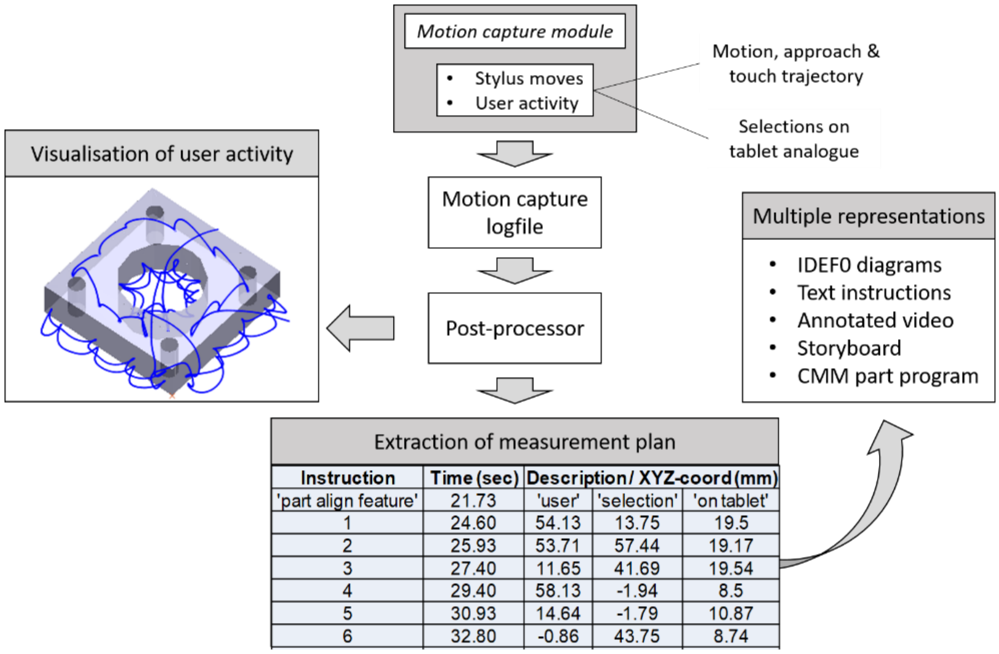


Figure 4.2 Initial technical framework of IPaCK and the proposed methodology

4.2.1 Apparatus and user activity logging

The experimental setup at this stage consists of a motion capture and 3D tracking with OptiTrack Flex 13 system (Figure 4.3), a hand-held stylus with two passive and one active LED markers attached to it and a tablet analogue as a user input device for different inspection planning activities (Figure 4.4). The optical tracker comes with its own software package (Figure 4.5) for recording, storing and editing the motion data files.

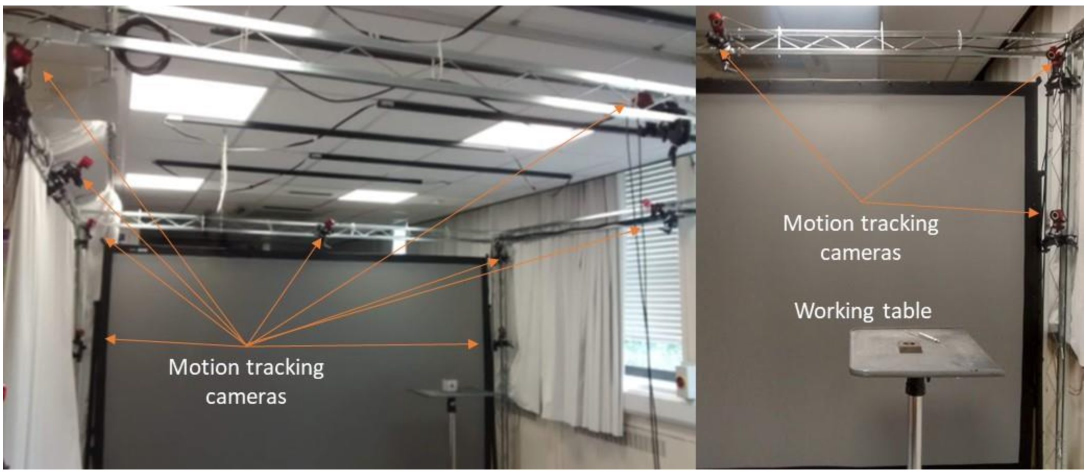
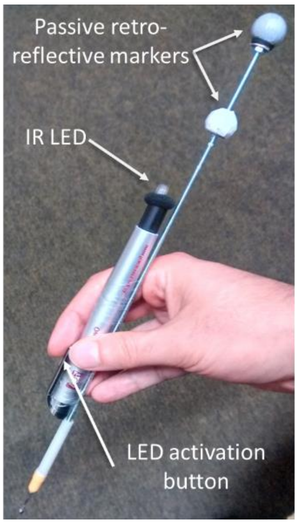


Figure 4.3 Experimental setup and motion capture volume for the current work

The two passive markers attached on the stylus are used for tracking the stylus' tip position. Using the markers' spatial coordinates, the position of the tip is calculated and mapped onto the component's digital model. The third marker is an IR-LED, activated when the button is pressed, indicating in the output log file that a touch point is probed and recorded. A series of such points formulates the point set for digitally reconstructing a geometrical feature of the part.



Inspection planning sub-activities					
Planning	Part align feature		Start	Tool 1	Tool 2
	Datum feature	Inspection feature	End	Tool 3	Tool 4
Geometry	Plane	Line	Circle	Cylinder	Freeform
Tolerance selection	Flatness	Straightness of an axis	Straightness of a surface	Circularity	Cylindricity
	Perpendicularity	Angularity	Parallelism	Profile of a surface	Position
	Concentricity	Symmetry			

Figure 4.4 Hand-held Inspection stylus and tablet analogue input devices

To log the decision making and user activity throughout the planning session, a paper-printed tablet analogue is used as the main input device. On this, there are different types of options available depending on the intended activity to perform; tool selection, measurement planning (alignment, datum, inspection feature), geometrical features (plane, line, circle, etc) and tolerancing features (position, parallelism, perpendicularity, etc).

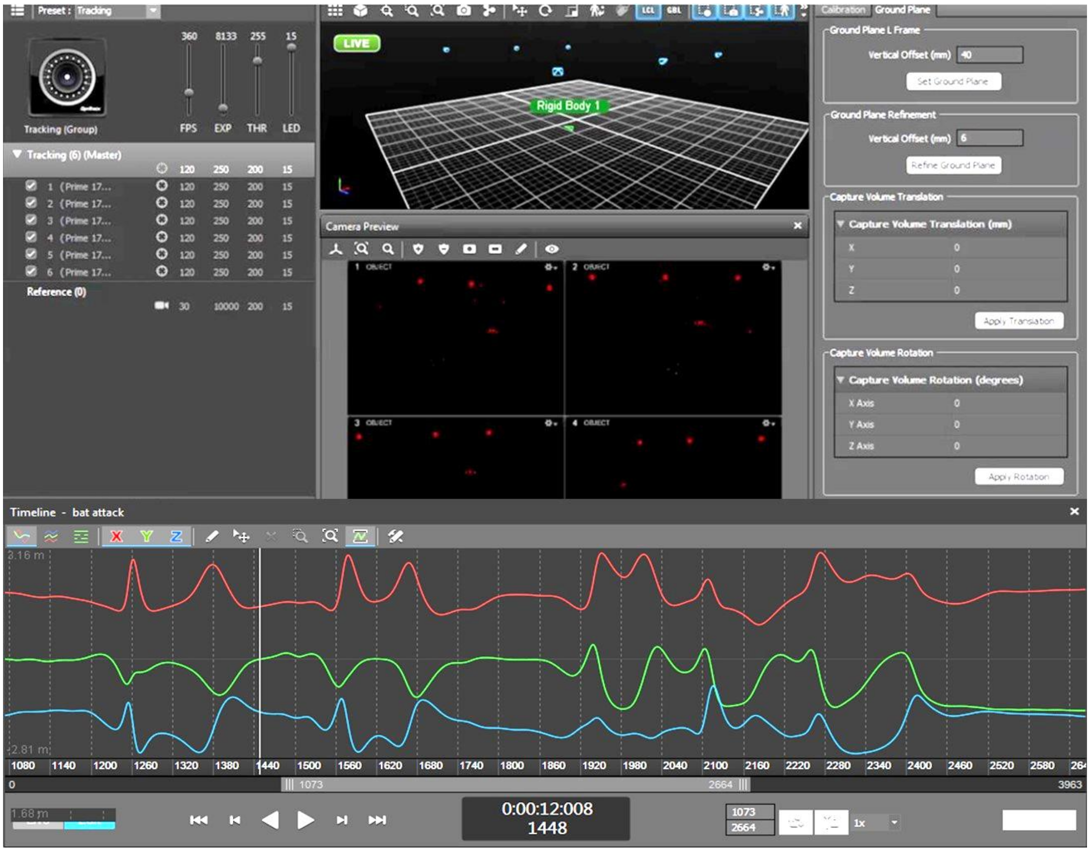


Figure 4.5 Motion capture operating software

The tablet analogue is calibrated within the OptiTrack application prior to the inspection planning session and its relative position is calculated. By mapping the tablet analogue's four corners to the stylus positions, the actual dimensions and position of each tablet analogue cell is known. Thus, when the stylus' tip position falls within the specific dimensional ranges, the system recognizes which "button" on the tablet is selected, indicating the respective user's choice of action. By using the tablet analogue in this way, the user logging module can detect and record the user's activity and sequence of steps performed in a chronological, time-phased order. A typical procedure followed during a planning session using IPaCK is illustrated in detail in Figure 4.6. As the user plans an inspection strategy, the markers' spatial positions, as well as the time when the LED marker is activated, are recorded in a comma-separated values (CSV) file, editable in a spreadsheet as shown in Table 5. This set up should be both user-friendly, quick and intuitive, as it does not require the user to interface directly with a CMM control system or a complex, menu-driven software package.

Procedure steps:

1. The user begins the planning session by selecting "START" button on tablet analogue.
2. The user selects planning sub-task (part alignment or datum feature) on the tablet. For tolerance checking, the related "button" must be selected first on the tablet.
3. The user selects shape/geometry (plane, line, circle, cylinder etc.) on the tablet.
4. The user probe the part on the required face or feature by touching it while pressing the LED activation key.
5. The user ends the planning session by selecting "END" button. Also the user may start over again, by selecting the "START" button.

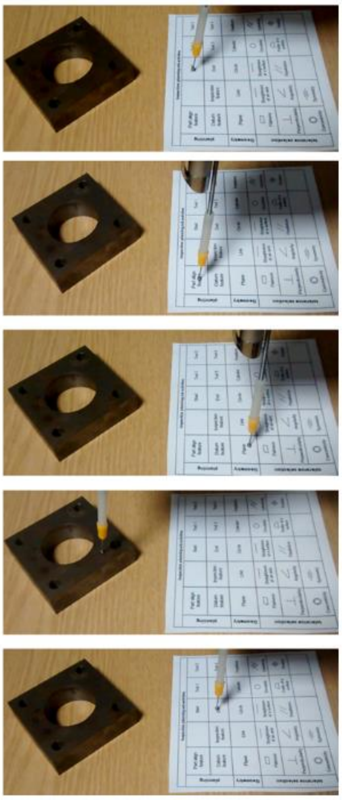


Figure 4.6 Procedure to follow in the experimental trial planning session

Table 4.1 Motion capture log file

Frame	Time	Markers tracked	X	Y	Z	Marker label	X	Y	Z	Marker label
0	8.33	2	292.80	−37.42	435.15	Mid	276.92	−23.66	261.37	Top
1	8.34	2	292.18	−37.15	432.14	Mid	276.73	−23.36	260.53	Top
2	8.35	2	291.85	−36.97	429.27	Mid	276.47	−23.19	259.68	Top
3	8.36	2	291.46	−36.38	426.16	Mid	276.25	−22.90	258.67	Top
4	8.37	2	291.44	−35.66	422.77	Mid	276.28	−22.64	257.68	Top
5	8.38	2	291.63	−34.85	419.11	Mid	276.43	−22.23	256.48	Top
6	8.38	2	292.15	−34.02	415.32	Mid	276.83	−21.74	255.26	Top
7	8.39	2	292.49	−32.84	411.66	Mid	277.33	−21.29	254.20	Top
8	8.4	2	292.59	−31.56	408.14	Mid	278.04	−21.13	252.95	Top
9	8.41	2	293.10	−30.60	404.83	Mid	278.38	−21.05	251.66	Top
10	8.42	2	293.86	−29.97	401.64	Mid	278.56	−21.00	250.37	Top
11	8.43	2	294.15	−29.62	398.45	Mid	278.81	−21.46	249.20	Top
12	8.43	2	294.34	−29.84	395.51	Mid	278.96	−21.95	248.28	Top
13	8.44	2	294.50	−30.63	392.96	Mid	278.91	−22.24	247.32	Top
14	8.45	2	294.29	−30.84	390.30	Mid	279.24	−22.50	246.43	Top
15	8.46	2	294.38	−30.80	387.54	Mid	279.18	−22.49	245.65	Top
16	8.47	2	294.63	−30.67	384.65	Mid	278.81	−22.34	244.92	Top
17	8.48	2	295.19	−30.79	381.79	Mid	278.40	−22.18	244.24	Top
18	8.48	2	295.36	−30.67	378.82	Mid	278.19	−22.28	243.54	Top
19	8.49	2	295.84	−30.76	375.95	Mid	277.92	−22.63	242.77	Top
20	8.5	2	296.04	−30.59	372.99	Mid	277.49	−23.19	242.00	Top

After having fully designed and implemented the elements and modules of IPaCK's tools, a small-scale trial was conducted with one participant for checking the basic functionality. No detailed usability study and analysis were carried out at this stage; however, various knowledge formats were generated and tested through a pilot study.

4.2.2 Knowledge representation formats

Various forms and structures are proposed in this section to address the challenge of capturing and representing knowledge. By post processing the output log-file, different knowledge formats of the measurement planning strategy can be automatically generated. The recommended knowledge formats identified from the literature are: motion and planning activity trajectories, plain text instructions, IDEF diagrams, storyboard and annotated video clip. These formats have successfully been used and validated in knowledge representation for engineering task analysis [133,167,168]. IDEF and process flow diagrams have also been used by other CMM inspection researchers [152,160,169,170].

To produce and generate all the different representation formats a post-processor was created using the Visualization Toolkit (VTK) library [171]. Additionally, for some of the formats, VBA macros (developed by the author) within an Excel spreadsheet were also employed. The following sections present each of the recommended knowledge formats with regards to partial meeting of research objective RO2 - design and development of an automatic knowledge representation tool. The proposed formats are now described.

4.2.2.1 Inspection plan

National Physical Laboratory [22] suggested a good practice for planning a CMM inspection of a component was to write down the intended measurement strategy in a list form so that it can be reviewed and checked for faults and errors. According to this, the first proposed output was an inspection plan showing in a chronological order all the features, tolerances and points logged during the planning session. This format is associated with the other visual and graphical representation formats. Furthermore, the plan contains IDs for the points and geometrical features inspected, the tool and total points used for each sub-activity.

The first section of the plan (Table 4.2) consists of the steps for aligning the component on the CMM; in this example, three features were probed: a plane, a line and a point, using the same inspection stylus (tool1). These are key steps within a planning strategy as identified in section 2.2.1 and are included in the data capture to represent key inspection planning decisions along with associated sub-activities and relevant information. The full inspection plan (generated automatically) presents the whole strategy for testing a true position tolerance of a 'hole' feature.

Table 4.2 Initial inspection plan format generated by IPaCK

Instruction	Time (sec)	X	Y	Z	ID	Tool	Points
Part alignment feature	22.14	4.51	-84.25	0.92	plane1	tool1	3
Touch	27.13	10.01	23.66	18.50	0		
Touch	28.25	35.03	66.29	18.50	1		
Touch	29.37	65.06	32.84	18.50	2		
Part alignment feature	31.15	6.86	-87.31	0.97	line1	tool1	2
Touch	33.53	9.96	0.00	10.01	3		
Touch	35.13	64.74	0.00	10.01	4		
Part alignment feature	37.06	10.00	-86.65	0.87	touch	tool1	1
Touch	38.92	0.00	34.91	8.50	5		
True position	42.00	92.55	-164.78	0.92	tolerance	tool1	
Datum feature	43.71	7.08	-104.59	0.97	plane2	tool1	8
Touch	46.47	10.01	23.66	18.50	6		
Touch	47.58	10.01	51.24	18.50	7		
Touch	48.58	20.02	61.60	18.50	8		
Touch	49.62	55.05	65.77	18.50	9		
Touch	51.10	60.055	49.867	18.50	10		
Touch	52.45	65.06	23.61	18.50	11		
Touch	53.90	50.045	8.5657	18.50	12		
Touch	55.05	20.02	8.83	18.50	13		
Datum feature	57.29	5.61	-106.42	0.92	plane3	tool1	4
Touch	59.62	9.96	0.00	15.01	14		
Touch	61.47	64.74	0.00	10.01	15		
Touch	62.88	69.72	0.00	5.00	16		
Touch	64.47	10.01	0.00	5.00	17		
Datum feature	66.93	7.19	-104.78	0.85	plane4	tool1	4
Touch	70.43	0.00	69.81	13.50	18		
Touch	72.18	0.00	9.97	13.50	19		
Touch	74.61	0.00	9.97	8.50	20		
Touch	76.28	0.00	64.83	8.50	21		
Inspection feature	79.42	28.50	-104.75	0.93	cylinder1	tool1	8
Touch	83.26	39.25	57.91	13.50	22		
Touch	84.99	57.90	37.45	13.50	23		
Touch	86.76	39.25	16.99	13.50	24		
Touch	88.41	18.19	44.87	13.50	25		
Touch	90.08	39.25	57.91	8.50	26		
Touch	91.49	57.55	33.67	8.50	27		
Touch	93.06	42.97	17.68	8.50	28		
Touch	94.49	16.80	37.45	8.50	29		

Strategic planning activity

Tactical planning activity

As observed from the plan, the main activity of inspecting a true-position tolerance consists of several steps that define three datum features before probing the hole feature. The related details are: geometry, number of points and tool used. By studying this output format, both strategic (tolerances and selected features sequence) and tactical (size and distribution of point sets) planning activity is described in a chronological order, with time-stamps. Thus, the required information is provided for analysing the planning task.

4.2.2.2 Strategic planning sequence

Strategic planning sequence (Figure 4.7) presents the strategic planning user activity; that is, the selection sequence of required features. Although this can be studied in isolation to other outputs, it can also be combined with other representations that indicate further details at each step. The significance of strategic planning sequence is to offer a quick review of feature order to probe along with their scope of use within the strategy, i.e. alignment, tolerance, datum or inspection feature. Figure 4.7 shows the numbered elements of the defined order. Each label explains the scope of use of each feature, i.e. PAF for part alignment feature, DF for datum feature and IF for inspection feature. Finally, a geometry for each feature with an ID number differentiates each one from others i.e. plane1 – plane2, etc.

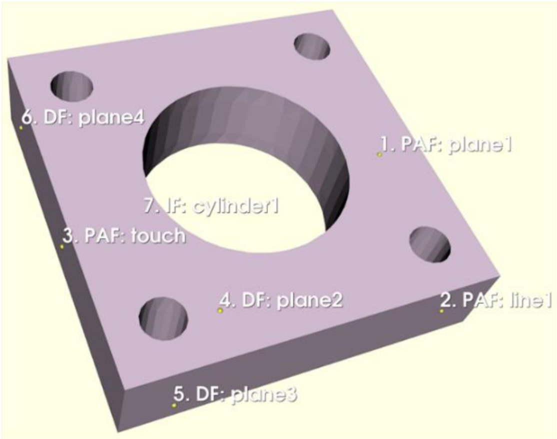


Figure 4.7 Example of the strategic planning sequence representation generated by IPaCK

4.2.2.3 User activity and motion trajectories

The next suggested output generated automatically, called tactical planning motion trajectory (Figure 4.8), presents the user activity and motion trajectory of a stylus as moved by the planner. The approaching segments of each point, called Chronocyclegraphs have been used successfully for representing knowledge generated in other engineering applications [141,172]. As illustrated in section 2.2.2, approach directions are key elements of any accessibility considerations during inspection planning. Therefore, this format allows the effective capture and representation of associated user activity when inspecting points across the various features of the component.

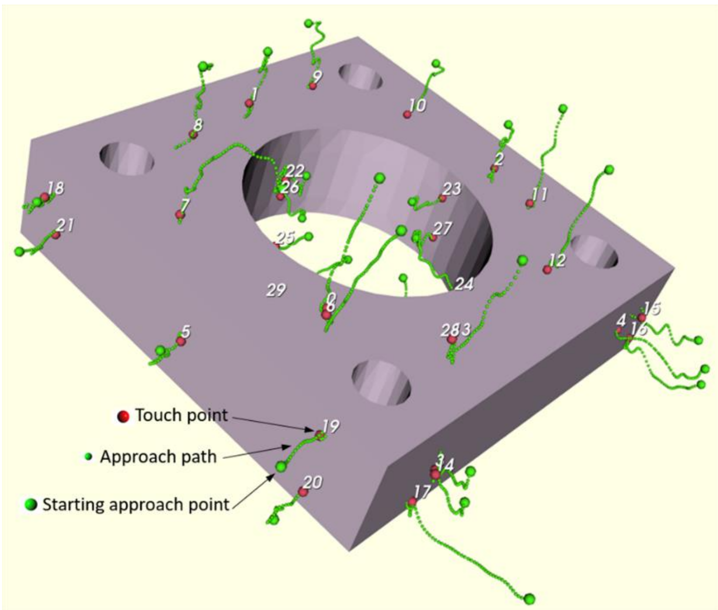


Figure 4.8 Example of the tactical planning motion trajectory generated by IPaCK

Each segment consists of a large green sphere indicating the starting approach point, the smaller green sphere shows the approach direction and path and finally the large red sphere represents the recorded contact point with the part. The number IDs on each segment highlights the order of the points as logged during the planning session. As mentioned in section 2.2.3, this format also serves as a basis for identifying and capturing user activity while planning the sample points on an inspection feature. This is critical to a planning strategy and therefore necessary to capture and represent within any proposed knowledge formats.

The planning activity motion trajectory not only visualises the intended strategy and planning, but also it offers indications of the planner's behaviour while generating the strategy, e.g. the spacing between the spheres indicates faster and confident moves. Chronocyclegraphs have been studied and associated with Therblig symbols in previous research [172]. This combination allows a rapid, in depth study of performed activities in a simple way. By processing and comparing different Therblig sequences for the same task, patterns of repeated behaviour can be detected facilitating the automation of a task or generation of best practices.

An extension of the previous output is shown in Figure 4.9; Groups of activities trajectory illustrates the planning strategy by separating it into three clusters: part alignment activity, datum feature activity and inspection feature activity, with each activity coloured differently. Recorded contact points are in red and labelled with numbers according to the inspection plan.

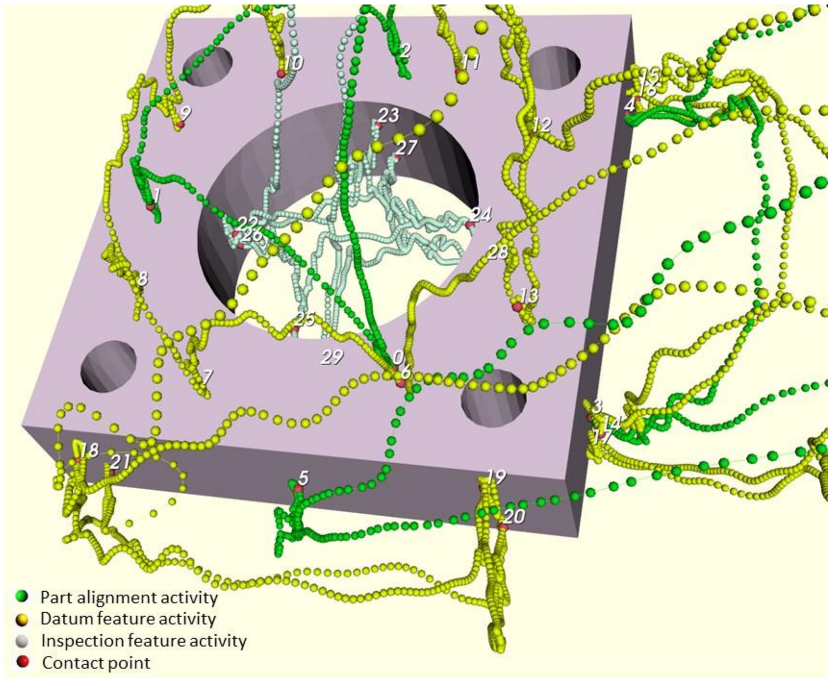


Figure 4.9 Example of the representation groups of planning activities generated by IPaCK

Figure 4.10 represents the same data as a sequence of logged inspection points, connected with straight lines, structured into the final inspection path as planned by the user. A ray-tracing algorithm (Appendix A.2) was found available [173], modified and integrated in the data post-processor to create collision-free paths. The algorithm uses as input the approach, start, retract and inspection points and conducts tests for intersections between paths (connecting lines) and the component. If an intersection is detected, the retract point's z-value is adjusted by 5mm and tested again for intersections, until a collision free path is reached.

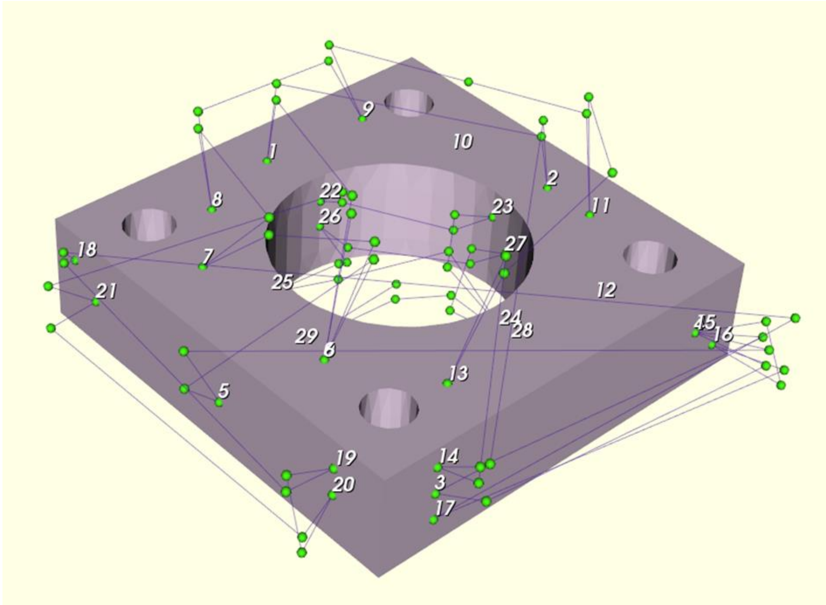


Figure 4.10 Example of the collision free inspection path generated by IPaCK

This format also contributes to the capture of the inspection strategy used so that the planning path is effectively and accurately represented. This requirement was highlighted in section 2.2.4 as critical data to capture and integrate throughout the suggested knowledge formats.

4.2.2.4 CMM part program

An additional format automatically generated by the data post-processing tool is a part program to drive a computer-controlled CMM. The point data are extracted from the inspection plan and converted into the CMM's coordinate system. Additionally, the part programming module adds safe go-to points when the machine's probing tool moves from one feature to another around the part. The program is produced in the DMIS code and adapted to be executable by the MODUS software package provided by Renishaw plc. However, the code generating algorithm can easily be modified to generate the output based on any other DMIS programming language. An example of such a program is shown in Figure 4.11.

```
MODE/PROG,MAN
GOTO/CART,13.78,23.47,24.26

$$<MEAS_PLANE name = "part alignment feature_plane1">
MODE/PROG,MAN
F(part alignment feature_plane1)=FEAT/PLANE,CART,36.6983,40.9272,0,0,0,1
MEAS/PLANE,F(part alignment feature_plane1),3
PTMEAS/CART,10.005,23.6583,0,0,0,1
PTMEAS/CART,35.03,66.2862,0,0,0,1
PTMEAS/CART,65.06,32.8371,0,0,0,1
ENDMES
$$<MEAS_PLANE = part alignment feature_plane1>

GOTO/CART,61.66,32.34,10.73
GOTO/CART,12.95,-6.87,0.26

$$<MEAS_LINE name = "part alignment feature_line1">
MODE/PROG,MAN
F(part alignment feature_line1)=FEAT/LINE,UNBND,CART,37.35,0,-8.495,0,-1,0
MEAS/LINE,F(part alignment feature_line1),2
PTMEAS/CART,9.96,0,-8.495,0,-1,0
PTMEAS/CART,64.74,0,-8.495,0,-1,0
ENDMES
$$<MEAS_LINE = part alignment feature_line1>

GOTO/CART,62.09,-15.22,0.42
GOTO/CART,-5.6,35.87,2.04

$$<MEAS_POINT name = "part alignment feature_touch">
MODE/PROG,MAN
F(part alignment feature_touch)=FEAT/POINT,CART,0,34.9067,-10.005,-1,0,0
MEAS/POINT,F(part alignment feature_touch),1
PTMEAS/CART,0,34.9067,-10.005,-1,0,0
ENDMES
$$<MEAS_POINT = part alignment feature_touch>

GOTO/CART,-5.6,35.87,-8.96
GOTO/CART,13.78,23.47,24.26

$$<MEAS_PLANE name = "datum feature_plane2">
MODE/PROG,MAN
F(datum feature_plane2)=FEAT/PLANE,CART,36.2813,36.6446,0,0,0,1
MEAS/PLANE,F(datum feature_plane2),8
PTMEAS/CART,10.005,23.6583,0,0,0,1
PTMEAS/CART,10.005,51.2449,0,0,0,1
PTMEAS/CART,20.015,61.603,0,0,0,1
PTMEAS/CART,55.05,65.7739,0,0,0,1
PTMEAS/CART,62.69,49.7,12.5,0,0,1
PTMEAS/CART,65.06,23.6125,0,0,0,1
PTMEAS/CART,39.2461,16.9877,-5,0,0,1
PTMEAS/CART,20.015,8.8319,0,0,0,1
ENDMES
$$<MEAS_PLANE = datum feature_plane2>

GOTO/CART,26.58,6.16,17.16
GOTO/CART,12.23,-5.8,-3.64

$$<MEAS_PLANE name = "datum feature_plane3">
MODE/PROG,MAN
F(datum feature_plane3)=FEAT/PLANE,CART,38.6062,0,-9.74625,0,-1,0
MEAS/PLANE,F(datum feature_plane3),4
PTMEAS/CART,9.96,0,-3.49,0,-1,0
PTMEAS/CART,64.74,0,-8.495,0,-1,0
PTMEAS/CART,69.72,0,-13.5,0,-1,0
PTMEAS/CART,10.005,0,-13.5,0,-1,0
ENDMES
$$<MEAS_PLANE = datum feature_plane3>

GOTO/CART,67.31,-15.22,3.72
GOTO/CART,-4.15,66.74,0.35

$$<MEAS_PLANE name = "datum feature_plane4">
MODE/PROG,MAN
F(datum feature_plane4)=FEAT/PLANE,CART,0,38.6467,-7.5025,-1,0,0
MEAS/PLANE,F(datum feature_plane4),4
PTMEAS/CART,0,69.8133,-5,-1,0,0
PTMEAS/CART,0,9.97333,-5,-1,0,0
PTMEAS/CART,0,9.97333,-10.005,-1,0,0
PTMEAS/CART,0,64.8267,-10.005,-1,0,0
ENDMES
$$<MEAS_PLANE = datum feature_plane4>

GOTO/CART,-10.15,62.19,0.73
GOTO/CART,37.53,50.94,1.53

$$<MEAS_CYLNDR name = "inspection feature_cylinder1">
MODE/PROG,MAN
F(inspection feature_cylinder1)=FEAT/CYLNDR,INNER,CART,38.8937,37.993,-7.5025,0,0,1,40
MEAS/CYLNDR,F(inspection feature_cylinder1),8
PTMEAS/CART,39.2461,57.9123,-5,0,-1,0
PTMEAS/CART,57.9,37.45,-5,-0.995584,-0.0922546,0.0173746
PTMEAS/CART,39.2461,16.9877,-5,-0.183722,0.982826,0.0173207
PTMEAS/CART,18.1877,44.8735,-5,0.895163,-0.445738,0
PTMEAS/CART,39.2461,57.9123,-10.005,-0.183749,-0.982973,0
PTMEAS/CART,57.5501,33.674,-10.005,-0.961825,0.273664,0
PTMEAS/CART,42.9738,17.6845,-10.005,-0.361241,0.932472,0
PTMEAS/CART,16.8,37.45,-10.005,0.995734,0.092268,0
ENDMES
$$<MEAS_CYLNDR = inspection feature_cylinder1>

GOTO/CART,38.03,38.32,-13.29
```

Figure 4.11 Example of a CMM part program generated by IPaCK

A part program could be considered as a knowledge representation; however, this format has been excluded from the evaluation process. Since in the experimental trials, inexperienced engineers would take part, they could not evaluate it as it requires quite extensive programming experience. Moreover, a part program is the main output from a CMM inspection planning task and it is already commonly used in the area. Therefore, there was no point of evaluating it. The purpose of this research was to devise new output formats and investigate the potential of them for representing inspection planning knowledge and strategy. However, in this section it is shown that a CMM program can be generated as output by the IPACK's tools.

4.2.2.5 Integrated Definition (IDEF0) diagram

VBA macros (Appendix A.4) within an Excel spreadsheet were developed in order to output a process flow chart in the form of an IDEF0 diagram using the generated inspection plan previously presented. IDEF0 is a tool to model functions, decisions, actions and activities of a system or organisation [145]. This method has been successfully used for modelling the activity and thought process during design and planning tasks in past works [166,174]. This format allows an easy to follow description of the planning steps highlighting key elements such as the feature geometry, scope of use, number of points and type of tool at each sub-activity. The reader can identify key decisions made during the strategy as well as the sequence of steps to follow. Two examples of this format are depicted in Figure 4.12, showing the part alignment stage and a hole's true position tolerance inspection key activities. The IDEF0 diagrams can also be combined with the inspection plan format to study the strategy with a more complete perspective.

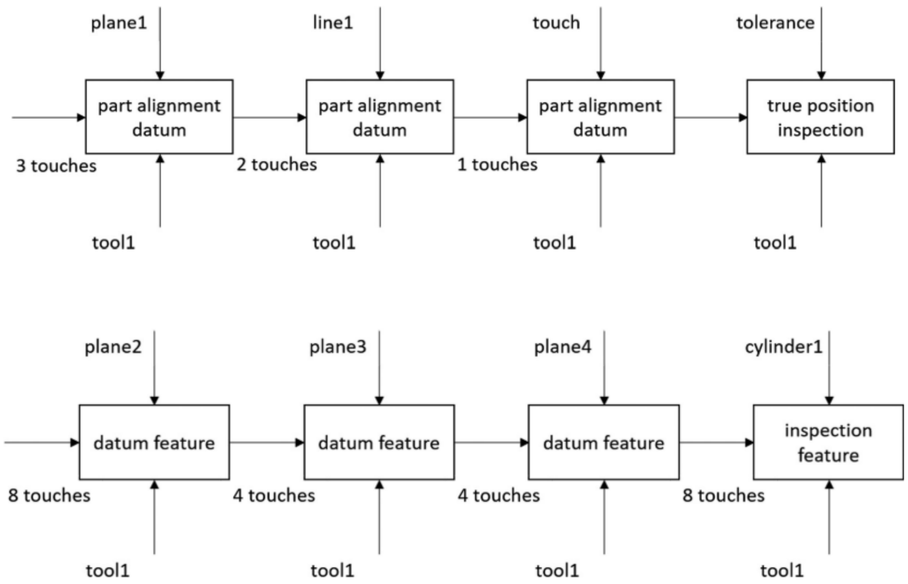


Figure 4.12 Examples of IDEF0 diagrams of planning strategy for part alignment (top) and true position inspection (bottom) generated by IPaCK

4.2.2.6 Plain text instructions

An additional representation format defined is plain text instructions (Figure 4.13) which provide a short description of each step of the planning strategy listed in a timed manner. By generating this structure, a set of instructions sorted in the chronological order as set by the human planner provides a convenient way for a quick and easy review of the planned strategy; this format has been suggested in previous works [175] specifically for helping novice users to understand and replicate the represented knowledge and strategy. Plain text instructions can also be an alternative richer textual form of the data included in the inspection plan.

Time (sec)	Instruction
--------------	--------------
22.14	Probe plane1 as part alignment feature using tool1 with 3 points
31.15	Probe line1 as part alignment feature using tool1 with 2 points
37.05	Probe a touch as part alignment feature using tool1 with 1 point
42.00	True position tolerance is under test
43.70	Probe plane2 as datum feature using tool1 with 8 points
57.29	Probe plane3 as datum feature using tool1 with 4 points
66.92	Probe plane4 as datum feature using tool1 with 4 points
79.41	Probe cylinder1 as inspection feature using tool1 with 8 points

Figure 4.13 Example of plain text representation format generated by IPaCK

4.2.2.7 Annotated video clip

Annotated video clips has been the most preferred forms of knowledge representation in previous research [166]. This study also includes this format. Figure 4.14 shows sample screenshots of an example video clip where the expert planner performs a strategy. The embedded subtitles describe the actions taking place at each step. To generate this format, a video recording device was used during the planning session and the output inspection plan was processed within a spreadsheet and VBA macros developed for this research (Appendix A.5) producing a subtitle text file with all the related information.

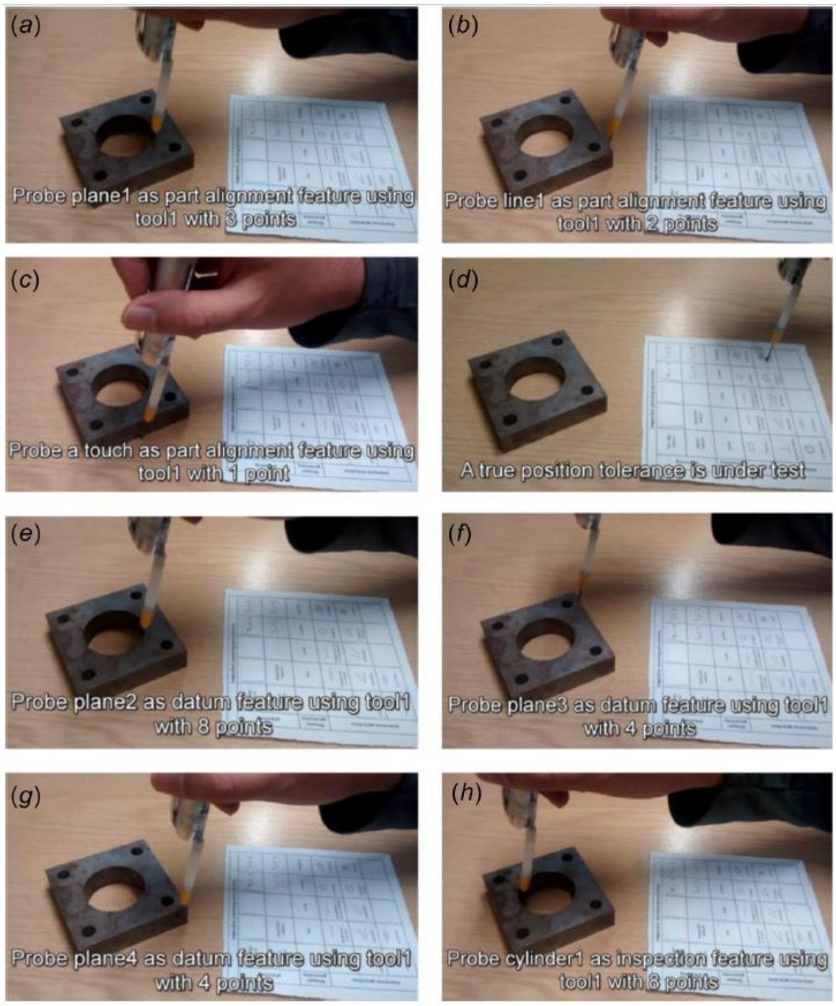


Figure 4.14 Screenshots of annotate video clip with embedded subtitles generated by IPaCK

4.2.2.8 Storyboard

As a last knowledge representation, a combination of different outputs can be structured to produce a storyboard. Sung et al. [133] showed that this format provides an improved overview of captured activity and strategy in a chronological order. A storyboard sample is shown in Figure 4.15, integrating the IDEF0 diagram, inspection plan section, textual description and a screenshot of the annotated video clip. It must be noted that although the different formats are generated automatically, the integration of them is done manually without however spending much time to produce the final output.

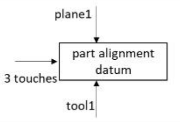
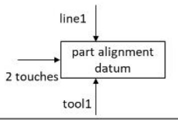
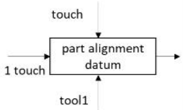
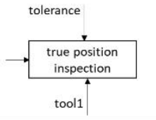
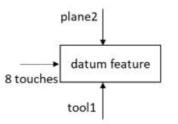
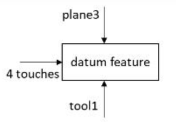
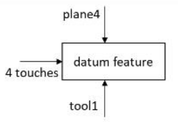
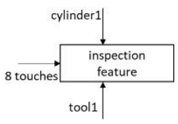
Time (sec)	IDEF	Inspection plan	Text instructions	Screenshot
22		part alignment feature,plane1,4.51,-84.25,0.92,22.1417,3,tool1 touch, 0, 10.005, 23.6583, 18.5, 0, 0, 1, 27.1333 touch, 1, 35.03, 66.2862, 18.5, 0, 0, 1, 28.25 touch, 2, 65.06, 32.8371, 18.5, 0, 0, 1, 29.3667	Probe plane1 as part alignment feature using tool1 with 3 points	
31		part alignment feature,line1, 6.62,-87.32,1.07,31.1667,2,tool1 touch, 3, 9.96, 0, 10.005, 0, -1, 0, 33.5333 touch, 4, 64.74, 0, 10.005, 0, -1, 0, 35.1333	Probe line1 as part alignment feature using tool1 with 2 points	
37		part alignment feature,touch,10,-86.65,0.87,37.0583,1,tool1 touch, 5, 0, 34.9067, 8.495, -1, 0, 0, 38.9167	Probe a touch as part alignment feature using tool1 with 1 point	
42		true position, tolerance,92.55,-164.78,0.92,42,tool1	A true position tolerance is under test	
43		datum feature,plane2,7.08,-104.59,0.97,43.7083,8,tool1 touch, 6, 10.005, 23.6583, 18.5, 0, 0, 1, 46.4667 touch, 7, 10.005, 51.2449, 18.5, 0, 0, 1, 47.5833 touch, 8, 20.015, 61.603, 18.5, 0, 0, 1, 48.5833 touch, 9, 55.05, 65.7739, 18.5, 0, 0, 1, 49.6167 touch, 10, 60.055, 49.8667, 18.5, 0, 0, 1, 51.1 touch, 11, 65.06, 23.6125, 18.5, 0, 0, 1, 52.45 touch, 12, 50.045, 8.56567, 18.5, 0, 0, 1, 53.9 touch, 13, 20.015, 8.8319, 18.5, 0, 0, 1, 55.05	Probe plane2 as datum feature using tool1 with 8 points	
57		datum feature,plane3,5.14,-106.27,1.05,57.3,4,tool1 touch, 14, 9.96, 0, 15.01, 0, -1, 0, 59.6167 touch, 15, 64.74, 0, 10.005, 0, -1, 0, 61.4667 touch, 16, 69.72, 0, 5, 0, -1, 0, 62.8833 touch, 17, 10.005, 0, 5, 0, -1, 0, 64.4667	Probe plane3 as datum feature using tool1 with 4 points	
66		datum feature,plane4,7.42,-104.4,1.03,66.9333,4,tool1 touch, 18, 0, 69.8133, 13.5, -1, 0, 0, 70.4333 touch, 19, 0, 9.97333, 13.5, -1, 0, 0, 72.1833 touch, 20, 0, 9.97333, 8.495, -1, 0, 0, 74.6083 touch, 21, 0, 64.8267, 8.495, -1, 0, 0, 76.275	Probe plane4 as datum feature using tool1 with 4 points	
79		inspection feature,cylinder1,28.5,-104.75,0.93,79.4167,8,tool1 touch, 22, 39.2461, 57.9123, 13.5, 0, -1, 0, 83.2583 touch, 23, 57.9, 37.45, 13.5, -0.9955, -0.09225, 0.01737, 84.9917 touch, 24, 39.2461, 16.9877, 13.5, -0.1837, 0.9828, 0.01732, 86.7583 touch, 25, 18.1877, 44.8735, 13.5, 0.895163, -0.445738, 0, 88.4083 touch, 26, 39.2461, 57.9123, 8.495, -0.183749, -0.982973, 0, 90.075 touch, 27, 57.5501, 33.674, 8.495, -0.961825, 0.273664, 0, 91.4917 touch, 28, 42.9738, 17.6845, 8.495, -0.361241, 0.932472, 0, 93.0583 touch, 29, 16.8, 37.45, 8.495, 0.995734, 0.092268, 0, 94.4917	Probe cylinder1 as inspection feature using tool1 with 8 points	

Figure 4.15 Storyboard knowledge representation generated by IPaCK

4.3 Pilot study - Knowledge representations evaluation

A pilot study was planned and carried out for evaluating the proposed knowledge and strategy representations. 20 experienced CMM planners responded to an online questionnaire structured and published using a free online surveys website [176]. In the current research, experience or expertise level will be treated as the amount of time (in years) spent in practising in CMM inspection planning tasks as suggested in previous works [177,178].

Potential participants of this pilot study were invited through a generic request to an online community [179] and a series of discussion groups for CMM inspection on a professionals networking website [180]. The only criterion for inviting individuals to participate in the pilot study was that their current profession is on CMM measurement and programming. With this condition, it was assumed that most of the daily workload of the participants is on CMM programming. No other pre-selection assessment was undertaken on the respondents at this stage, as the purpose of this pilot study was mainly to obtain initial feedback and personal viewpoints on the designed knowledge representations. Also, it was assumed that a statement of the level of experience (in years) in CMM measurements by each of the participants would be valid for the purposes of the study.

The main objective of this pilot study was the evaluation of the proposed knowledge representations (presented in the section 4.2.2) in the aspects of ease of understanding, usefulness and overall performance. Additionally, the participants were asked to state their preferred combination of two formats for representing the intended planning strategy. Such an approach has been employed in previous research [4] for evaluating similar representations in design tasks. The quality of the represented strategy was not assessed as the purpose of the pilot study was to obtain initial feedback from experienced CMM planners on the proposed formats and how well they perform as representations.

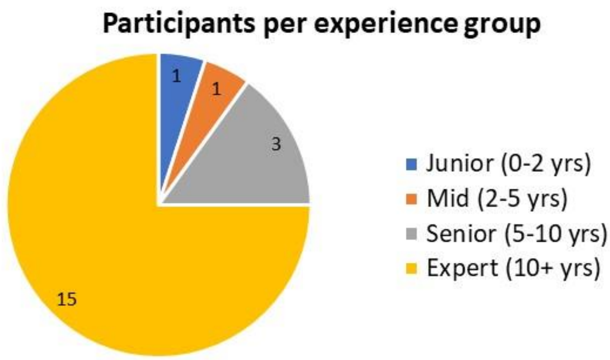
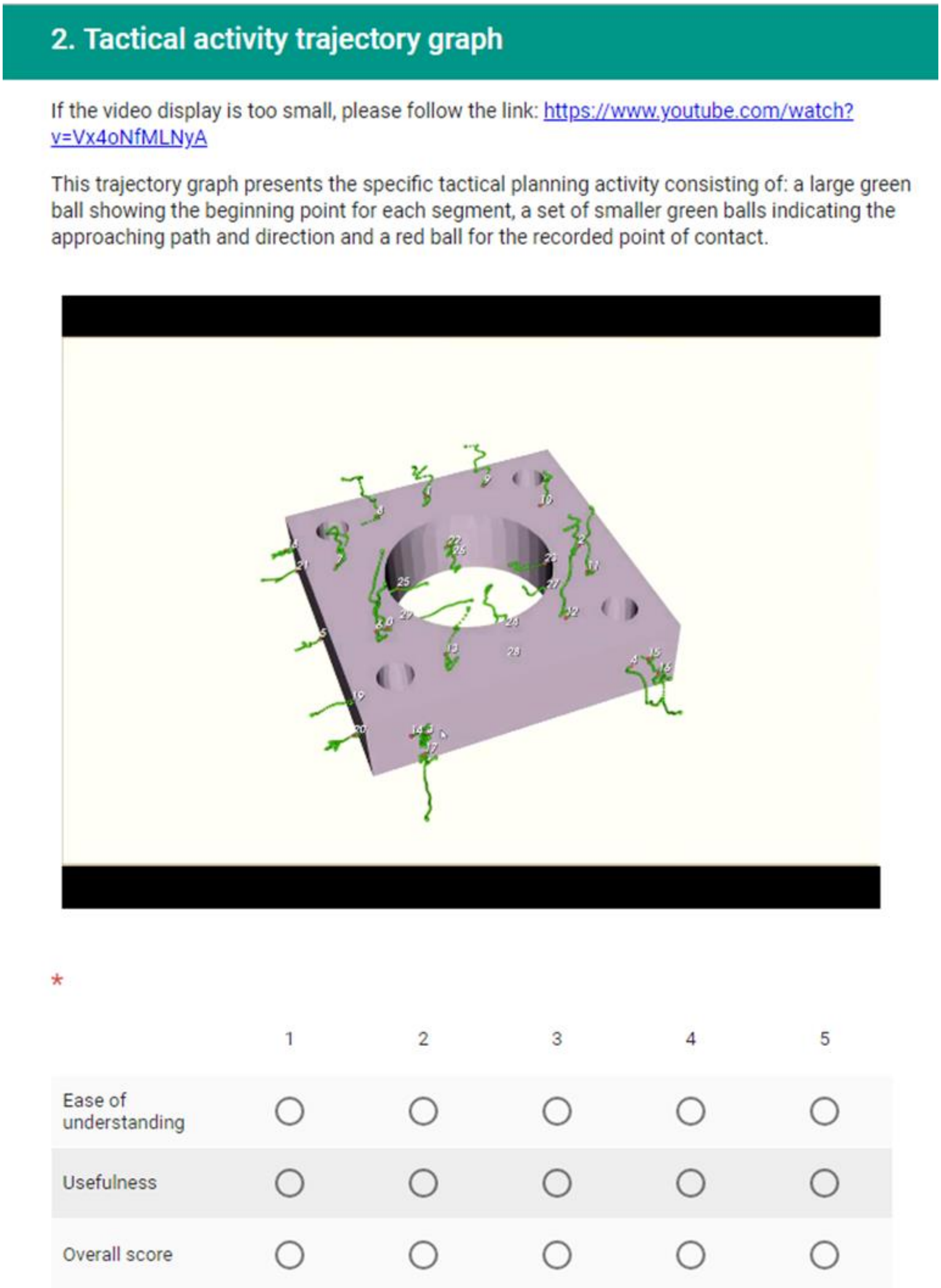


Figure 4.16 Participants per experience grop of knowledge representations evaluation pilot study

In Figure 4.16, the experience of the participants validates that the responses are of high quality and reliability since most of the engineers possess over 10 years of experience in

CMM inspection planning. Therefore, feedback from this pilot study can effectively be used for further improvements on specific issues raised by the experienced participants.

Each of the designed formats was rated with a score from 1 (lowest) to 5 (highest) for ease of understanding, usefulness and overall performance. These three evaluation aspects confirm and validate to what level each format can help in understanding and following the captured strategy, including how well these specific forms represent the inspection plan. In each question a brief description of the format was provided. A sample of the questionnaire is shown in the Figure 4.17 which illustrates the tactical planning activity of the measurement. The complete questionnaire can be found in Appendix B.1.



2. Tactical activity trajectory graph

If the video display is too small, please follow the link: https://www.youtube.com/watch?v=Vx4oNfMLNyA

This trajectory graph presents the specific tactical planning activity consisting of: a large green ball showing the beginning point for each segment, a set of smaller green balls indicating the approaching path and direction and a red ball for the recorded point of contact.

*

	1	2	3	4	5
Ease of understanding	○	○	○	○	○
Usefulness	○	○	○	○	○
Overall score	○	○	○	○	○

Figure 4.17 Example section of the questionnaire used in the pilot study

4.3.1 Pilot study results

The raw data results given in Appendix C.1 and illustrated graphically in Figure 4.18 show that the participants were able to understand and follow the strategy represented in all the tested knowledge formats. They gave the highest average score for *overall performance* (58%) and *usefulness* (56%) to the storyboard as this provided a complete structure with multiple representations and is built to provide an easy to follow step-by-step guide. In the aspect of *understanding*, plain text instructions received the highest average (64%) due to its clarity and simplicity of description. Other formats such as strategic planning sequence and annotated video clip were also rated close to the first one, the plain text instructions.

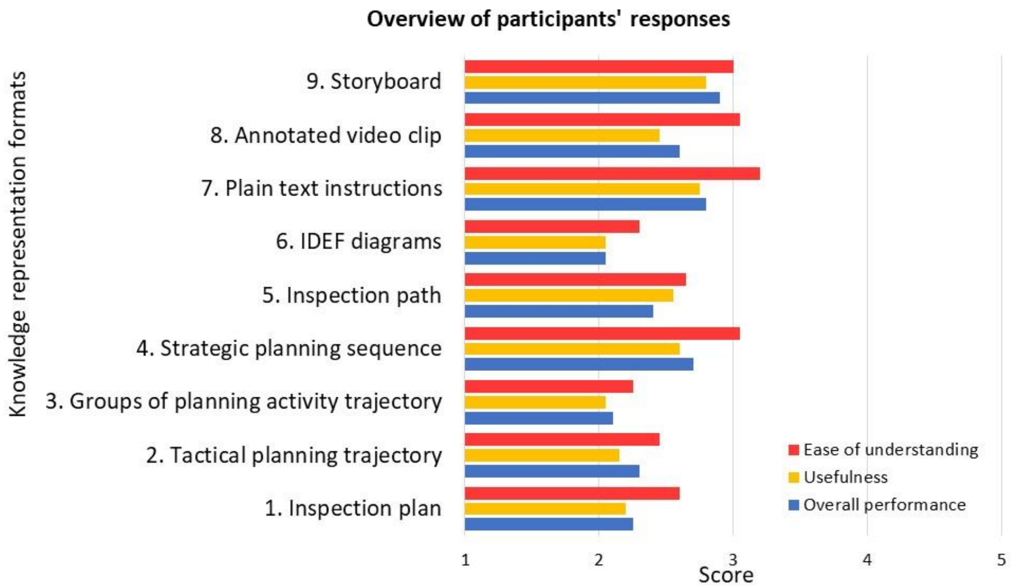


Figure 4.18 Pilot study results - Average ratings of representation formats in the aspects: easure of understanding, usefulness, overall performance

The participants of the pilot study were also asked to state their preferred combination of any two formats. Figure 4.19 presents the preferences of the selected combinations as stated by the participants. The most preferred combination was the storyboard along with annotated video clip which as similarly was found in a previous study [4].

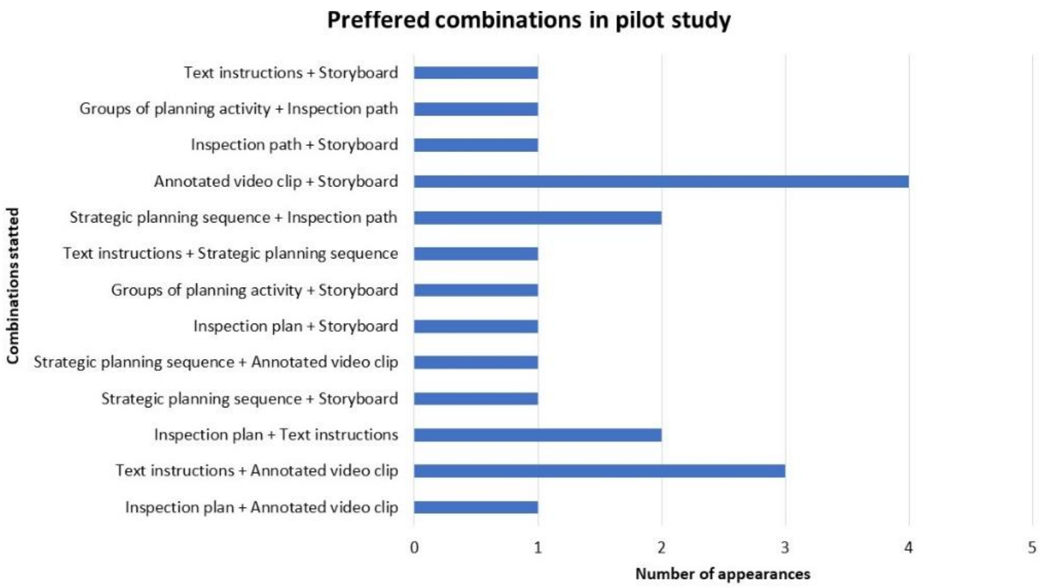


Figure 4.19 Pilot study results – Number of appearances of chosen combinations

In Figure 4.20 the number of appearances of each format in the preferred combinations is shown. The storyboard and annotated video clip were the two most frequent options amongst these with 9 appearances each of them.

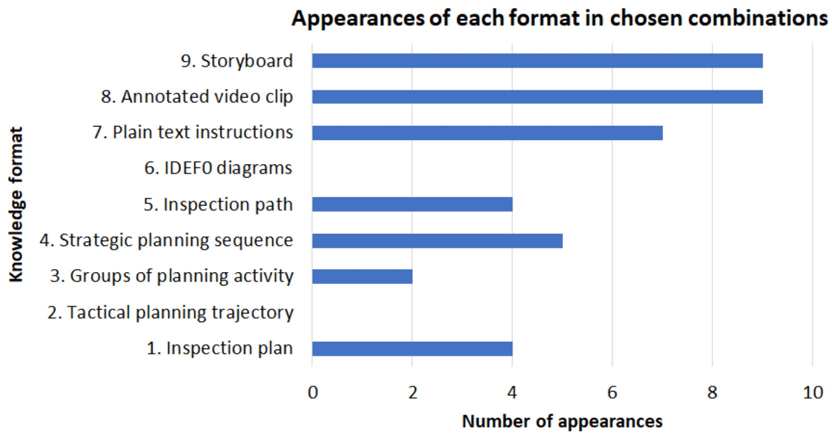


Figure 4.20 Pilot study results - Number of appearances of each format in chosen combinations

From the results, the more visual an output is the easier the understanding and to follow was perceived. Furthermore, outputs structured clearly as step-guides were preferred over just text instructions and strategic planning sequence graph.

Finally, each participant freely commented on the aspects of this pilot study. One mentioned *"Keep it simple and visual - users haven't got the time/patience to read through text/code."* This statement appears to be pertinent considering the preference for more visual and simple forms of representations. Other comments relate to displaying the normal vectors of touch points and the need to show the alignment stage's coordinate system during the planning session, which will aid to a better description of the measurement strategy. Based on these responses research objective (RO4) has been achieved, and the formats will be subsequently improved.

4.3.2 Lessons learnt

The main purpose for carrying out this pilot study was to test and confirm the basic functionality of IPaCK and methodology as well as to detect any problems and weaknesses so that the main experimental study including a larger range of users could be informed and updated properly.

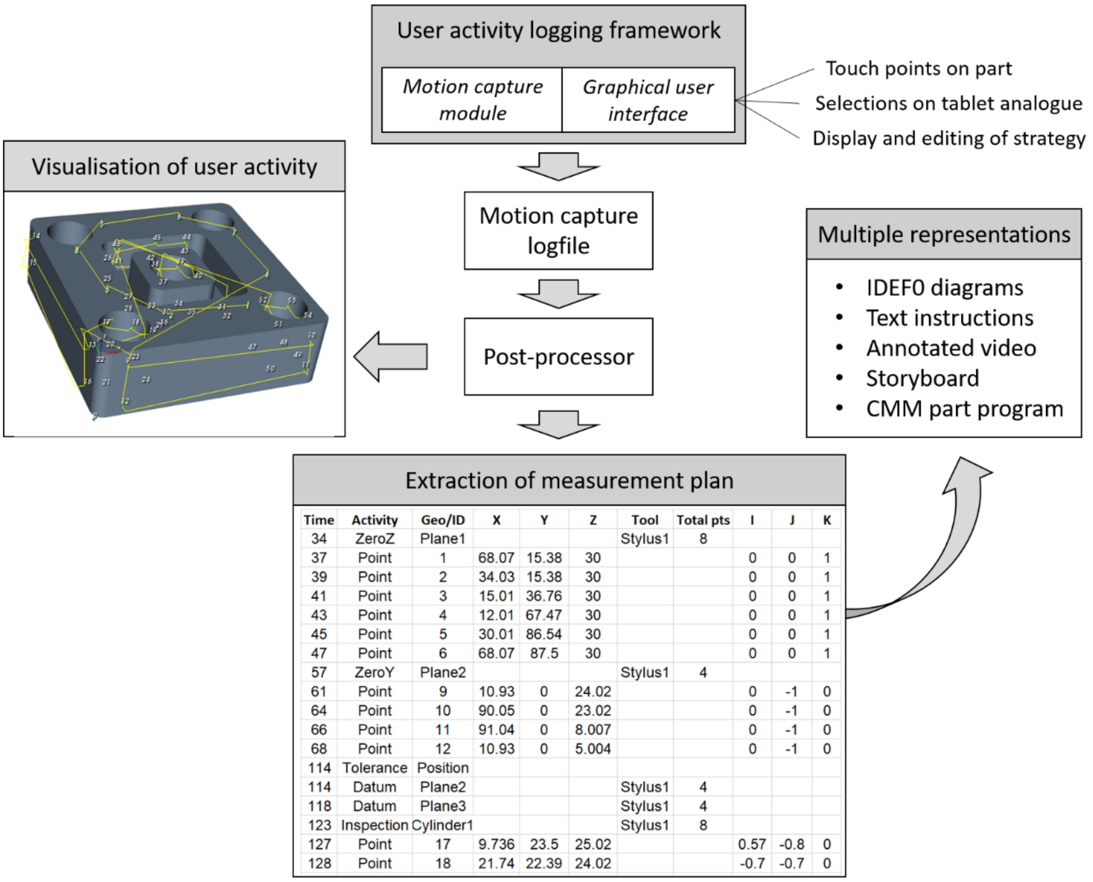
The most important observation was that experienced planners were able to understand how IPaCK works and that its automatically generated output formats can represent CMM inspection planning domain knowledge. The feedback obtained through the system's functionality test and online survey also highlighted the need for further improvements:

- A requirement for a real time interactive digital interface for informing the user what steps have been carried out, how they have been made and how they can be edited.
- Modifications to the marker-stylus so that higher precision motion tracking is enabled.
- Updating the knowledge representation formats to be more compact, simple and visual.
- The use of combinations of formats to represent knowledge and strategies in a more complete manner.

At this point in the research, it can be stated that the first research objective has been partly met with regards to design and developing a user logging system for CMM inspection planning strategies capture (RO1). The next objective related to structuring proper knowledge representations and building a tool for automated generation of them have been addressed completely (RO2 and RO4). IPaCK's functionality enables planning CMM measurements as well as logging user activity; it can also automatically generate a range of validated knowledge representation formats. However, IPaCK's interface and its outputs required more rigorous testing and evaluation.

4.4 Final prototype

From the findings and feedback, modifications are presented here to better capture and represent the activity and decision making in planning a CMM measurement strategy. The main modification concerns the addition of a graphical user interface to inform the planner what activity has been completed and options for editing this. The updated technical framework is schematically presented in the following Figure 4.21. Further changes are discussed in the following sections.



Time	Activity	Geo/ID	X	Y	Z	Tool	Total pts	I	J	K
34	ZeroZ	Plane1				Stylus1	8			
37	Point	1	68.07	15.38	30			0	0	1
39	Point	2	34.03	15.38	30			0	0	1
41	Point	3	15.01	36.76	30			0	0	1
43	Point	4	12.01	67.47	30			0	0	1
45	Point	5	30.01	86.54	30			0	0	1
47	Point	6	68.07	87.5	30			0	0	1
57	ZeroY	Plane2				Stylus1	4			
61	Point	9	10.93	0	24.02			0	-1	0
64	Point	10	90.05	0	23.02			0	-1	0
66	Point	11	91.04	0	8.007			0	-1	0
68	Point	12	10.93	0	5.004			0	-1	0
114	Tolerance	Position								
114	Datum	Plane2				Stylus1	4			
118	Datum	Plane3				Stylus1	4			
123	Inspection	Cylinder1				Stylus1	8			
127	Point	17	9.736	23.5	25.02			0.57	-0.8	0
128	Point	18	21.74	22.39	24.02			-0.7	-0.7	0

Figure 4.21 Final technical framework of IPaCK and proposed methodology

4.4.1 Updated apparatus and user activity logging

Although the underlying framework (utilising motion tracking technology) remains the same, necessary improvements to the experimental setup were identified through the pilot study. To advance IPaCK's interactivity and user experience during a planning session the following were included:

- a hand-held stylus with 4 passive retro-reflective spherical markers and an IR-LED,
- an extended tablet analogue with more options,
- a graphical user interface, showing at real time the steps and points recorded.

Four passive markers were now used to improve the calculation of the stylus' tip position (Figure 4.22). Moreover, the IR-LED button's functionality was modified; by pressing the button (stylus' clip), an inspection point was now recorded.

Z zero	Y zero	X zero	Datum	Inspection
Tool 1	Tool 2	Tool 3		Point
Plane	Line	Circle	Cylinder	Freeform
Flatness	Straightness	Circularity	Cylindricity	Perpendicularity
Angularity	Parallelism	Profile	Position	Concentricity
Symmetry				

Figure 4.22 Updated IPaCK's user input devices: Hand-held stylus (left) – tablet analogue (right)

Another enhancement relates to the tablet analogue available planning options. The part alignment button was replaced with three distinct buttons that define X, Y and Z zero levels, necessary to construct the part alignment stage's spatial coordinate system (Figure 4.22). With this addition, decision making during the part alignment stage is broken down at a more detailed level, providing further insight into the strategy used.

Finally, the main improvement was to the graphical user interface (GUI) (Figure 4.23). This interface was developed using the Qt framework and libraries [181] and the C++ programming language. The key benefit for this update is the display of the steps performed in real time on a computer monitor, both as a graphical output, mapping the points on the digital model of the component, and as a procedural list for informing the user what has already logged in much greater detail. A set of 'edit' buttons embedded in the interface allowing the user to modify the strategy by repeating, deleting, inserting or undoing a step.

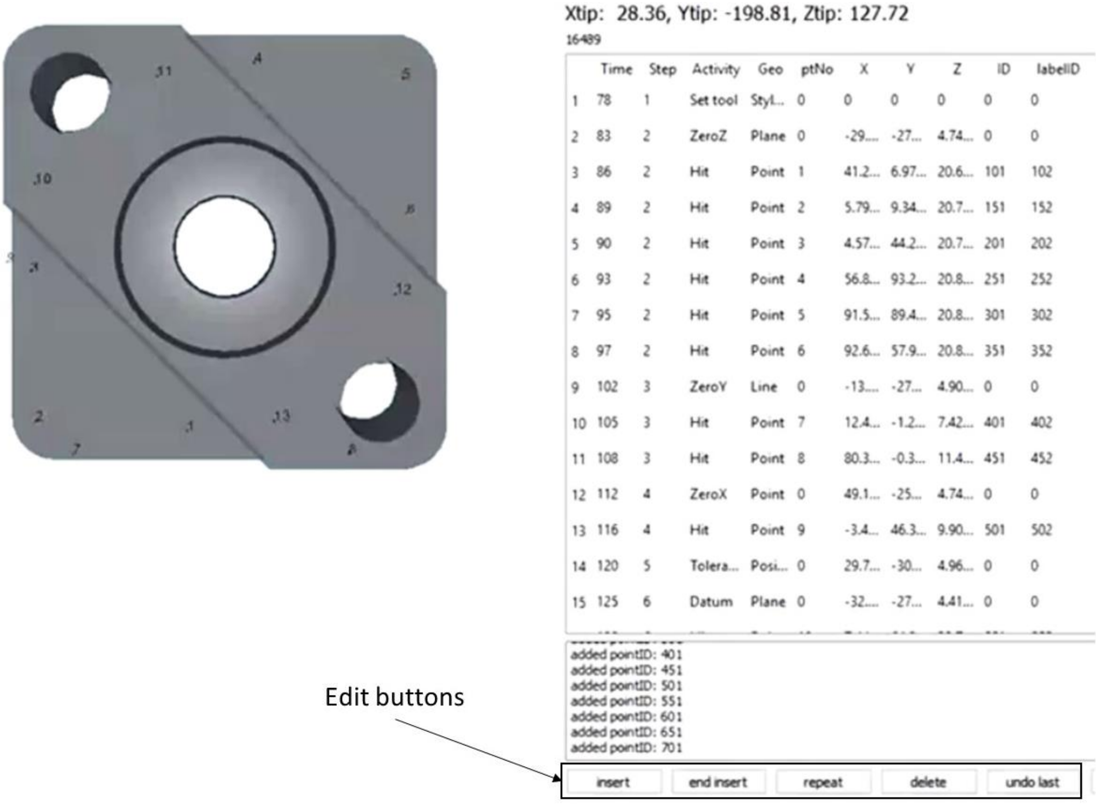
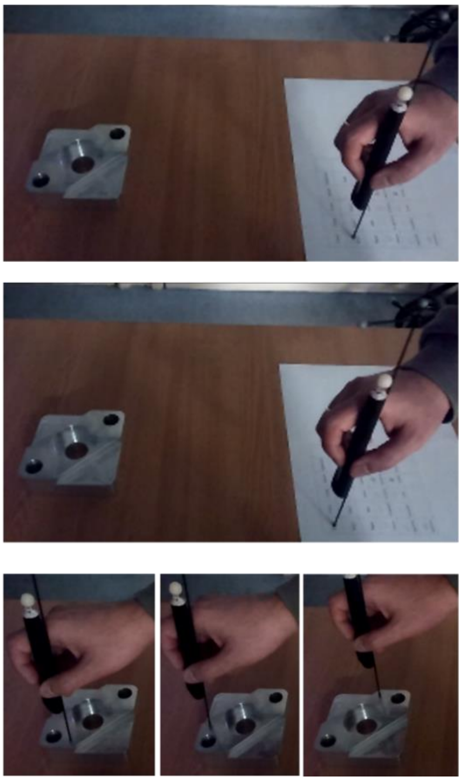


Figure 4.23 Graphical user interface and display of logged activity and steps.

Another modification implemented was the addition of playing a sound related to the contact point registered or option selected on tablet analogue. These then appear directly on the interface's digital display, providing the user both visual and sound feedback on the performed steps and actions. The updated functionality of the IPaCK and a typical procedure followed during a planning session is illustrated in detail in Figure 4.24 as well as in the related video in Appendix A.8

Procedure steps:



1. The user begins planning by setting the inspection tool on the tablet analogue.

2. Then the required planning sub-activity and geometry to measure are set by "hitting" the respective boxes on the grid.

3. After, the user touches the component with the stylus' tip and presses the clip-button for recording each contact point to form the required feature.

Figure 4.24 Procedure to follow during the experimental measurement planning session Appendix A.8

The output data log-file includes a list of all the activity performed (Table 4.3) along with each points' spatial coordinates, capturing the activity data in a temporal manner and describing the decision making of the user during planning an inspection. In its final form, the log-file does not include the whole motion trajectory of the stylus but only the key steps and moves related to a point or an activity on order to ease computational load during data processing steps for tracking and real time reporting. Hence, instead of storing the complete path of used markers as in the pilot study, only the stylus-tip position data at specific times are logged leading to a significantly reduced log-file size and data processing time. These data are stored and exported in the form of a table, including each planning sub-activity performed, the x, y, z coordinates of tip's position in mm, the numbered label of each point recorded and geometrical and tolerancing information.

Table 4.3 IPaCK's user logging output data file

Time (Sec)	Activity	Geo/Feature	Point ID	X-Y-Z (mm)			index
30	setTool	Stylus1	0	0	0	0	0
34	ZeroZ	Plane	0	4.213	-170.5	4.886	0
37	Hit	Point	1	68.41	15.29	31.9	101
39	Hit	Point	2	33.77	15.287	32.35	151
41	Hit	Point	3	15.04	36.494	32.03	201
43	Hit	Point	4	12.21	67.338	32.19	251
45	Hit	Point	5	30.35	86.624	32.07	301
47	Hit	Point	6	68.12	87.817	31.8	351
48	Hit	Point	7	87.75	69.719	31.7	401
51	Hit	Point	8	87.01	34.863	31.7	451
57	ZeroY	Plane	0	9.709	-176.5	4.866	0
61	Hit	Point	9	10.57	-0.522	24.02	501
64	Hit	Point	10	90.18	-1.803	23.51	551
66	Hit	Point	11	91.37	-2.171	7.824	601
68	Hit	Point	12	11.3	-0.88	5.305	651
80	ZeroX	Plane	0	8.514	-169.4	4.699	0
83	Hit	Point	13	-1.25	11.446	24.18	701
86	Hit	Point	14	-2.62	90.708	25.22	751
88	Hit	Point	15	-1.83	92.662	9.752	801
91	Hit	Point	16	-2.19	13.255	6.132	851
98	Tolerance	Position	0	65.15	-211	4.847	0
114	Datum	Plane	0	10.57	-0.522	24.02	999
118	Datum	Plane	0	-1.25	11.446	24.18	999
123	Inspection	Cylinder	0	65.94	-174.8	2.365	0
127	Hit	Point	17	10.04	22.586	25.07	901
128	Hit	Point	18	22.2	22.395	24.38	951
130	Hit	Point	19	22.58	13.283	25.91	1001
132	Hit	Point	20	9.189	11.535	25.28	1051
134	Hit	Point	21	9.072	11.337	7.462	1101
136	Hit	Point	22	8.879	22.015	7.851	1151
138	Hit	Point	23	21.8	20.606	7.636	1201
140	Hit	Point	24	21.61	10.045	5.57	1251
152	Tolerance	Position	0	67.32	-210.3	4.743	0
160	Datum	Plane	0	7.434	-171.7	4.691	0
163	Hit	Point	25	25.95	64.104	17.44	1301
166	Hit	Point	26	26.95	65.888	26.3	1351
169	Hit	Point	27	26.45	40.023	24.34	1401
170	Hit	Point	28	27.06	38.712	18.54	1451
175	Datum	Plane	0	5.146	-175.1	4.735	0
178	Hit	Point	29	34.1	26.013	19.05	1501
179	Hit	Point	30	35.67	26.754	25.08	1551
182	Hit	Point	31	61.5	26.598	24.19	1601
183	Hit	Point	32	63.92	26.74	19.3	1651
189	Inspection	Cylinder	0	65.9	-174.6	4.594	0
192	Hit	Point	33	45.94	58.193	4.381	1701
194	Hit	Point	34	57.07	56.291	5.277	1751
195	Hit	Point	35	57.64	46.324	7.702	1801
197	Hit	Point	36	45.07	43.415	7.313	1851
199	Hit	Point	37	43.26	45.127	25.89	1901
201	Hit	Point	38	44.96	56.207	26.27	1951
203	Hit	Point	39	55.35	56.984	25.77	2001
204	Hit	Point	40	56.94	44.423	27	2051

4.4.2 Final knowledge representations

In this section, the final combined knowledge representations are presented along with the modifications applied after considering the feedback and comments received from the pilot study.

4.4.2.1 Inspection plan and tactical planning trajectory

As in the previous version of IPaCK's outputs, the inspection plan (Table 4.4) is a key representation of the intended strategy. A modification applied, considered one of the comments from the pilot study stated that it would be beneficial to include the normal vector for each measurement point in the inspection plan and the rest of outputs. With the use of the normals, a CMM planner can understand the required approaching direction for selecting each point. Moreover, the part alignment process was split up and represented as subsequent steps, showing the separate actions for defining X, Y and Z zero levels in order to construct the alignment's coordinate system. This facilitates another requirement as pointed out from the experienced planners' feedback.

An example of the updated inspection plan is shown in Table 4.4. The first section shows the steps for aligning the part virtually on the CMM table. In this example, three planes were created with their respective labels shown under the column Geo/ID. Below, the point sets for each feature follow the line stating the activity, feature type, tool used and total number of points. According to the implemented modifications, each line illustrating a contact point includes also three columns for the I, J and K components of the respective normal vector.

The main inspection routine shows the strategy for measuring the selected features and tolerances. The details are displayed in the order in which each activity was performed and logged. First, the type of tolerance is selected, followed by the datum features related to this tolerance and finally the feature under inspection. When a line for setting a datum or inspection feature is not followed by a point's details, it is implied that a previously selected feature has been reused and the same feature label is added to highlight this. By studying this format, the measurement strategy is represented both strategically and tactically, facilitating a better understanding of the plan at both a high and low level of detail. The time on each line can be used for analysing the efficiency of the strategy in terms of how long it takes to conduct the whole plan as well as all the sub-steps.

Table 4.4 Example of updated inspection plan generated by IPaCK

Stage	Time (sec)	Activity	Geo/ID	X (mm)	Y (mm)	Z (mm)	Tool	Total pts	Normal vectors		
									I	J	K
Part alignment stage	34	ZeroZ	Plane1				Stylus1	8			
	37	Point	1	68.07	15.38	30			0	0	1
	39	Point	2	34.03	15.38	30			0	0	1
	41	Point	3	15.01	36.76	30			0	0	1
	43	Point	4	12.01	67.47	30			0	0	1
	45	Point	5	30.01	86.54	30			0	0	1
	47	Point	6	68.07	87.5	30			0	0	1
	48	Point	7	88.09	69.5	30			0	0	1
	51	Point	8	87.09	34.67	30			0	0	1
	57	ZeroY	Plane2				Stylus1	4			
	61	Point	9	10.93	0	24.02			0	-1	0
	64	Point	10	90.05	0	23.02			0	-1	0
	66	Point	11	91.04	0	8.007			0	-1	0
	68	Point	12	10.93	0	5.004			0	-1	0
	80	ZeroX	Plane3				Stylus1	4			
	83	Point	13	0	11.92	24.02			-1	0	0
	86	Point	14	0	91.04	25.02			-1	0	0
	88	Point	15	0	93.02	10.01			-1	0	0
	91	Point	16	0	12.91	6.005			-1	0	0
Main planning routine	114	Tolerance	Position								
	114	Datum	Plane2				Stylus1	4			
	118	Datum	Plane3				Stylus1	4			
	123	Inspection	Cylinder1				Stylus1	8			
	127	Point	17	9.736	23.5	25.02			0.6	-0.8	0
	128	Point	18	21.74	22.39	24.02			-0.7	-0.7	0
	130	Point	19	24.83	13.16	26.03			-1	0.2	0
	132	Point	20	6.498	9.736	25.02			0.9	0.5	0
	134	Point	21	6.498	9.736	7.006			0.9	0.5	0
	136	Point	22	8.263	22.39	8.007			0.6	-0.8	0
	138	Point	23	22.98	21.03	8.007			-0.8	-0.6	0
	140	Point	24	22.98	8.974	6.005			-0.8	0.6	0
	152	Tolerance	Position								
	160	Datum	Plane4				Stylus1	4			
	163	Point	25	25	64.15	17			1	0	0
	166	Point	26	25	66.1	26.01			1	0	0
	169	Point	27	25	39.76	24.01			1	0	0
	170	Point	28	25	38.78	19			1	0	0
	175	Datum	Plane5				Stylus1	4			
	178	Point	29	33.9	25	19			0	1	0
	179	Point	30	35.85	25	25.01			0	1	0
	182	Point	31	61.22	25	24.01			0	1	0
	183	Point	32	64.15	25	19			0	1	0
	189	Inspection	Cylinder2				Stylus1	8			
	192	Point	33	45.54	58.95	4.003			0.4	-0.9	0
	194	Point	34	57.39	56.74	5.004			-0.8	-0.6	0
	195	Point	35	58.95	45.54	8.007			-0.9	0.5	0
	197	Point	36	43.97	42.02	7.006			0.6	0.8	0
	199	Point	37	42.02	43.97	26.03			0.8	0.6	0
	201	Point	38	43.97	57.98	26.03			0.6	-0.8	0
	203	Point	39	56.03	57.98	26.03			-0.6	-0.8	0
	204	Point	40	57.98	43.97	27.03			-0.8	0.6	0

A graphical output generated automatically by the IPaCK represents the tactical planning user activity (Figure 4.25). On this output the point sets used for selecting each of the features within the strategy are given; each point is labelled with a number following the same sequence as in the inspection plan. The direction of the normal vector for each point is displayed with a yellow line, indicating the approach direction for selecting the respective point. In addition to this, the coordinate system set by the user during the planning session appears on the digital display, highlighting how the part is oriented on the CMM table virtually. These modifications were made considering the feedback acquired from experienced CMM planners through the pilot study. Aiming to represent the tactical planning activity of the strategy, the combination of inspection plan and tactical planning trajectory comprise the first knowledge format in the main experimentation stage 2 (Chapter 6).

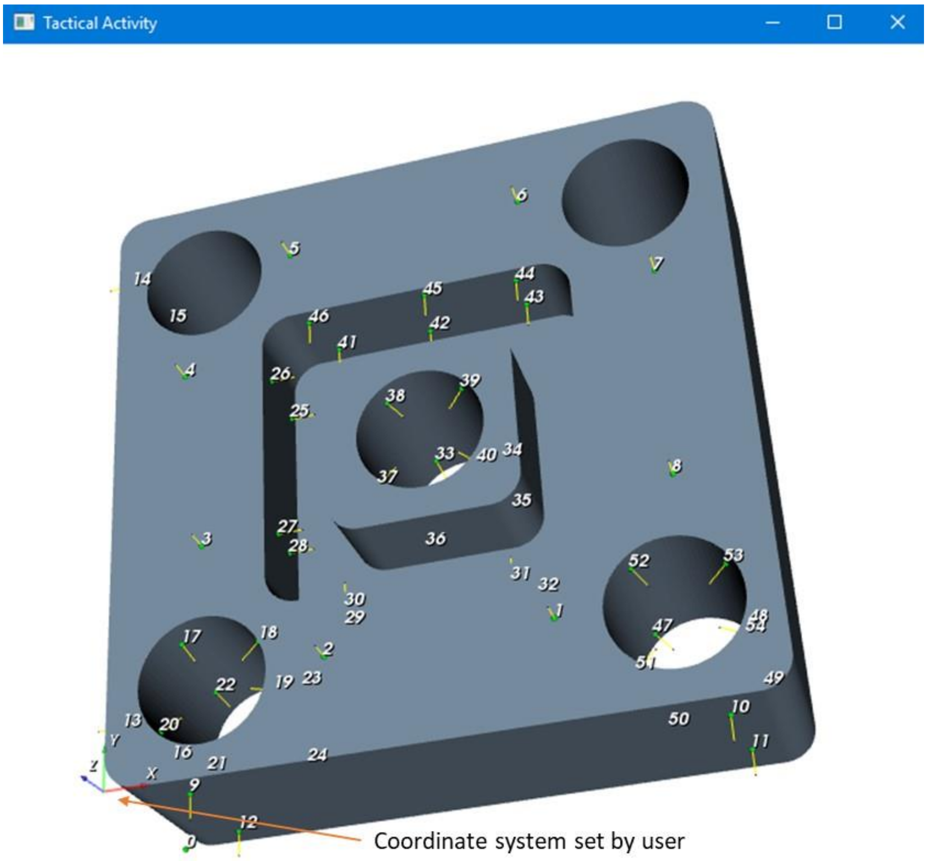


Figure 4.25 Example of updated tactical planning trajectory representation generated by IPaCK

Based on the experienced CMM planners' responses in the pilot study, the tactical planning activity trajectory was not preferred in any combination. Also, it was rated with relatively low scores 49%, 43% and 46% in the aspects of ease of understanding, usefulness and overall performance respectively. However, it was worth investigating how its performance would change after the recommended modifications on it and when studied in combination with another format.

4.4.2.2 Inspection plan and strategic planning trajectory

The next combination of knowledge representations consists of the inspection plan (Table 4.4) and a visual format illustrating the strategic planning activity (Figure 4.26, Figure 4.27). In this automatically generated output, the key steps performed are displayed in a list, labelled with a number showing the activity order. The same number-labels appear on the model of the component under measurement, highlighting which features are involved in the planned strategy. In this way, a quick overview of the strategic thinking is provided, giving a representation of the strategic planning steps and sequence of them. By combining this output with the inspection plan, all the necessary details are available to the user to help them understand the planning task performed, with a focus to the strategic aspect of the plan.

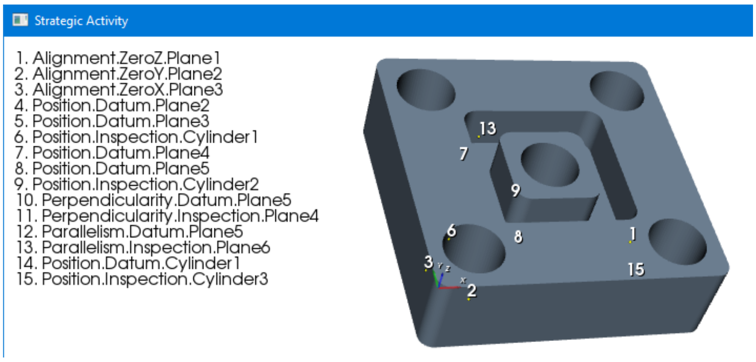


Figure 4.26, Example of Strategic planning activity representation generated by IPaCK

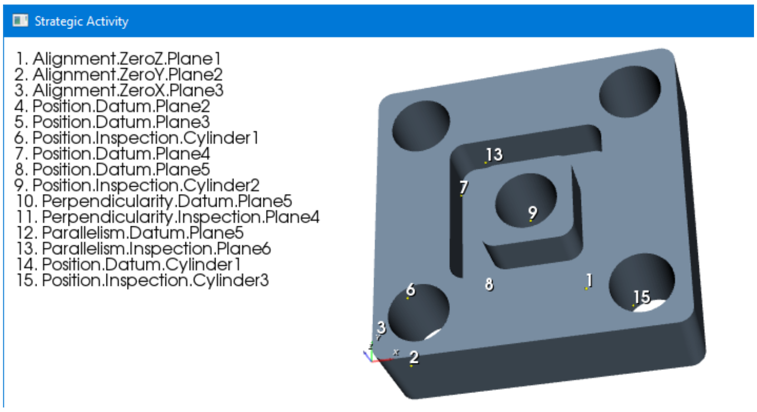


Figure 4.27 Example of Strategic planning activity representation generated by IPaCK – different angle view

Strategic planning trajectory was rated relatively highly compared to other formats in the pilot study (ease of understanding: 61%, usefulness: 52%, overall: 54%) and was selected five times within the stated representation combinations. Thus, it was decided to be included in the main experimentation study.

4.4.2.3 Inspection plan and IDEF0 diagram

IDEF0 knowledge representations (Figure 4.28) accompany the generated inspection plan (previously presented) as a set of diagrams. The IDEF0 diagrams are produced automatically by post-processing the inspection plan within an Excel spreadsheet using VBA macros. In this spreadsheet, the complete strategy is separated into different sub-diagrams for each step, describing the key decisions of the user in a procedural and schematic manner. With this combination the tactical and strategic planning activities are represented, with a focus to the latter, aiming to offer a quick and easy to follow guide of the conducted inspection plan.

Considering the obtained responses from the pilot study, IDEF0 received the lowest scores (ease of understanding: 41%, usefulness 41%, overall: 46%). However, the format was studied in isolation to other outputs. Therefore, it was decided to study its performance further when combined with another format, acceptable by the CMM planners; the inspection plan in this case.

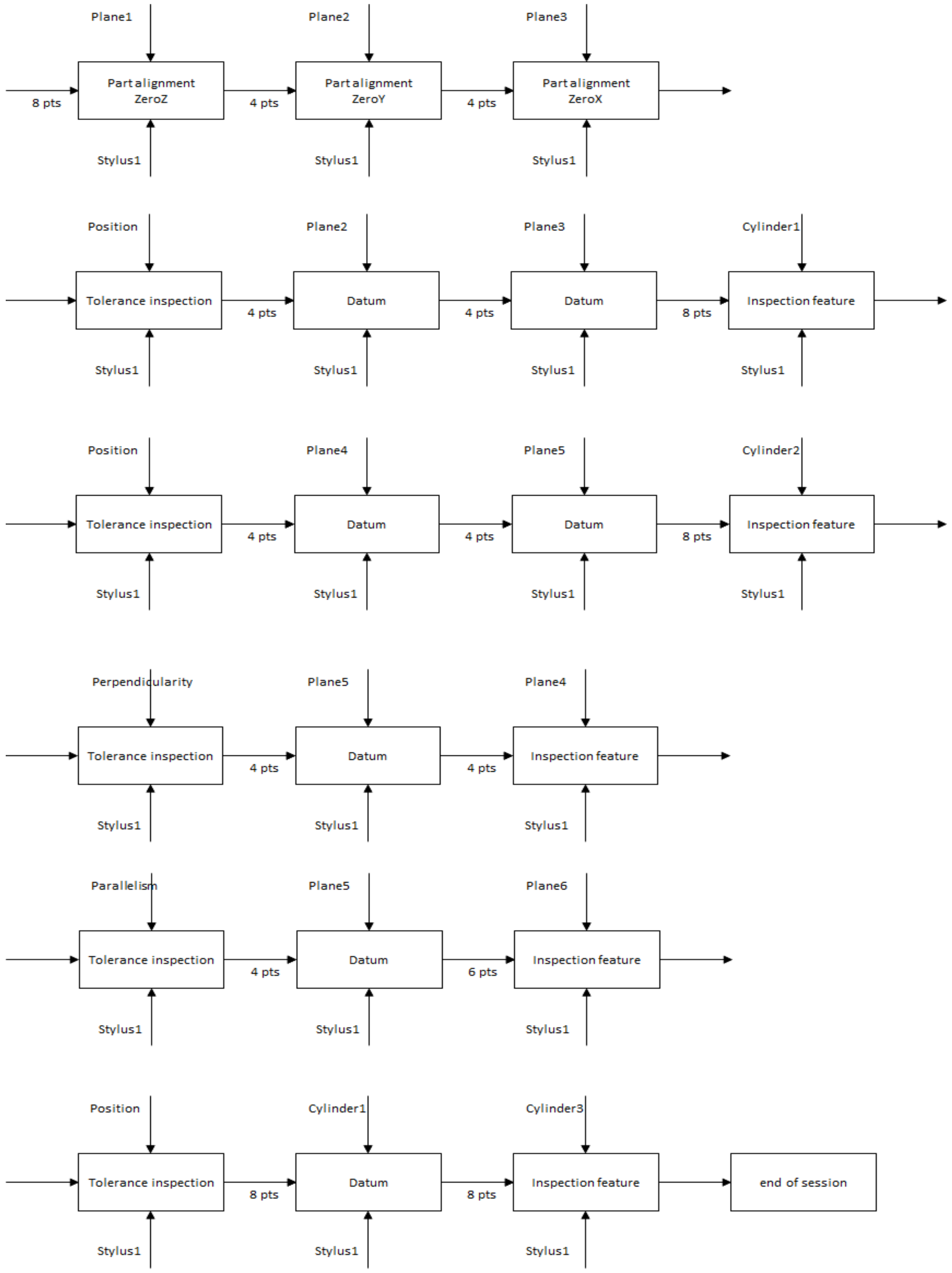


Figure 4.28 Example of IDEF0 diagrams representation generated by IPaCK

4.4.2.4 Annotated video clip

As indicated by the pilot study, visual outputs were preferred for describing a measurement planning task, with video clips being the highest rated; therefore, no modifications were required. To obtain the video, a recording device was used for capturing the whole planning session. The subtitles are generated automatically by post-processing the inspection plan using VBA macros within an Excel spreadsheet and output in an ASCII file format. Key steps logged in the plan are described textually in a chronological order. To reproduce the video and embed the subtitles file a video player was used. An example of the subtitles file is shown in Figure 4.29 and screenshots from the annotated video clip (Appendix A.9) are presented in Figure 4.30. Annotated video clip was one of the two most popular formats based on the pilot study results, being included nine times in the stated combination preferences. Therefore, it was selected for further study in the main experimentation.

Time	Activity	Geo/ID	X	Y	Z	Tool	Total pts	I	J	K
34	ZeroZ	Plane1				Stylus1	8			
37	Point	1	68.07	15.38	30			0	0	1
39	Point	2	34.03	15.38	30			0	0	1
41	Point	3	15.01	36.76	30			0	0	1
43	Point	4	12.01	67.47	30			0	0	1
45	Point	5	30.01	86.54	30			0	0	1
47	Point	6	68.07	87.5	30			0	0	1
48	Point	7	88.09	69.5	30			0	0	1
51	Point	8	87.09	34.67	30			0	0	1
57	ZeroY	Plane2				Stylus1	4			
61	Point	9	10.93	0	24.02			0	-1	0
64	Point	10	90.05	0	23.02			0	-1	0
66	Point	11	91.04	0	8.007			0	-1	0
68	Point	12	10.93	0	5.004			0	-1	0
80	ZeroX	Plane3				Stylus1	4			
83	Point	13	0	11.92	24.02			-1	0	0
86	Point	14	0	91.04	25.02			-1	0	0
88	Point	15	0	93.02	10.01			-1	0	0
91	Point	16	0	12.91	6.005			-1	0	0
114	Tolerance	Position								
114	Datum	Plane2				Stylus1	4			
118	Datum	Plane3				Stylus1	4			

video.sub - Notepad

File Edit Format View Help

1
00:00:34 --> 00:00:39
Probe 8 points on Plane1 with Stylus1. Set as ZeroZ

2
00:00:57 --> 00:00:62
Probe 4 points on Plane2 with Stylus1. Set as ZeroY

3
00:00:80 --> 00:00:85
Probe 4 points on Plane3 with Stylus1. Set as ZeroX

4
00:00:113 --> 00:00:114
Inspection of Position tolerance

5
00:00:115--> 00:00:116
Reuse Plane2. Set as Datum

6
00:00:118 --> 00:00:123
Reuse Plane3. Set as Datum

Figure 4.29 Example of subtitles file in contrast with the inspection plan generated by IPaCK (Appendix A.9)

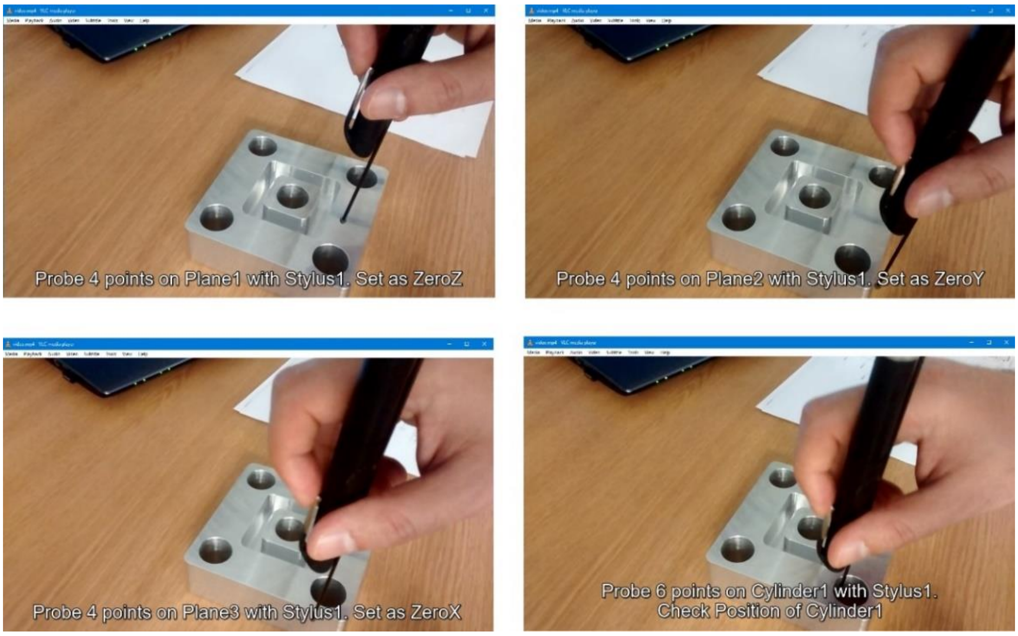


Figure 4.30 Example of annotated video clip screenshots generated by IPaCK

4.4.2.5 Storyboard

Storyboards combine multiple representations. The pilot study confirms such combinations are useful in understanding the rationale and decision making behind a planning task. Figure 4.31 illustrates a storyboard with IDEF0 sub-diagrams, textual description and a display of the model with inspection points used along with time stamps at each step.

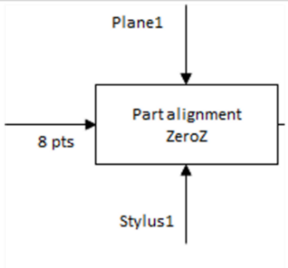
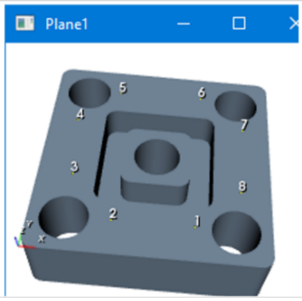
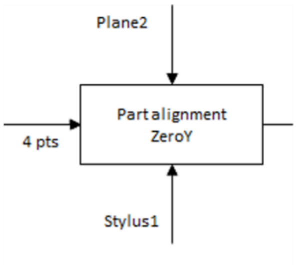
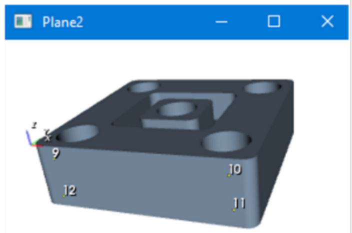
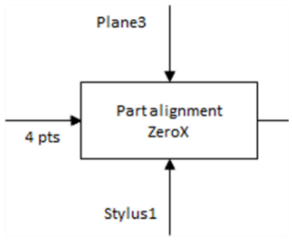
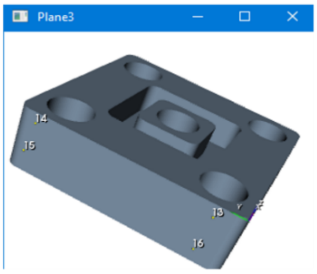
Time	IDEF0	Text	Screenshot
34		Probe 8 points on Plane1 with Stylus1. Set as ZeroZ	
57		Probe 4 points on Plane2 with Stylus1. Set as ZeroY	
80		Probe 4 points on Plane3 with Stylus1. Set as ZeroX	

Figure 4.31 Example of storyboard knowledge representation generated by IPaCK

Due to the depth and simplicity of the structure, a storyboard can support CMM operators with different level of experience. Novice operators could use it as training material and repeat the same strategy. Experienced users benefit from this format both operationally in a generic informative strategic approach and how to plan a new different measurement plan. The tactical details provided with a storyboard could aid also as a reference for generating inspection strategies for different components with similar groups or individual features.

Storyboard was the most popular format together with annotated video clip (both were selected nine times) in the stated representation preferences through the pilot study. Furthermore, it received the highest scores in usefulness (56%) and overall performance (58%). Thus, it qualified for use in the main experimentation study.

4.4.3 *Other knowledge representations*

Further to the previously presented formats, additional outputs were developed which were not assessed. The reason for not evaluating these is that the following outputs were very similar to and are already covered by the final selected representations.

4.4.3.1 *Inspection path*

The generated inspection path (Figure 4.32) is another form of the tactical planning activity graph. The difference is that the points relate to lines illustrating the trajectory that a CMM inspection probe would follow. To create this path, the ray-tracing algorithm shown in Appendix A.2 was developed and employed for checking if an intersection occurs between the generated line and the component. The inspection path format was not considered in the main experimental study as its represented knowledge is already included in the tactical planning trajectory.

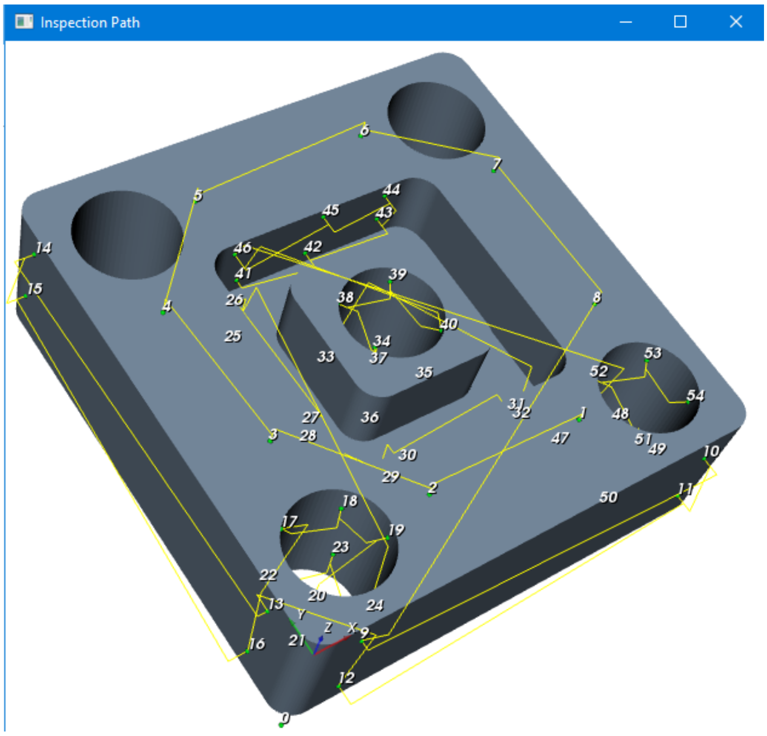


Figure 4.32 Example of the inspection path representation generated by IPaCK

4.4.3.2 *Text instructions*

Another representation format automatically generated by VBA macros in the Excel spreadsheet is a text file containing all the steps of the strategy and relative instructions. It is a simple and straightforward way of presenting the strategy should facilitate easy and quick understanding of the inspection method. That is, this output can be easily used as a guide for training or repeating the same strategy. Additionally, it can be combined with any of the previous visual outputs for enhancing the study of the logged planning strategy. Figure 4.33 below illustrates an example of such a format. Plain text instructions are included as annotations in the proposed video clip output.

```
instructions.txt - Notepad
File  Edit  Format  View  Help
Step      Instruction
====      ===========
1         Probe 8 points on Plane1 with Stylus1. Set as ZeroZ
2         Probe 4 points on Plane2 with Stylus1. Set as ZeroY
3         Probe 4 points on Plane3 with Stylus1. Set as ZeroX
4         Inspection of Position tolerance
5         Reuse Plane2. Set as Datum
6         Reuse Plane3. Set as Datum
7         Probe 8 points on Cylinder1 with Stylus1. Check Position of Cylinder1
8         Inspection of Position tolerance
9         Probe 4 points on Plane4 with Stylus1. Set as Datum
10        Probe 4 points on Plane5 with Stylus1. Set as Datum
11        Probe 8 points on Cylinder2 with Stylus1. Check Position of Cylinder2
12        Inspection of Perpendicularity tolerance
13        Reuse Plane5. Set as Datum
14        Reuse Plane4 for Inspection. Check Perpendicularity of Plane4
15        Inspection of Parallelism tolerance
16        Reuse Plane5. Set as Datum
17        Probe 6 points on Plane6 with Stylus1. Check Parallelism of Plane6
18        Inspection of Position tolerance
19        Reuse Cylinder1. Set as Datum
20        Probe 8 points on Cylinder3 with Stylus1. Check Position of Cylinder3
```

Figure 4.33 Example of the plain text instructions representation generated by IPaCK

4.4.3.3 CMM part program

The last output generated includes the part program for driving a computer controlled CMM. By post-processing the output inspection plan, all the logged activity is converted into DMIS language code for commanding a real CMM automatically. Note that for running a part program, a manual alignment of the component on the CMM table is necessary to inform the CMM software where the part is located within the measurement volume. An example of this output is shown in Figure 4.34.

CMM part program output was not included in the main experimentation as it required a lot of experience to read and understand it. In addition, a CMM part program is an output of a software package to be executed by a CMM. Experienced CMM planners can directly understand the planned strategy using a part program as stated in the pilot study feedback. Therefore, there was no need of including this in the next experiments.

```
CMM_program.txt - Notepad
File  Edit  Format  View  Help
MODE/PROG,MAN

$$<MEAS_PLANE name = "Plane1">
MODE/PROG,MAN
F(Plane1)=FEAT/PLANE,CART,50.2973,51.6512,30,0,0,1
MEAS/PLANE,F(Plane1),8
PTMEAS/CART,68.067,15.3846,30
PTMEAS/CART,34.033,15.3846,30
PTMEAS/CART,15.014,36.7643,30
PTMEAS/CART,12.011,67.4738,30
PTMEAS/CART,30.0134,86.5385,30
PTMEAS/CART,68.067,87.5,30
PTMEAS/CART,88.087,69.4975,30
PTMEAS/CART,87.086,34.6665,30
ENDMES
$$<MEAS_PLANE = Plane1>

GOTO/CART,87.086,34.6665,32
GOTO/CART,10.9341,-4,34.023

$$<MEAS_PLANE name = "Plane2">
MODE/PROG,MAN
F(Plane2)=FEAT/PLANE,CART,50.7418,0,15.014,0,-1,0
MEAS/PLANE,F(Plane2),4
PTMEAS/CART,10.9341,0,24.023
PTMEAS/CART,90.0549,0,23.022
PTMEAS/CART,91.044,0,8.007
PTMEAS/CART,10.9341,0,5.004
ENDMES
$$<MEAS_PLANE = Plane2>

GOTO/CART,10.9341,-2,30.004
GOTO/CART,-4,11.9231,34.023

$$<MEAS_PLANE name = "Plane3">
MODE/PROG,MAN
F(Plane3)=FEAT/PLANE,CART,0,52.2253,16.2652,-1,0,0
MEAS/PLANE,F(Plane3),4
PTMEAS/CART,0,11.9231,24.023
PTMEAS/CART,0,91.044,25.024
PTMEAS/CART,0,93.022,10.009
PTMEAS/CART,0,12.9121,6.005
ENDMES
$$<MEAS_PLANE = Plane3>
```

```
CMM_program.txt - Notepad
File  Edit  Format  View  Help
GOTO/CART,-2,12.9121,31.005
GOTO/CART,11.9962,20.2022,30.024

$$<MEAS_CYLNDR name = "Cylinder1">
MODE/PROG,MAN
F(Cylinder1)=FEAT/CYLNDR,INNER,CART,15.4402,16.3645,16.1401,0,0,1,19.999
MEAS/CYLNDR,F(Cylinder1),8
PTMEAS/CART,9.73568,23.5022,25.024
PTMEAS/CART,21.737,22.3901,24.023
PTMEAS/CART,24.8297,13.1625,26.025
PTMEAS/CART,6.49783,9.73568,25.024
PTMEAS/CART,6.49783,9.73568,7.006
PTMEAS/CART,8.26304,22.3901,8.007
PTMEAS/CART,22.9802,21.0263,8.007
PTMEAS/CART,22.9802,8.97365,6.005
ENDMES
$$<MEAS_CYLNDR = Cylinder1>

GOTO/CART,21.3302,10.1039,31.005
GOTO/CART,29,64.1463,32.001

$$<MEAS_PLANE name = "Plane4">
MODE/PROG,MAN
F(Plane4)=FEAT/PLANE,CART,25,52.1951,21.5055,1,0,0
MEAS/PLANE,F(Plane4),4
PTMEAS/CART,25,64.1463,17.001
PTMEAS/CART,25,66.0976,26.01
PTMEAS/CART,25,39.7561,24.008
PTMEAS/CART,25,38.7805,19.003
ENDMES
$$<MEAS_PLANE = Plane4>

GOTO/CART,27,38.7805,19.003
GOTO/CART,33.9024,29,19.003

$$<MEAS_PLANE name = "Plane5">
MODE/PROG,MAN
F(Plane5)=FEAT/PLANE,CART,48.7805,25,21.7557,0,1,0
MEAS/PLANE,F(Plane5),4
PTMEAS/CART,33.9024,25,19.003
PTMEAS/CART,35.8537,25,25.009
PTMEAS/CART,61.2195,25,24.008
PTMEAS/CART,64.1463,25,19.003
ENDMES
```

Figure 4.34 Example of the CMM part program generated by IPaCK

4.5 Summary

In this chapter, the proposed IPaCK system, methodology and tools were presented. Unique elements are: a novel associative user logging-inspection planning interface developed to emulate the operation of a real CMM; the capability to capture in real-time the intended measurement strategy as it is being planned; capturing the CMM planning knowledge and representing it. The required basic functional options for such a task are integrated enabling the user to think and act in a manner similar to the operation of a real CMM and associated software. By achieving this, research objective RO1 was partially met at an early stage: "To design and develop a novel prototype for planning CMM measurements and logging user activity." Further validation of this is closely linked to meeting the objective for testing and usability evaluation of IPaCK (RO3) which will be presented in Chapter 5.

Prior to these, a pilot study was required that would provide initial feedback on system performance and to further inform and update the proposed solution. A single user trial with a novice user was carried out to check the system's functionality and generate a series of proposed knowledge formats, while a survey facilitated the evaluation of the outputs and feedback. 20 experienced CMM planners participated in this pilot study, answering an online questionnaire. These tasks aided in the partial meeting of the first two research objectives: i) the design and development of a user logging tool for CMM inspection planning tasks (RO1); ii) the automated generation of inspection planning knowledge representations (RO2).

Furthermore, a series of different knowledge and strategy planning representations were validated by experienced planners resulting in benefits for novice and even experienced metrology and CMM users. Hence, the objective (RO2) was achieved: "To design proper knowledge representations of an inspection planning strategy and build a tool for generating these automatically".

The preliminary evaluation to acquire initial feedback on IPaCK suggested that the impact of the proposed representation formats can support the entire spectrum of CMM operator experience in terms of ease of understanding, usefulness and overall performance. The results revealed that the current knowledge representations could positively affect and help in inspection planning. This provides the foundation for addressing RO4: "to test and validate the generated knowledge outputs and representations."

In the following chapters, more in-depth case studies to evaluate IPaCK to ascertain its usability and scope for industrial implementation will be conducted. The focus will be on the user logging tool and knowledge representations performance as well as how user activity data could be used for comparing planning strategies and detecting common patterns of activity.

Chapter 5 Experimental results and analysis 1 - CMM inspection planning strategy capture

5.1 Introduction

With a refined IPaCK, a series of user trials was conducted to evaluate its usability and level of technology readiness and address RO3. This Chapter will also present how IPaCK was used to capture, formalise and reuse different strategies and associated knowledge.

A specific comparative case study was carried out with both novice and experienced CMM planners. The inspection thinking patterns detected are analysed to reveal common sequences of planning activities. The level of quality of each inspection plan will be compared against a benchmark for each of the test components. Finally, a time-based performance test is conducted to compare IPaCK against a conventional and current (real) CMM system.

5.2 Experimental methodology and tests

To assess the IPaCK's usability, it was necessary to carry out a series of experimental trials. Within these, two groups of participants were involved: novice and experienced CMM planning engineers. 10 novice users with a basic engineering background (undergraduate and postgraduate mechanical engineering students) and no experience in CMM inspection participated in the trials for planning the inspections of two components using IPaCK. Prior to the trials, they were trained for 30 minutes, where they watched a video of how a real CMM works, how the tolerancing annotations on a design drawing are converted into inspection planning activities (using a simple component and tolerances e.g. position, parallelism, perpendicularity) and finally how the IPaCK prototype works. The two components involved in the trials are shown in Figure 5.1 and Figure 5.2.

Figure 5.1 Part 1 used in experimental trials

Figure 5.2 Part 2 used in experimental trials

To engage experienced CMM planners at this stage of the experimentation, it was decided to invite them to participate remotely. By watching a demonstration video, they would evaluate IPaCK's usability. Considering the fact that skilled CMM planners with exposure to different metrology systems, they could understand the functionality of the prototype and therefore evaluate it properly without necessarily trying it out. For example, an operator experienced in using a manual milling machine or lathe can understand the function of a CNC machine and evaluate it. Consequently, it was possible to engage 74 experienced CMM inspection planners in this step of the study.

For the usability study, the two groups completed a System Usability Scale (SUS) questionnaire [182] to rate the prototype's functionality. This was selected as it has been used extensively for assessing engineering systems computer interfaces [183] and produces reliable results for various sample sizes [184]. The questionnaire comprises 10 statements relating to the functionality of the system under examination. Five positive (odd numbered) and five negative (even numbered) statements are used to balance any bias in the questionnaire. Each respondent is required to rate the level of agreement through a five-point Likert scale varying from "1 – strongly disagree" to "5 – strongly agree". The structure of a SUS questionnaire is shown in Figure 5.3.

	Strongly disagree 1	2	3	4	Strongly agree 5
I think that I would like to use this system frequently					
I found the system unnecessarily complex					
I thought the system was easy to use					
I think that I would need the support of a technical person to be able to use this system					
I found the various functions in the system were well integrated					
I thought there was too much inconsistency in this system					
I would imagine that most people would learn to use this system very quickly					
I found the system very cumbersome to use					
I felt very confident using the system					
I needed to learn a lot of things before I could get going with this system					

Figure 5.3 Example of the SUS questionnaire used in the usability evaluation of IPaCK

To calculate the SUS score, each positive statement equals scale position minus 1 and each negative statement equals 5 minus the scale position. The sum of these is multiplied by 2.5 to normalise the score between the values 0 – 100. Although the final score is a useful usability measure, Bangor et al. [185] introduced an adjective rating scale (Figure 5.4), giving a clear and easy to understand guide for assessing usability.

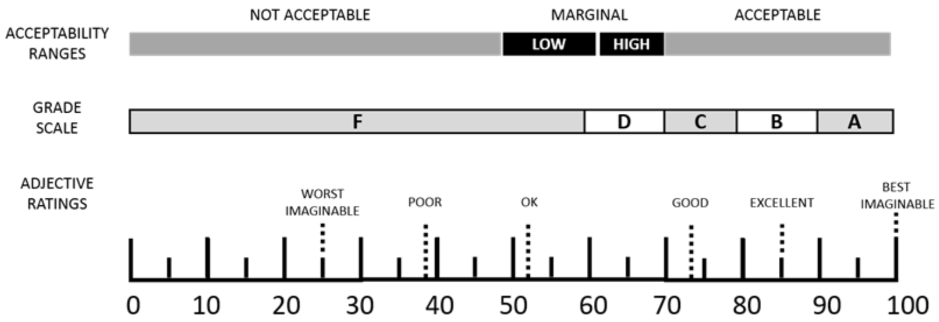


Figure 5.4 Adjective rating scale for classifying a system's usability and acceptability [185]

Finally, each participant had to study five combinations of knowledge representations as presented in Chapter 4 and rate them for ease of understanding, usefulness and overall performance. As Chapter 5 is focused on capturing inspection planning activity and comparing the strategies, the results from the knowledge representations evaluation study will be presented in Chapter 6. The experimental method for planning inspection routines and evaluating the prototype's usability is described in this chapter and is illustrated in Figure 5.5.

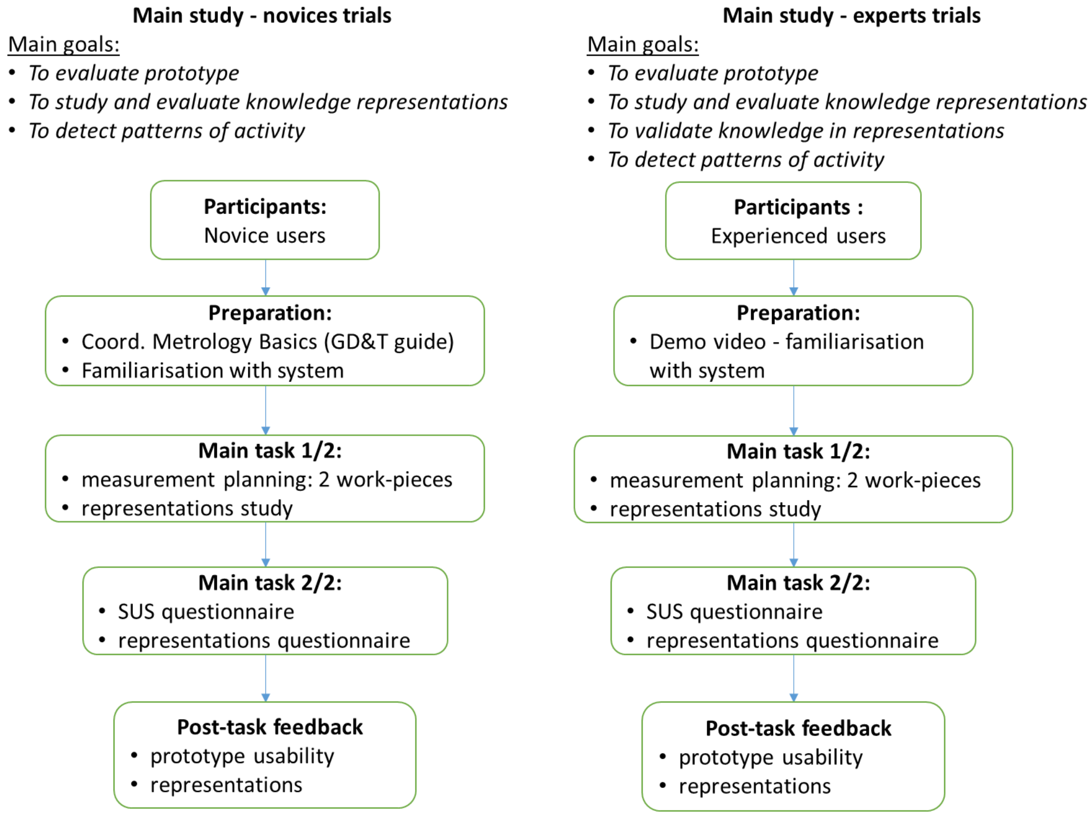


Figure 5.5 Overview of design of experiments for the main experimental stage

5.3 IPaCK usability testing

In the usability evaluation of IPaCK 10 novice planners and 74 experienced CMM planners participated. In Table 5.1, a classification of all the participants depending on their prior experience in CMM inspection is shown, forming five groups in total and providing a more rigorous comparison of the IPaCK tools' usability and how this is correlated with experience in CMM planning and use.

Table 5.1 Classification of participants in IPaCK's usability study in CMM experience groups

CMM experience in years	Group of expertise	Method of participation	Group name
Basic training	Trial novice	User trial	Trial Nov.
$0 < exp < 2$	Online junior	Online questionnaire	Online Jun.
$2 \le exp < 5$	Online intermediate	Online questionnaire	Online Int.
$5 \le exp < 10$	Online senior	Online questionnaire	Online Sen.
≥ 10	Online expert	Online questionnaire	Online Exp.

Two group sets were considered during the evaluation of the IPaCK system.

Set 1: The first set comprised two high level groups: one comprising Trial Novice planners and the other Online Experienced planners. Experimental data analysis was then possible giving an indication of how IPaCK compared between these broad categories.

Set 2: As shown in Figure 5.6, for a more detailed level analyses the experienced planners were divided into four groups, according to the derived groups of experience, namely: Online Junior, Online Intermediate, Online Senior and Online Expert. These were used to determine if there were any differences based on the level of expertise and exposure to CMM planning methods.

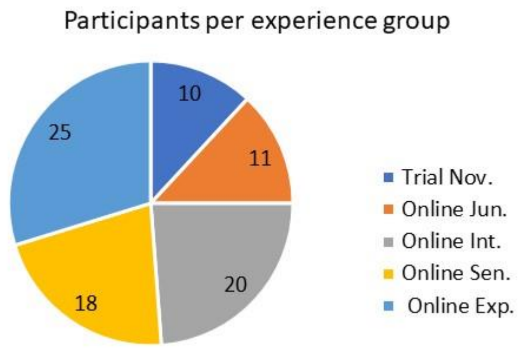


Figure 5.6 IPaCK's usability study – distribution of participants per group of CMM experience

An overview of the average SUS scores of participants in Set 1 is shown in Figure 5.7 (data given in Appendix E, Table E. 1, Table E. 2).

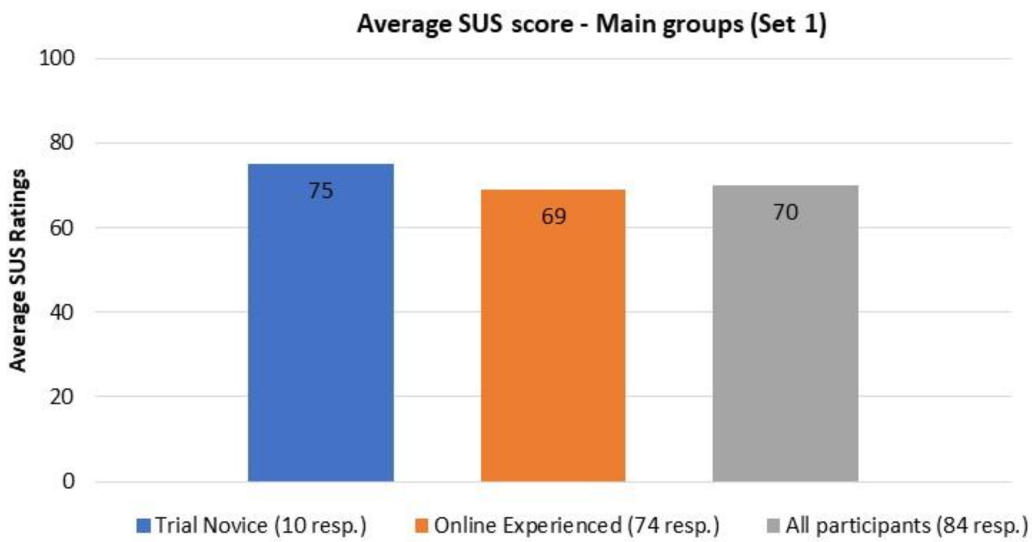


Figure 5.7 IPaCK usability study results - Average ratings for novice, experienced and all participants (Set 1)

Within the usability context, IPaCK received a total SUS score of 70 from the whole set. Based on the scale proposed by Bangor et al. [185], this characterises the system as 'high OK' and falls into the 'acceptable' range. The experienced users have scored it slightly lower with an average of 69 whilst the novice users have given a score of 75. Considering all the responses and each major group's average, IPaCK is perceived to be a usable approach for inspection planning. Set 2 results in Figure 5.8 (Data: Table E. 1, Table E. 3, Table E. 4, Table E. 5, Table E. 6) shows the usability scores across the subjects' experience ranges.

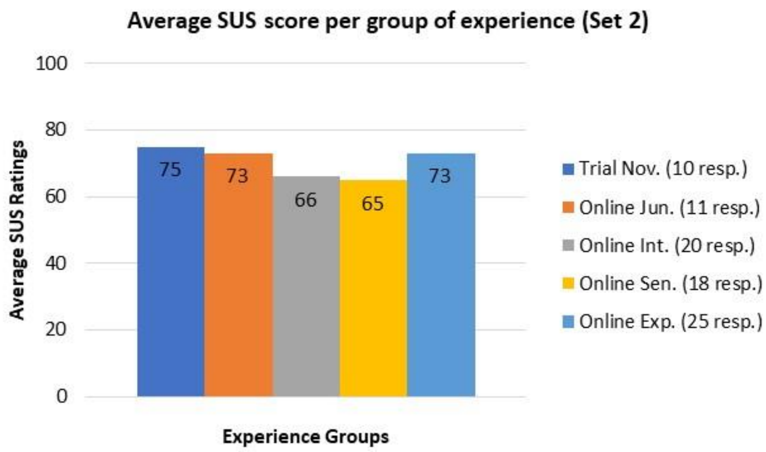


Figure 5.8 IPaCK's usability study results - Average ratings per participants' group of experience (Set 2)

The lowest average score of 65 was given by the group of Online Seniors, meaning that even at its lowest rating IPaCK classifies as 'high OK' and 'high marginal' in the acceptability scale. The Trial Novice users have given the system the highest average score of 75, which is interpreted as 'good' and 'acceptable' in the adjective and acceptability scales.

To further analyse the responses in Set 2 and detect any statistically significant differences, parametric t-Test was used for normally distributed samples. For comparing non-normally distributed samples the non-parametric Mann-Whitney test was employed. All the statistical analysis was conducted with a 5% confidence level.

A normality check of data distributions was conducted on all groups prior to statistical tests using a Shapiro-Wilk normality test. According to previous research [186,187] is the most powerful normality test for all distributions (symmetric and asymmetric) as well as for a wide range of sample sizes tested at confidence levels 5% and 10%. Although, it is always required to carry out normality tests, their power weakens as the sample size lowers. Table 5.2 below presents the results of the normality tests for each group in Set 2. Based on these results, in the following statistical analysis and testing when the group of Trial novices was involved, the non-parametric test Mann-Whitney was used, while for the rest of the comparison, parametric t-Test was employed.

Table 5.2 IPaCK's usability study - Results of normality tests per group of experience (Set 2)

User group	SW Test statistic	p-value	Normality
Trial novices (N_1=10)	0.8252	0.0332	Non-normal
Online Junior (N_2=11)	0.8723	0.0873	Normal
Online Intermediate (N_3=20)	0.9798	0.9319	Normal
Online Senior (N_4=18)	0.9600	0.6023	Normal
Online Expert (N_5=25)	0.9626	0.4687	Normal

A comparison of all groups in Set 2 across experience level was conducted to determine if there were any statistically significant differences between them. The null and alternative hypotheses for each of the groups' comparison with a significance level a=5% were as follows:

- H_0: The two groups' ratings were the same (no statistically significant difference).
- H_1: The two groups were not the same (existence of statistically significant difference).

The results are given in Table 5.3.

Table 5.3 Statistical testing results for each experience group of participants (Set 2)

$N_{Tr. Nov.}$=10 $N_{On. Jun.}$=11 $N_{On. Int.}$=20 $N_{On. Sen.}$=18 $N_{On. Exp.}$=25	**Statistically significant difference** **H_0: no difference - H_1: existence of difference, a=5%** *Tests 1-4:Mann-Whitney U test, Tests 5-10: two sample t-Test*					
	U_m	U_{SD}	*z*	*p (2-tail)*	*Result*	Groups' average scores
Tr. Nov. vs On. Jun. (Test 1)	55	14.085	0.354	0.7226	H_0	Trial Nov. 75; Online Jun. 73
Tr. Nov. vs On. Int. (Test 2)	100	22.624	1.878	0.0603	H_0	Trial Nov. 75; Online Int. 66
Tr. Nov. vs On. Sen. (Test 3)	90	20.765	2.118	0.0340	H_1	Trial Nov. 75; Online Sen. 65
Tr. Nov. vs On. Exp. (Test 4)	125	27.257	0.055	0.9561	H_0	Trial Nov. 75; Online Exp. 73
	t-statistic			*p (2-tail)*	*Result*	Groups' average scores
Online Jun. vs Online Int. (Test 5)	2.1427			0.0413	H_1	Online Jun. 73; Online Int. 66
Online Jun. vs Online Sen. (Test 6)	2.3084			0.0289	H_1	Online Jun. 73; Online Sen. 65
Online Jun. vs Online Exp. (Test 7)	0.1248			0.9016	H_0	Online Jun. 73; Online Exp. 73
Online Int. vs Online Sen. (Test 8)	0.1681			0.8674	H_0	Online Int. 66; Online Sen. 65
Online Int. vs Online Exp. (Test 9)	-2.0668			0.0448	H_1	Online Int. 66; Online Exp. 73
Online Sen. vs Online Exp. (Test 10)	-2.2963			0.0268	H_1	Online Sen. 65; Online Exp. 73

From the results it was found that the groups with less experience perceive IPaCK's usability in the same way as the most experienced participants group, giving the highest scores (Trial Novices: 75, Online Juniors: 73 and Online Experts: 73). On the other hand, the two groups with intermediate experience rated the prototype's usability lower, showing similar perceptions and preferences for its functionality.

The high results from the usability survey validates research objective RO1 and partially addresses RO3 with regards to developing and evaluating the IPaCK's usability, confirming in this way its capabilities of planning CMM inspection strategies. Furthermore, having IPaCK system evaluated at an early stage by novice and experienced CMM planners and obtaining positive feedback on its functionality there is enough evidence to classify the prototype in the third level of Technology Readiness Scale (Analytical and experimental critical function and/or characteristic proof of concept) [188]. This prototype system can provide the sponsor company of this project, Renishaw plc, with novel capabilities for logging CMM inspection planning activity.

5.4 Comparison and evaluation of strategic planning approaches

5.4.1 Common activity and patterns detection

Key objective of the current experimental stage is the detection of common CMM planning practices. For this step, Set 1 was employed to provide a direct comparison between the strategies employed between the novice and experienced CMM planners. The two participants' groups were allocated the task of planning a measurement strategy for two trial components shown in Figure 5.9 and Figure 5.10. The questionnaire employed for this stage of experimentation can be found in Appendix B.2

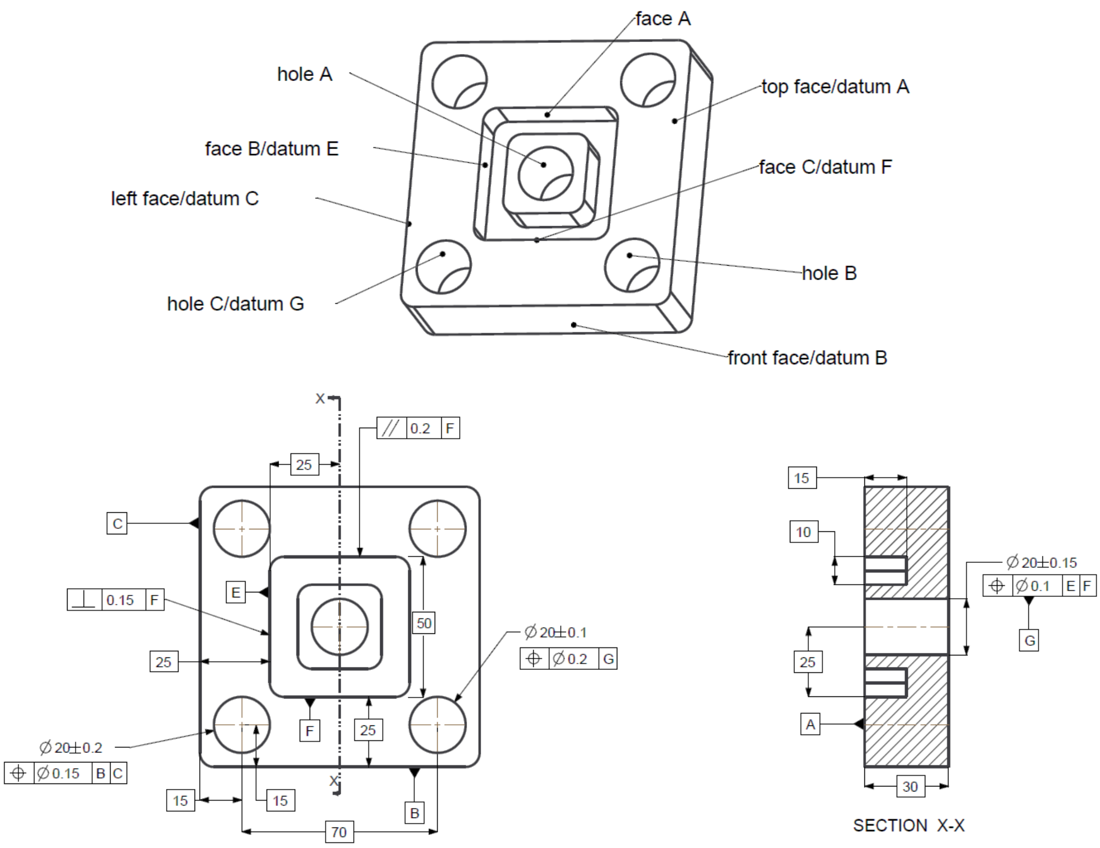


Figure 5.9 Part 1 tolerance specifications and feature indices for trial task 1

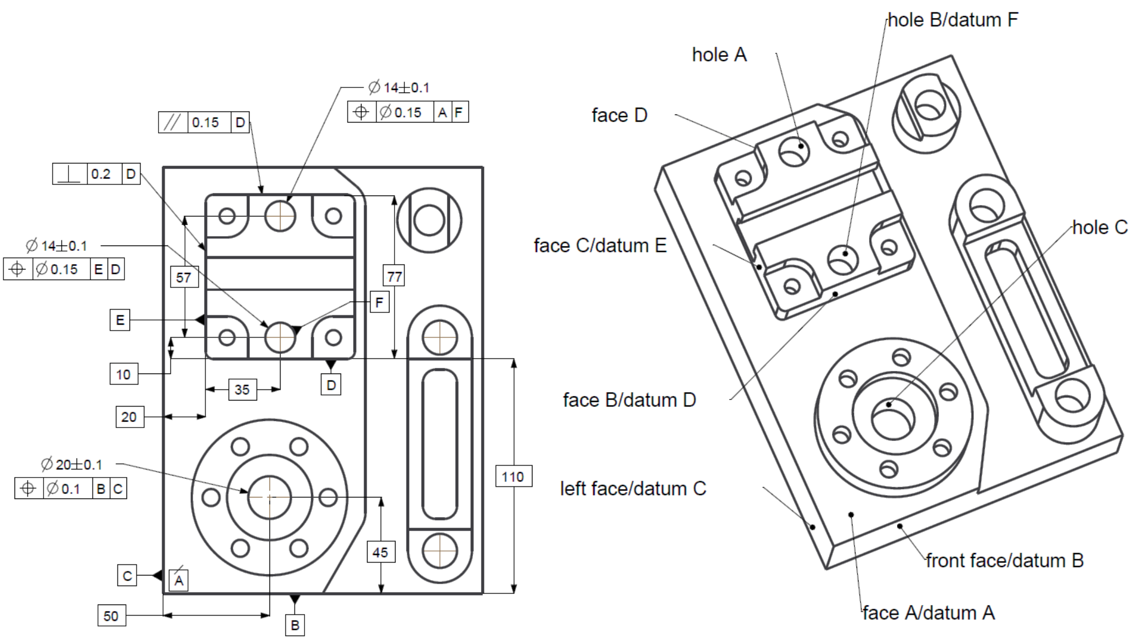


Figure 5.10 Part 2 tolerance specifications and feature indices for trial task 2

The novice user group planned their measurement strategy using IPaCK's logging tool, while the experienced CMM planners participating remotely were asked to create the plans by filling in an online form. Of the experienced planning group, 17 participants completed the task for Part 1 while only 13 planned the Part 2. To avoid any impact on the results, the responses of four participants filling only Part 1 were rejected. Therefore, 13 responses were involved in the comparative study.

Strategic inspection planning sequences were extracted from novice group trials using the strategic planning trajectory output (Figure 5.11, Figure 5.12) of IPaCK as presented in section 4.4.2.2, while the experienced group had responded to the questionnaire, listing their sequences for selecting features. By labelling each feature with a number randomly, as shown in Figure 5.9 and Figure 5.10, the sequences were structured and outlined in Table 5.4 and Table 5.5.

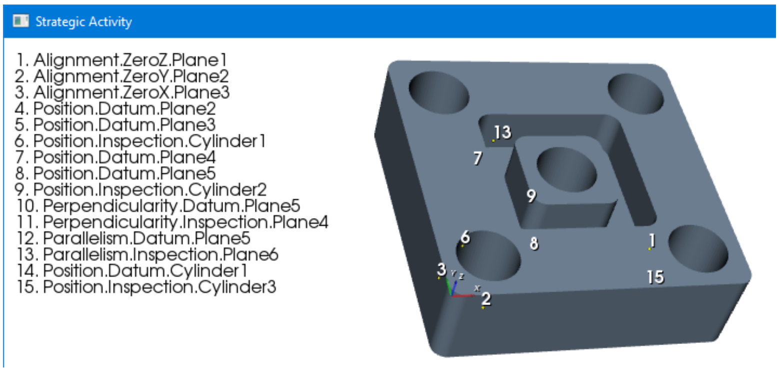


Figure 5.11 Strategic planning trajectory for Part 1

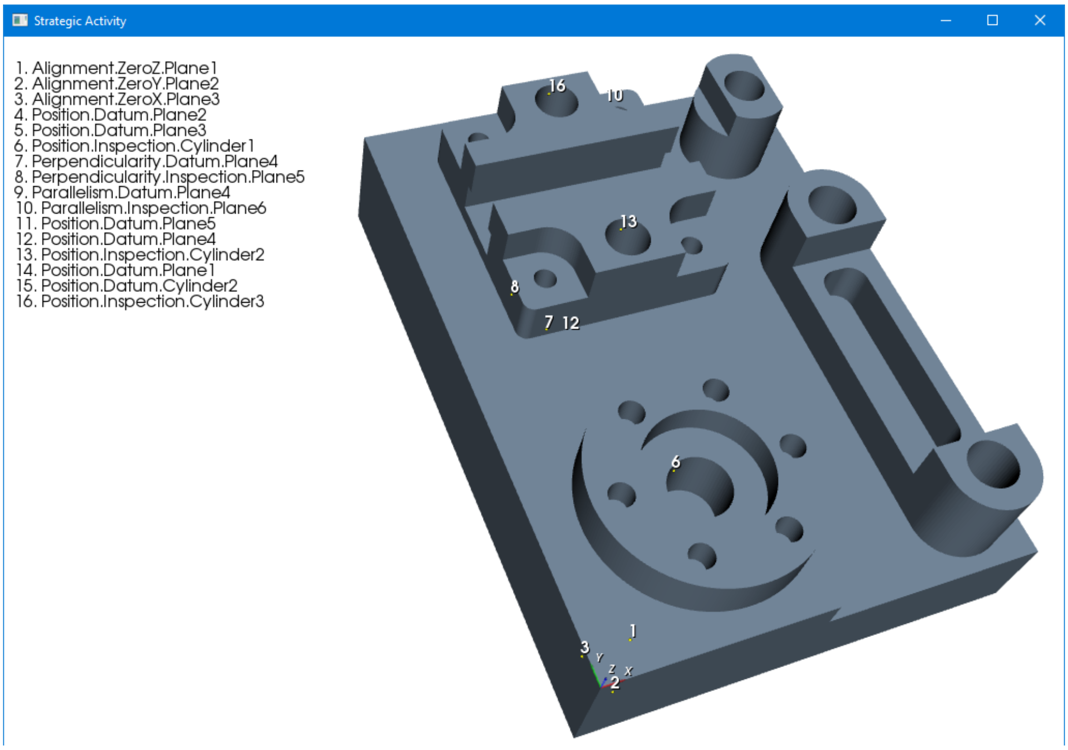


Figure 5.12 Strategic planning trajectory for Part 2

Table 5.4 Set 1 planning strategies for Part 1

Part 1 probing sequences	
Novice (10 responses)	**Experienced (13 responses)**
1 2 3 5 6 7 8 4 9	1 4 2 3 6 5 8 7 9
7 1 5 6 8 2 3 4 9	1 2 3 8 5 6 9 4 7
1 2 3 4 6 5 8 7 9	1 2 3 4 9 7 5 6 8
1 2 3 4 9 6 8 5 7	1 2 3 4 9 6 5 8 7
1 2 3 6 8 5 7 4 9	1 2 3 4 9 5 6 7 8
1 2 3 4 6 8 5 7 9	1 2 3 4 9 5 6 8 7
1 2 3 4 9 6 5 8 7	1 7 8 5 6 9 4 3 2
2 3 1 4 9 6 8 5 7	1 2 7 4 9 3 8 5 6
1 2 3 4 9 6 5 8 7	1 2 7 6 8 5 3 4 9
1 2 3 5 6 7 8 4 9	1 3 2 4 9 5 6 7 8
	1 2 3 7 5 6 8 4 9
	1 3 2 4 9 5 6 8 7
	1 2 3 4 9 6 5 8 7

Table 5.5 Set 1 planning strategies for Part 2

Part 2 probing sequences	
Novice (10 responses)	**Experienced (13 responses)**
1 2 3 4 5 6 7 8 9	1 2 3 4 5 8 6 7 9
2 3 1 4 5 6 7 8 9	1 2 3 6 7 9 8 5 4
1 2 3 4 5 6 8 7 9	1 2 3 4 5 6 8 7 9
1 2 3 4 8 9 5 7 6	1 2 3 4 9 8 6 5 7
1 2 3 4 5 6 8 9 7	1 2 3 4 5 6 7 8 9
1 2 3 4 5 7 6 8 9	1 4 2 3 5 6 8 9 7
1 2 3 4 5 6 7 8 9	1 2 3 4 5 6 9 7 8
2 3 1 4 5 6 8 7 9	1 2 3 4 7 8 6 9 5
1 2 3 4 5 6 7 8 9	1 2 4 5 7 6 8 3 9
1 2 3 4 5 6 8 7 9	1 5 8 6 7 9 2 3 4
	1 2 3 8 9 5 7 6 4
	1 2 3 4 5 6 8 9 7
	1 2 3 4 5 8 6 7 9

To compare the planning strategies and detect commonly used sub-sequences, a MATLAB code (Appendix B.3) called Pattern Detection Tool (PADET) was developed. This was algorithm reads a matrix, compares each row of the matrix against the others and counts the appearances of the various sub-series of digits by considering parameters such as the minimum required length of a sub-set and the minimum number of appearances of this set. Subsequently, all the different patterns detected are plotted on a histogram showing the results graphically. The reason for applying this kind of algorithm is that all the strategic planning sequences captured using IPaCK were structured as series of digits. Also, there was need to search through the strategies captured and identify the most commonly used sub-sequences; PADET facilitated this comparison and analysis.

At this experimental stage, the required inputs for PADET initially were three features (or digits) minimum length and at least three appearances of a sequence. These limits were subsequently increased to four features (digits) and four appearances. This combination of settings gave a focus on longer and more frequent sub-sequences. Figure 5.13 - Figure 5.28 depict the patterns of activity detected among the novice and experienced plans for Part 1 and Part 2.

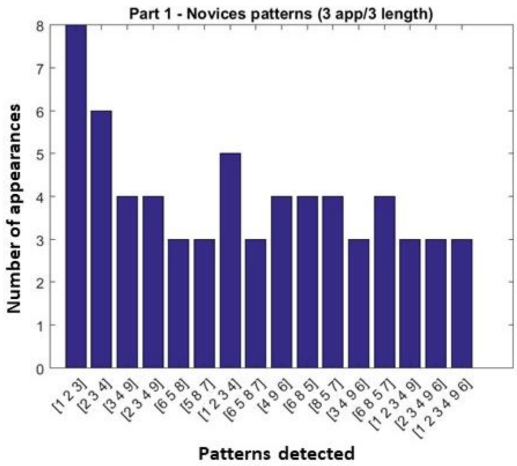


Figure 5.13 Novice planners, Part 1 - Patterns with at least 3 features length and 3 appearances

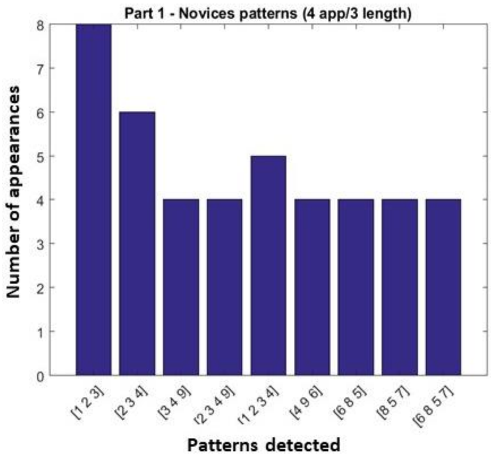


Figure 5.14 Novice planners, Part 1 - Patterns with at least 3 features length and 4 appearances

As shown in Figure 5.13 and Figure 5.14, from the strategies planned by novice users on Part 1, the most commonly followed sequence of three features was 1-2-3, which are the features related to the alignment stage of the workpiece. This sequence appeared eight times out of 10 responses. The second most frequent set was 2-3-4 with six appearances, which relates to the inspection of hole C's true position tolerance to features required for the part alignment step, i.e. front face and left face. The longest sequence of features detected was 1-2-3-4-9-6 with three appearances out of 10 responses. The selection order reveals another link between hole B and hole C (hole C functioning as datum for the true position tolerance of hole B, according to Part 2 tolerancing specification).

To focus on longer sequences, the inputs of PADET for minimum pattern length and appearances, were set to four features (digits) combined with three and four minimum appearances. Figure 5.15 and Figure 5.16 clearly indicate half of the novice planners followed the same part alignment process, followed by the inspection of hole B's true position tolerance (feature set: 1-2-3-4). Considering that the novice participants had been trained in tolerancing annotations only for 30 minutes prior to the trial, 50% of them were able to interpret this connection, i.e. the features in part alignment are used as datums in hole C's true position tolerance and plan in the same way. Moreover, 40% of the novice planners understood the relation between hole C and hole B for the hole B's true position inspection. This is another indication of IPaCK's performance, allowing a novice user to plan a CMM inspection very quickly.

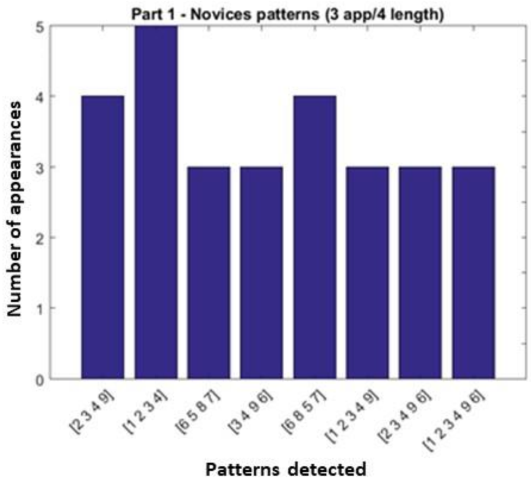


Figure 5.15 Novice planners, Part 1 - Patterns with at least 4 features length and 3 appearances

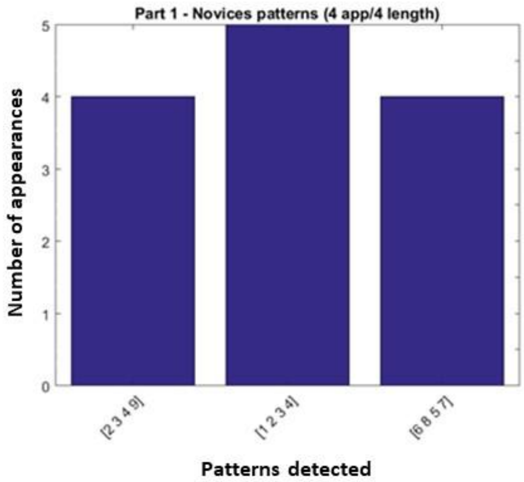


Figure 5.16 Novice planners, Part 1 - Patterns with at least 4 features length and 4 appearances

The same approach and analysis were conducted for the experienced planners' strategies on the Part 1. Patterns and sequences of three features appearing three and four times respectively are shown in Figure 5.17 and Figure 5.18.

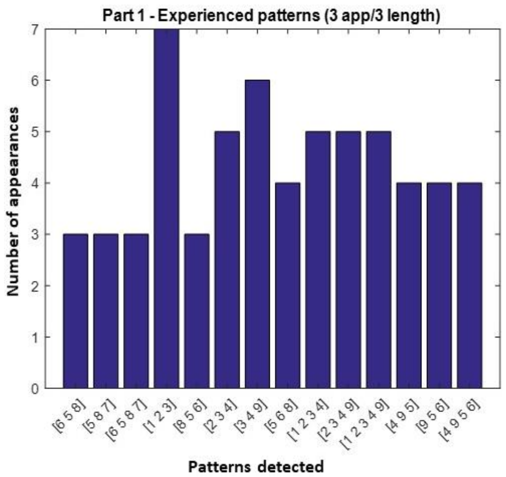


Figure 5.17 Experienced planners, Part 1 - Patterns with at least 3 features length and 3 appearances

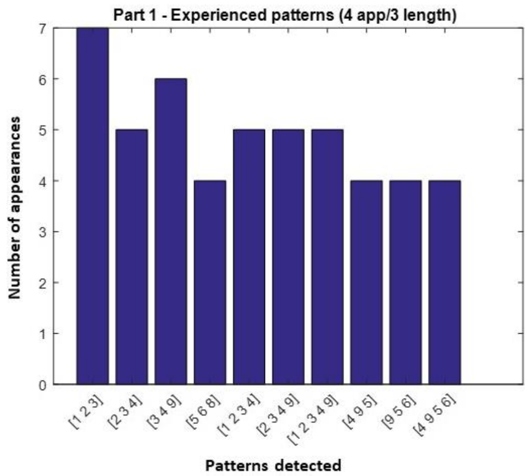


Figure 5.18 Experienced planners, Part 1 - Patterns with at least 3 features length and 4 appearances

It can be observed that the most frequent combination, appearing 10 times out of 13 responses, was 1-2-3 for the part alignment stage. The second most frequent feature set was 3-4-9 with seven appearances, showing the connection of the features hole C and hole B that form the true position tolerance of hole B. This validates further the planning of novice users, who detected successfully the link between hole C and hole B. The longest combination appeared three times was found to be 1-2-3-4-9-5-6, with the sub-set 1-2-3-4-9 being the second longest most common combination with six appearances. These two sets reveal another sequence: the alignment of the part is followed by inspecting the hole's C true position and perpendicularity of face B. In addition, selecting face C after hole B indicates that experienced planners considered this transition as the shortest distance compared to moving to and selecting another feature.

Looking for longer sequences with at least four features, the strategies were scanned and compared for combinations with a minimum of three and four minimum appearances. From the results depicted in the Figure 5.19 and Figure 5.20, the previously detected patterns are illustrated more clearly.

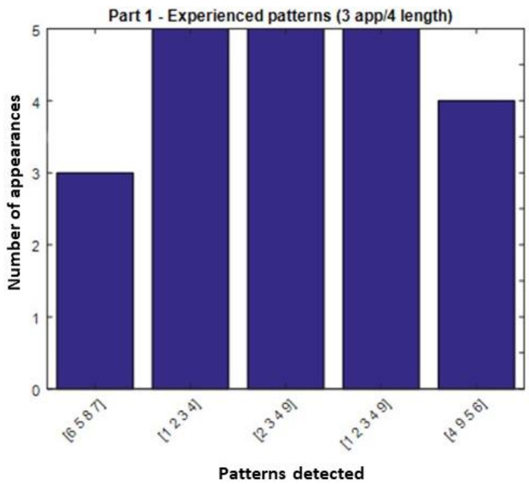


Figure 5.19 Experienced planners, Part 1 - Patterns with at least 4 features length and 3 appearances

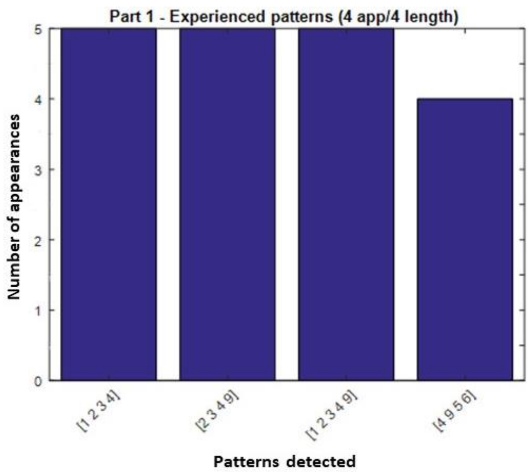
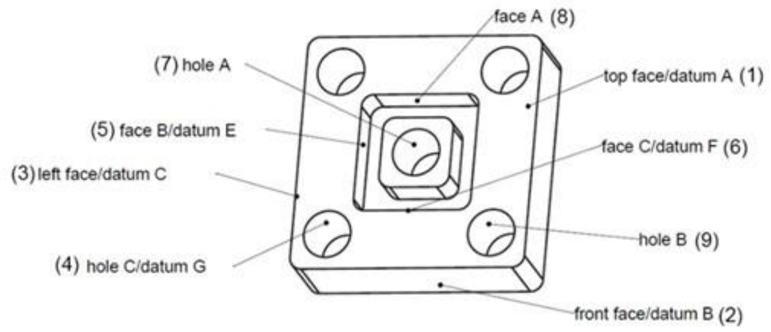


Figure 5.20 Experienced planners, Part 1 - Patterns with at least 4 features length and 4 appearances

Comparing the strategies of novice and the experienced participants, Table 5.6 summarizes the patterns detected with minimum three features appeared four times at least in planning on the Part 1.

Table 5.6 Detected patterns from all participants' planning strategies for Part 1



Patterns from novice strategies		Patterns from experienced strategies	
Sequence	Appearances	Sequence	Appearances
1-2-3	8	1-2-3	7
2-3-4	6	2-3-4	5
3-4-9	4	3-4-9	6
4-9-6	4	5-6-8	4
6-8-5	4	4-9-5	4
8-5-7	4	9-5-6	4
1-2-3-4	5	1-2-3-4	5
2-3-4-9	4	2-3-4-9	5
6-8-5-7	4	4-9-5-6	4
-	-	1-2-3-4-9	5

The two groups showed the same preference for the part alignment step. Regarding the planning of tolerances' inspection, a similar range of different approaches was employed by both groups. Five patterns were exactly the same with similar frequencies for the two groups. Specifically, experienced planners employed a range of up to 10 patterns that appeared at least four times. In contrast, novice strategies appeared to have nine patterns with at least four appearances. This becomes clearer when analysing patterns with at least four digits length appearing at least four times. Novice users employed three different sets with the longest sequence having four digits and five appearances, while experienced participants had four four-digit patterns with at least four appearances. The longest set had five features and was created by five experienced planners. This is reasonable due to the high-level expertise of the CMM planners and the different thought processes they might follow based on their experience.

From a rationale point of view, it can be said that both groups followed a datum-oriented approach to plan their strategies on the simple component. That is, they preferred selecting features used as datums in tolerances first and then the features under a tolerance with the IPaCK system proving a useful tool for capturing this.

The same analysis was repeated for strategies planned by novice and experienced users on Part 2. Regarding the novices, Figure 5.21 and Figure 5.22 illustrate the patterns detected with at least three and four digits and frequency of at least three and four times.

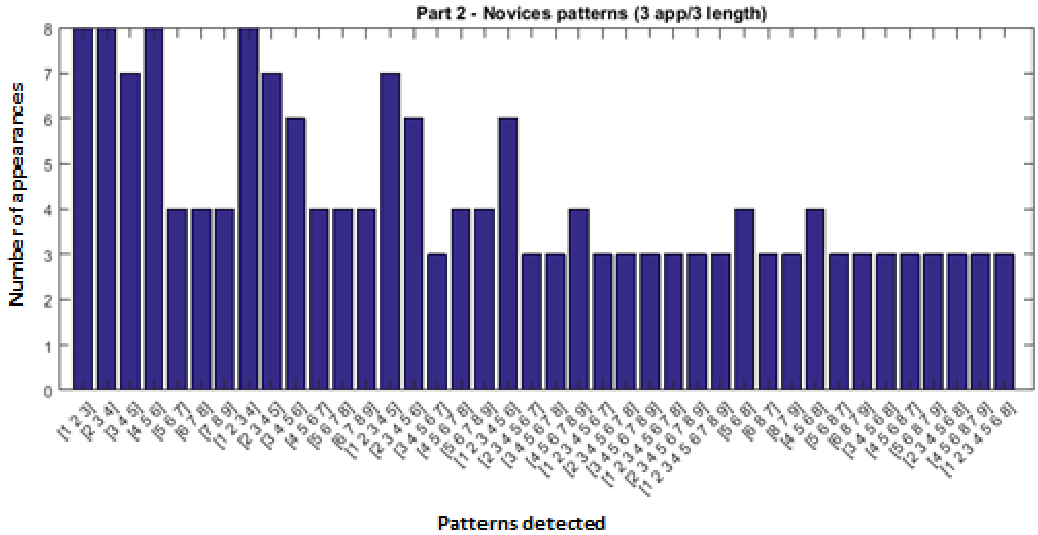


Figure 5.21 Novice planners, Part 2 - Patterns with at least 3 features length and 3 appearances

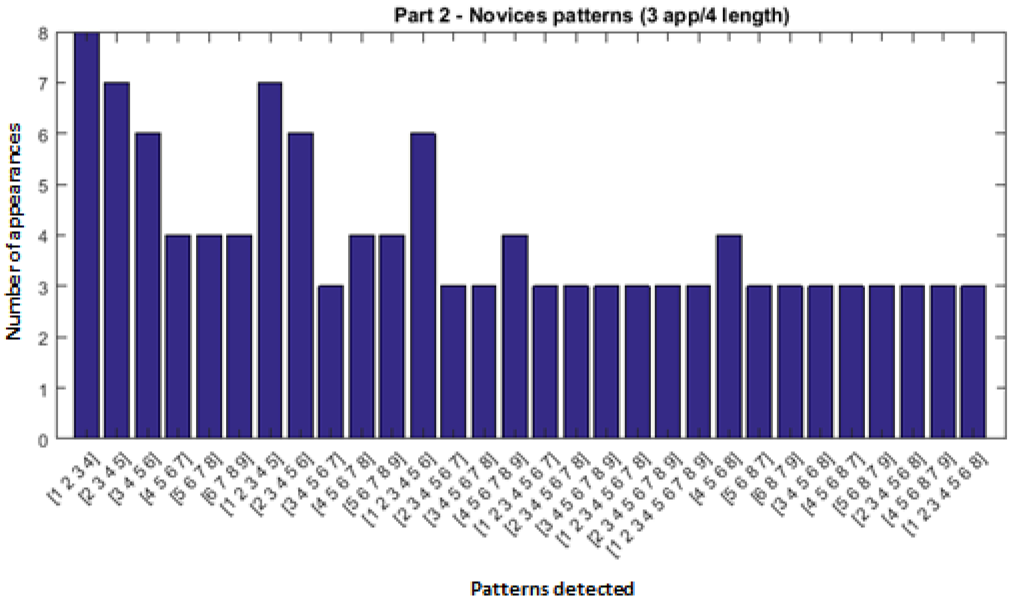


Figure 5.22 Novice planners, Part 2 - Patterns with at least 4 features length and 3 appearances

A first observation from the Figure 5.21 and Figure 5.22 is the wide variety of different sequences and sub-sets of features within the strategies planned by novice users. Considering the design of the part, it was found that a lot of possible combinations can be generated. The most common patterns of three features were 1-2-3 (part alignment stage), 2-3-4 (hole's C true position inspection) and 4-5-6 (perpendicularity of face E) appearing eight times, while 1-2-3-4 was the most common four-digit combination with eight appearances. These sequences highlight that novice planners were able to discover more connections between features and interpret tolerances into planning sub-activities, compared to the strategies on Part 1. This might also be the result of their further familiarisation with the IPaCK's interface, after having already carried out planning on Part 1. In addition, the longest sequence was 1-2-3-4-5-6-7-8-9 appeared three times covering all the features required for inspecting the annotated tolerances. It is important to note that in Part 2 planning, the novice group's plans led to a long pattern involving all the features. This is another impact of the experience they acquired through the planning task on Part 1.

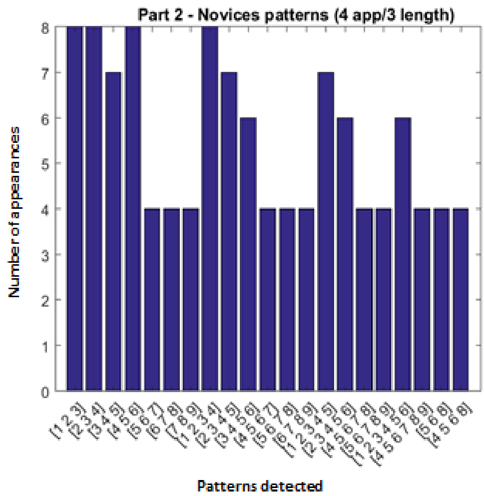


Figure 5.23 Novice planners, Part 2 - Patterns with at least 3 features length and 4 appearances

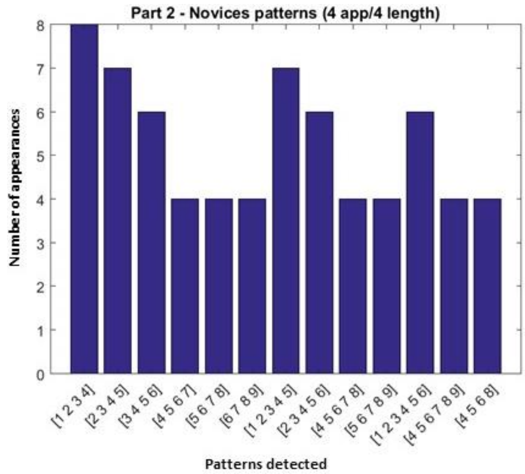


Figure 5.24 Novice planners, Part 2 - Patterns with at least 4 features length and 4 appearances

Figure 5.23 and Figure 5.24 present more distinctly the patterns obtained when limiting to sets with at least four appearances. The longest most common sub-sequence is 1-2-3-4-5-6, appeared six times out of ten plans. This pattern indicates that novice planners preferred to move from hole C to face B and then to face C compared to other possible routes; a strategy that involves the shortest distance between features.

Experienced planners for Part 2 show a vastly different strategy (Figure 5.25 - Figure 5.28). From observation, the most commonly used features set was 1-2-3 (part alignment), which appeared ten times out of thirteen followed by 2-3-4 (nine appearances), linking part alignment stage features with the true position checking of hole C. Patterns 1-2-3-4-5 and 2-3-4-5 indicate a preference for moving to the next closest feature to select. The longest pattern was 1-2-3-4-5-6 with five appearances. Apart from this specific pattern, no other was returned from the data processing tool appeared at least three times. This indicates that there were alternative less common sub-sequences followed by the experienced planners less than three times and therefore were not detected as patterns.

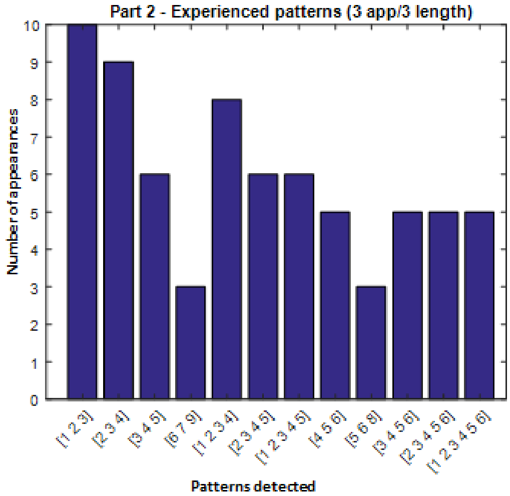


Figure 5.25 Experienced planners, Part 2 - Patterns with at least 3 features length and 3 appearances (experienced)

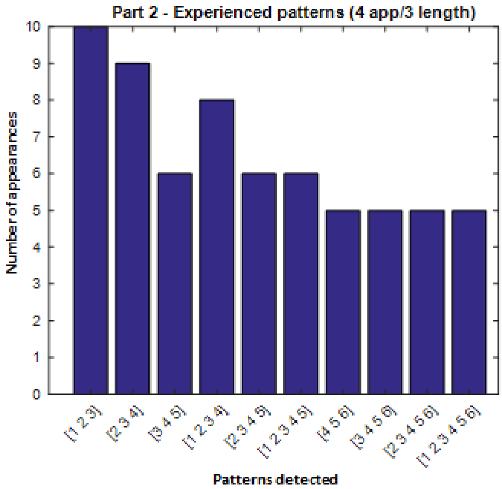


Figure 5.26 Experienced planners, Part 2 - Patterns with at least 3 features length and 4 appearances (experienced)

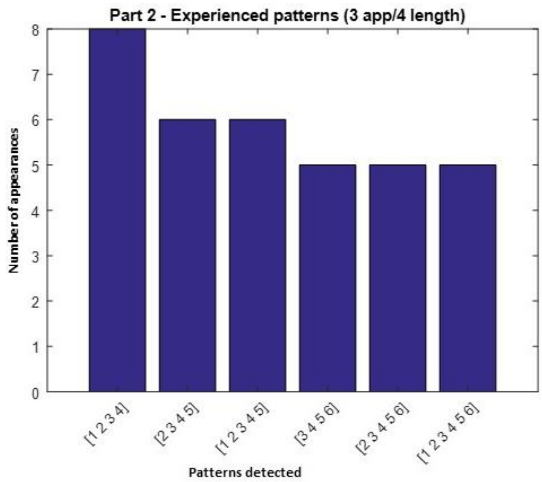


Figure 5.27 Experienced planners, Part 2 - Patterns with at least 4 features length and 3 appearances (experienced)

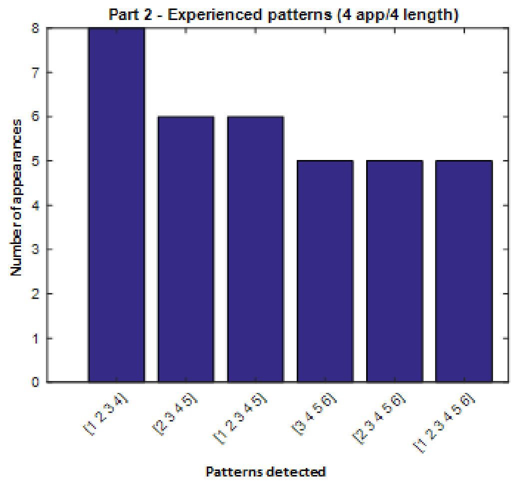
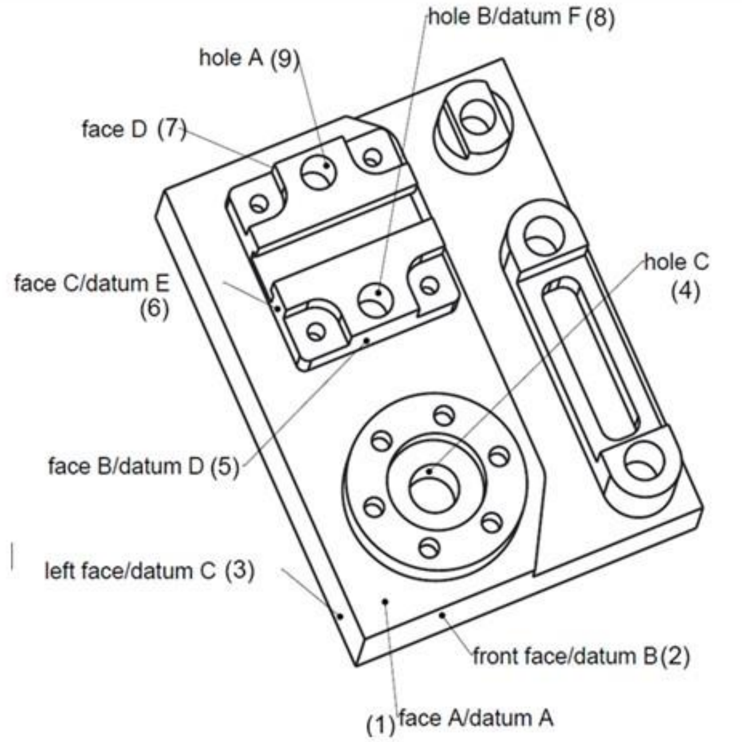


Figure 5.28 Experienced planners, Part 2 - Patterns with at least 4 features length and 4 appearances (experienced)

Table 5.7 summarizes the patterns detected for both novice and experienced planners for the Part 2.

Table 5.7 Detected patterns with at least four appearances from all participants' planning strategies for Part 2



Patterns from novice strategies		Patterns from experienced strategies	
Feature sequence	Appearances	Feature sequence	Appearances
1-2-3	8	1-2-3	10
2-3-4	8	2-3-4	9
3-4-5	7	3-4-5	6
4-5-6	8	4-5-6	5
5-6-7	4	-	-
6-7-8	4	-	-
7-8-9	4	-	-
5-6-8	4	-	-
1-2-3-4	8	1-2-3-4	8
2-3-4-5	7	2-3-4-5	6
3-4-5-6	6	3-4-5-6	5
4-5-6-7	4	-	-
5-6-7-8	4	-	-
6-7-8-9	4	-	-
4-5-6-8	4	-	-
1-2-3-4-5	7	1-2-3-4-5	6
2-3-4-5-6	6	2-3-4-5-6	5
4-5-6-7-8	4	-	-
5-6-7-8-9	4	-	-
1-2-3-4-5-6	6	1-2-3-4-5-6	5
4-5-6-7-8-9	4	-	-

In a similar manner to Part 1 planning task, both groups followed the sub-sequence 1-2-3 for the part alignment step as the most common routine. Regarding the measurement planning of the tolerances, novice planners followed several patterns resulting from the two longest sequences: 1-2-3-4-5-6 and 4-5-6-7-8-9. The former pattern was also found in experienced group's plans. The strategies of experienced users led to a significantly smaller number of different patterns compared to the novices, indicating that shorter sets of features appeared less than three times out of 13 plans in total.

The different levels of experience of the experienced planners, and the multiple possible sequences due to the geometry and tolerancing specifications of Part 2, led to less frequent and shorter sub-sequences, resulting in less repeated planning patterns. In contrast, the novice group's plans for Part 2 contained longer sequences compared to their planning for Part 1, possibly due to their further familiarisation with IPaCK and the associated inspection planning task.

On closer examination of each group's sequences, both novice and experienced planners followed a datum-oriented planning approach for Part 2. Both groups set a priority in selecting datum features first followed by the toleranced features. It also emerged that novice planners also considered the shortest distance between features when planning Part 2. Thus, in some instances, novices planned sequences tended to move from one feature to its next closest.

Research objective RO1 concerned the design and development of tools capable of capturing CMM inspection planning strategies. The validation of IPaCK's usability with novice and experienced planners satisfactorily addressed RO1, while the positive feedback contributed to RO3. The IPaCK methodology successfully differentiated CMM planning strategies and detection of repeated patterns of activity, addressing research objective RO5 and associated question RQ4.

5.4.2 Evaluating the quality of strategic planning

Throughout the literature, no methods were found for comparing strategic planning sequences in CMM measurement. In an effort to deal with this challenge, a novel solution is proposed in this work. The basic idea is that a benchmark sequence of features can be formulated using the previously detected patterns from the strategies planned by the experienced users. Subsequently, each sequence planned for the two components will be compared against this benchmark sequence. The number of differences between these will characterise the quality of each plan. This will be quantified by counting the differences between the sequences under-comparison. Given the lack of previous relevant work in evaluating various CMM inspection planning strategies, this approach constitutes a novel proposal for this kind of comparison and was applied successfully.

Considering first, the most frequent and then the longest identified patterns of activity from the experienced group's plans, the benchmark sequences for each of the two test components are shown in Table 5.8. The last three features in the best sequences were defined based on patterns with three appearances or less. On the table, the patterns considered for the formulation of the benchmark sequences are highlighted.

Table 5.8 Patterns considered from experienced strategies and benchmark sequences for Part 1 and Part 2

Part 1 - Experienced strategies' patterns		Part 2 - Experienced strategies' patterns	
Sequence	Appearances	Features' sequence	Appearances
1-2-3	7	1-2-3	10
2-3-4	5	2-3-4	9
3-4-9	6	3-4-5	6
5-6-8	4	4-5-6	5
4-9-5	4	1-2-3-4	8
9-5-6	4	2-3-4-5	6
1-2-3-4	5	3-4-5-6	5
2-3-4-9	5	1-2-3-4-5	6
4-9-5-6	4	2-3-4-5-6	5
1-2-3-4-9	5	1-2-3-4-5-6	5
Benchmark sequence: 1-2-3-4-9-5-6-8-7		Benchmark sequence: 1-2-3-4-5-6-8-7-9	

To conduct the comparison of strategies, given that all sequences are expressed in the form of digits series, an Edit Distance algorithm was developed, again in MATLAB (Appendix B.4). The algorithm compares two strings of digits (each planned sequence against the best one) and counts the differences in digits' positions between them. For example, if the tested sequence is 1-2-3-4 and the ideal is 1-3-4-2, there are two differences in the second and forth positions of the tested sequence compared to the ideal. This gives a measure of a plan's quality level in terms of how close each plan is to the ideal.

Table 5.9 shows all the features sequences planned by novice and experienced participants along with the number of differences for planning for Part 1 compared to the ideal. The average values provided indicate the level of deviation of the two sets of strategies compared to the ideal sequence. It was found that three novice sequences were close to the ideal sequence with only two differences, while only one of the experienced plans meeting the benchmark. Moreover, four plans were very close to the best sequence with only two differences. In this case, the experienced participants' plans were found to be closer to the benchmark than those of the novice planners, considering the average number of differences for each group.

Table 5.9 Comparison of novice and experienced strategies against benchmark for Part 1

Novice planning sequences			Experienced planning sequences		
Participant No	Test sequence	Number of differences	Participant No	Test sequence	Number of differences
1	1 2 3 5 6 7 8 4 9	5	1	1 4 2 3 6 5 8 7 9	5
2	7 1 5 6 8 2 3 4 9	8	2	1 2 3 8 5 6 9 4 7	4
3	1 2 3 4 6 5 8 7 9	3	3	1 2 3 4 9 7 5 6 8	2
4	1 2 3 4 9 6 8 5 7	2	4	1 2 3 4 9 6 5 8 7	2
5	1 2 3 6 8 5 7 4 9	5	5	1 2 3 4 9 5 6 7 8	2
6	1 2 3 4 6 8 5 7 9	4	6	1 2 3 4 9 5 6 8 7	0
7	1 2 3 4 9 6 5 8 7	2	7	1 7 8 5 6 9 4 3 2	8
8	2 3 1 4 9 6 8 5 7	4	8	1 2 7 4 9 3 8 5 6	5
9	1 2 3 4 9 6 5 8 7	2	9	1 2 7 6 8 5 3 4 9	6
10	1 2 3 5 6 7 8 4 9	5	10	1 3 2 4 9 5 6 7 8	4
	Average	4	11	1 2 3 7 5 6 8 4 9	4
			12	1 3 2 4 9 5 6 8 7	5
			13	1 2 3 4 9 6 5 8 7	2
				Average	3.5

Table 5.10 Comparison of novice and experienced strategies against benchmark for Part 2

Novice planning sequences			Experienced planning sequences		
Participant No	Test sequence	Number of differences	Participant No	Test sequence	Number of differences
1	1 2 3 4 5 6 7 8 9	2	1	1 2 3 4 5 8 6 7 9	2
2	2 3 1 4 5 6 7 8 9	4	2	1 2 3 6 7 9 8 5 4	5
3	1 2 3 4 5 6 8 7 9	0	3	1 2 3 5 6 8 7 4 9	0
4	1 2 3 4 8 9 5 7 6	4	4	1 2 3 4 9 8 6 5 7	4
5	1 2 3 4 5 6 8 9 7	2	5	1 2 3 5 6 8 4 7 9	2
6	1 2 3 4 5 7 6 8 9	2	6	1 4 2 3 5 6 8 9 7	4
7	1 2 3 4 5 6 7 8 9	2	7	1 2 3 9 8 4 7 6 5	2
8	2 3 1 4 5 6 8 7 9	2	8	1 2 3 4 7 8 6 9 5	4
9	1 2 3 4 5 6 7 8 9	2	9	1 2 4 5 7 6 8 3 9	3
10	1 2 3 4 5 6 8 7 9	0	10	1 5 8 6 7 9 2 3 4	8
	Average	2.4	11	1 2 3 8 9 5 7 6 4	6
			12	1 2 3 5 6 8 9 7 4	2
			13	1 2 3 4 5 6 7 8 9	2
				Average	3.3

Similarly, strategies on Part 2 were analysed and compared (Table 5.10). For inspection planning, only two sequences met the benchmark and six were found with two differences. One experienced planner matched the best sequence while five others were close to this recoding only two differences in their plans.

Considering the average differences for each group, the novice planners were found to be closer to the ideal sequence when compared to the experienced planners. The latter employed a range of different approaches due to their expertise. This highlights the variety of approaches employed by the experienced planners in relation to their strategic thinking, indicating the lack of commonly followed practices in inspection planning.

On the other hand, novice planners have very little exposure to the interpretation of geometric and tolerancing annotations and tend to follow similar approaches; especially after obtaining further practical experience after planning Part 1. They were unable to convert tolerances into planning activities other than the way in which they were trained. The experienced planners were more creative and confident in following their rationale based on their level of expertise.

Also, it is apparent from the novice group's strategies when comparing these against the experts' plans that they were found to be sensible and reasonable for the purposes of this comparison. Therefore, it was not necessary to involve experts in functional user trials.

Although used within a constrained and limited experimental environment, in the future this methodology has the potential to provide more comprehensive results with more robust criteria relating to a set of plans' quality and effectiveness especially with a larger number of expert planners involved in any future comparative study.

5.5 CMM part programming

The last step for evaluating IPaCK involves a comparison of the system used for generating a plan and associated CMM part program against planning an inspection sequence and generating a part program using an actual CMM. The purpose of this benchmarking was to investigate if IPaCK facilitates faster measurement planning against a real CMM when extended to automatically generate a CMM control program from the user logged data.

As supplement to the usability study, a comparison of IPaCK use against its conventional CMM equivalent was carried out. It is essential to note that the prototype was designed and built to facilitate fast inspection planning as well as being oriented to novice users; this would allow the effective capture of intuitively generated knowledge during a planning session. The IPaCK system does not aim to replace a CMM and therefore the comparison with programming a CMM was kept at a generic level considering only task completion time.

To carry out this, the average times of the participants IPaCK's trial for planning inspections on the two parts (Table 5.11) were calculated. Note the significant variation in the completion times among the strategies developed. This is primarily due to the different number of points involved for selecting each of the features and, secondly, in the level of confidence and familiarisation obtained by each participant during the trials.

Also, it was observed that except for one participant, all the users planned more quickly for the second component (a more complex design), demonstrating that they had been sufficiently familiarised with the system after carrying out the task for the Part 1. Table 5.11 below shows the times taken for each participant to plan measurements on both components using IPaCK as well as the respective average values.

Table 5.11 Individual task completion times and average values in each trial test using IPaCK

	Task completion time (min)	
Participant	Part 1	Part 2
1	8.1	9.2
2	15.8	10.2
3	15.8	13.5
4	19.6	13.3
5	19.2	12.4
6	8.7	8.2
7	14.5	12.7
8	16.0	11.3
9	7.5	9.1
10	14.6	9.6
Average	14.0	11.0

With the aid of the generated outputs presented in section 4.3.2, the two plans closest to the average completion times were selected and replicated on an actual CMM. These were: Plan 7 for Part 1 (14.5 min) and Plan 8 for Part 2 (11.3 min). The equipment employed was a CE Johansson 3-axis CMM (Figure 5.29) equipped with a Renishaw PH10M probe head operated with Modus 1.1 part programming software (Figure 5.30).

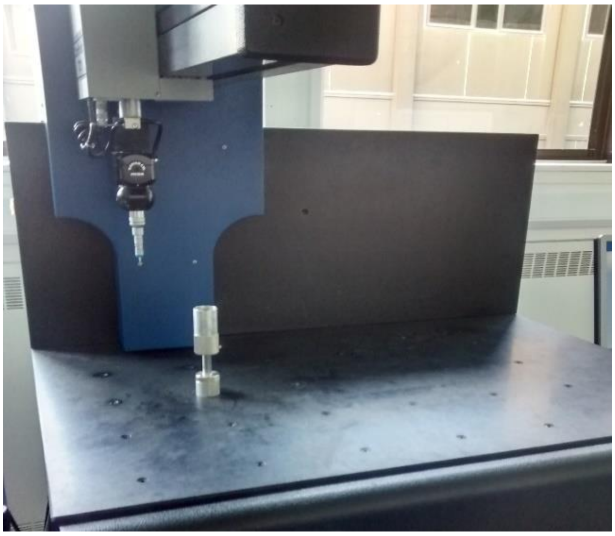


Figure 5.29 CE Johansson CMM available in the Metrology lab of Heriot-Watt University

Part programs generated by IPaCK and using the CE Johansson CMM can be found in Appendix C.3 (Part 1-Plan 7) and Appendix C.4 (Part 2 – Plan 8).

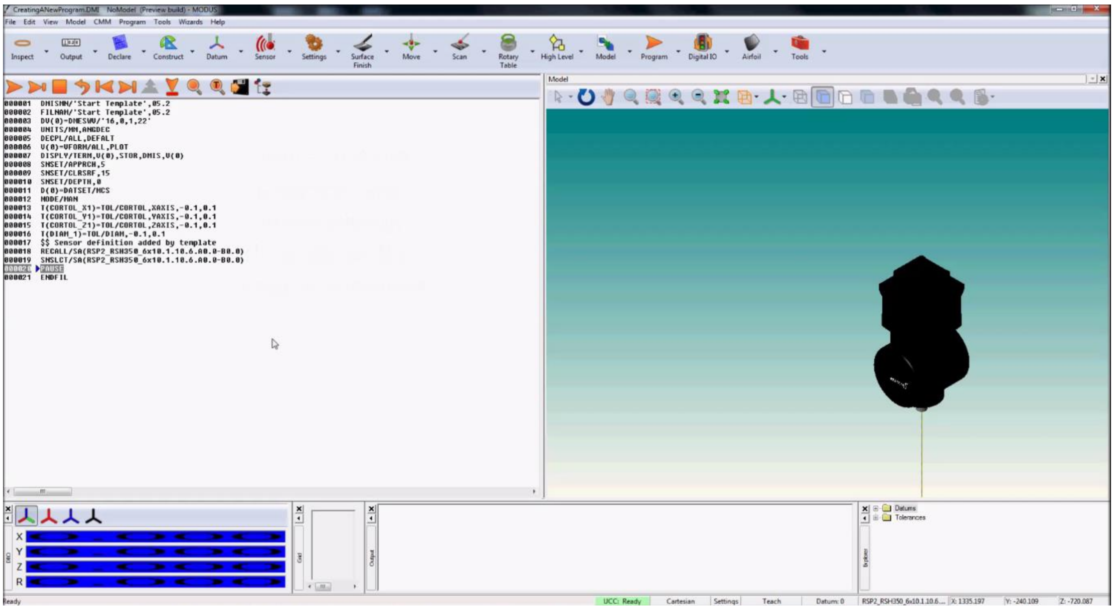


Figure 5.30 Modus environment for programming a CMM

The task completion times (TCT) for replicating the defined inspection planning tasks for the two trial components are shown in Table 5.12. For Part 1 it was 32 minutes which is 2.3 times slower compared to the respective average TCT using IPaCK and 34 minutes for Part 2; that is 3.1 times slower compared to the average time when planning on Part 2 using IPaCK.

Table 5.12 Task completion times for Part 1 and Part 2 planning using a CMM

Task completion time (min)	
Part 1	**Part 2**
32	34

It is essential to highlight the differences of the two planning methodologies and how these link to the differences in the average task completion times for the two tasks. IPaCK is a very simple and completely freeform unrestricted planning environment design to allow a user to express their thought process and cognition with regards to planning a measurement. Thus, no implicit guidance is provided through prompts to select and set specific options on operating the software as happens with a CMM programming package. On the other hand, when using a CMM, the planning software requires a lot of input by a user for setting a range of parameters in the planning session, for example the angles of the probe head, the speed of probing system, the approach and retract distances, the fitting algorithms for producing the substitute geometries of the physical component and many others. All of these are necessary for creating a measurement plan with a CMM, adding substantially to the total completion time; these are not required when using IPaCK. Moreover, the two systems employ very different ways of carrying out planning. On IPaCK, the inspection stylus is moved by the user quickly from point-to-point and from feature to feature while implicitly and consciously considering any possible collisions, whereas on the CMM the probing system is moved manually using a joystick at a relatively low speed. This was the case in the experimentation conducted, adding further time in the total planning task. If the user has selected one of the software suggested inspection routes, then it calculates a collision free inspection path saving this amount of time.

IPaCK's purpose is solely to facilitate a quick and simplified environment for planning CMM-like inspections and capturing relevant expert knowledge and not necessarily for generating an actual CMM part program per se. In this vein, the two systems are quite different such that various parameters mentioned previously affect their use and effectiveness. Therefore, task completion time was selected as a key metric for an additional evaluation of the IPaCK prototype, supplementary to the main usability study. For all the above reasons, the durations of planning using IPacK for the two components were found to be shorter than when using the CMM.

By achieving this initial evaluation of IPaCK's usability and functionality in rapidly planning CMM measurements, future research can include additional metrics with regards to inspection planning. These can be related to the execution time for inspection, accuracy, repeatability and measurement uncertainty. In addition, other parameters that could be taken into consideration can be the number of measurement points regarding the percentage of features covered using the input sampling points, the ratio of time to number of points as well as time spent on thinking before actual planning. All of these can lead to further insights into a measurement planning strategy and could be enabled by redesigning and further developing the IPaCK prototype.

Although IPaCK it is not meant to replace a CMM, it is apparent that it can facilitate the rapid generation of measurement strategies and respective part programs as an additional benefit when combined with its main purpose: capturing CMM inspection planning activity and knowledge and formalise them automatically in multiple formats. With this part of experimentation, RO3 - to test and evaluate the planning prototype's usability and compare it against a conventional CMM in terms of TCT- is fully achieved and a thorough usability evaluation completed, presenting the key benefits and contributions IPaCK's use can offer to CMM measurement planning.

5.6 Summary

In this first stage of experimental results and analysis, the usability evaluation of IPaCK was presented, proving its novel capabilities for logging user activity and inspection planning tasks.

The SUS scores demonstrated that the novice planners rated IPaCK more highly than the experienced engineers but with no statistically significant difference, forming a common perception and acceptability level. Both main groups ranked IPaCK within the 'high OK' range of the acceptability scale. However, a comparative statistical analysis showed mixed differences across the derived sub-groups of experienced participants. Groups with little or no experience and much more experience provided higher scores on IPaCK's usability compared to participants with intermediate levels of expertise. With regards to novice planners, IPaCK was found to be intuitive, easy to learn and use, confirming that it can enhance inexperienced planners' familiarisation with CMM inspection and associated planning strategy principles.

Therefore, part of research objective (RO3) related to 'test and evaluate the prototype's usability' was met. In addition, the design and development of IPaCK as a tool for logging and capturing CMM inspection planning strategies (RO1) was partially addressed. Further validation with regards to the generated knowledge outputs will be reported in Chapter 6.

IPaCK's novel methodology for comparing and evaluating planning strategies was also demonstrated. With the aid of IPaCK's outputs (strategic activity trajectory) and the identified patterns from the users' strategic inspection plans, best sequences were defined and applied to measure the inspection plans' quality. The evaluation of the experienced group's plans reveals the variety of different inspection planning strategies, illustrating the absence of standardised CMM inspection planning methods.

With the results obtained, and associated analysis presented in Chapter 5, there is scientific evidence that IPaCK can enable capturing of CMM inspection planning strategies and knowledge with a view to compare various plans and detecting repeated patterns of activity (RO5). This can eventually lead to a capability for structuring best sequences to evaluate the quality of strategic inspection planning thinking and rationale (RO6). Therefore, research question RQ4 (Can patterns of activity be detected?) and RQ5 (Can best practices be created?) were answered. Thus, the potential to fill the key industrial and research gaps in the domain of Coordinate Metrology has been demonstrated:

- A lack of standardised CMM inspection planning strategies.
- A lack of a methodology for comparing planning strategies, detecting repeated patterns and structuring best practices.

To completely meet research objective (RO3), a practical comparison between IPaCK and a real CMM was carried out with the former being quicker at generating the associated measurement strategy and inspection plans as well as CMM part programs. The results are encouraging, indicating the potential of IPaCK to facilitate rapid CMM inspection planning. Moreover, the IPaCK system offers a unique capability to capture the knowledge and experience of CMM inspection planning; this is investigated in the following chapter.

In conclusion, the usability study responses obtained from the experienced participants classified IPaCK in the third level of Technology Readiness Level scale (TRL-3). It is also highlighted its industrial acceptance and potential contribution to supporting CMM inspection planning tasks. From an industrial point of view, this chapter highlights the potential benefits of the underpinning science and technology researched.

Chapter 6 Experimental results and analysis 2 – The evaluation and validation of CMM inspection planning knowledge representations

6.1 Introduction

The second stage of the main study concerned the evaluation of the structured knowledge representations. A major contribution of this research to the CMM inspection planning field was to capture, evaluate and reuse knowledge associated with inspection thinking and planning. The purpose of Chapter 6 is to extrapolate and validate from the feedback obtained from both the novice and experienced engineer's their views on the knowledge and experience residing within the planning activities. The usefulness, ease of understanding and overall performance of each one of the selected formats generated from the logged data were evaluated by the participants and scored. Having acquired the results, a statistical analysis and comparison between the two main groups (Set 1) was conducted to identify any significant differences. Additionally, further comparisons were carried out regarding how participants' sub-groups with different levels of experience (Set 2) understand and perceive the use and performance of the suggested representations.

6.2 Experimental methodology

On completion of the inspection planning tasks on the two components (Figure 5.9 and Figure 5.10) and IPaCK's functionality and usability assessment, novice and experienced planners were asked to study a set of knowledge formats; i.e. representation combinations of an already prepared planning strategy. Then, they completed a questionnaire to rate each format with respect to their performance in representing the intended strategy and knowledge. The final formats to evaluate were presented and explained in detail in the Chapter 4 (section 4.4.2) are as follows:

- Inspection Plan + Tactical Planning Trajectory.
- Inspection Plan + Strategic Planning Trajectory.
- Inspection Plan + IDEF0 Diagram.
- Annotated Video clip.
- Storyboard.

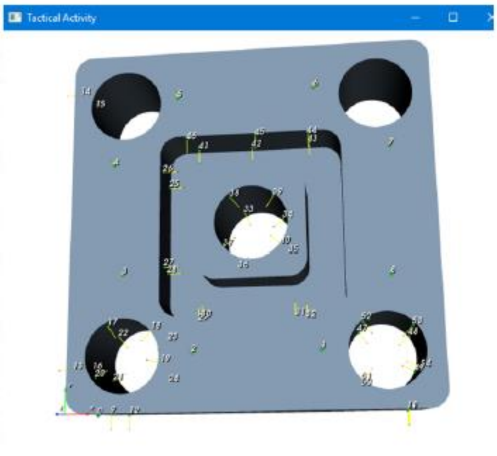
The questionnaire consisted of three neutral statements related to the usefulness of each combination, ease of understanding and level of output's performance in representing the planned strategy. Each respondent had to rate the representations using a five-point Likert scale, varying from “1-lowest” to “5-highest”. Feedback was requested for each individual format in the end of each sub-section as well as the end of questionnaire for further comments. An example of the questionnaire is given in Figure 6.1 and Figure 6.2; the full questionnaire can be found in Appendix D.3.

1. Inspection plan - tactical planning trajectory

In this format the followed strategy is displayed as a list of steps (inspection plan) in a chronological order with details on how each tolerance is checked, what geometrical features are used and the number of points with XYZ coordinates and associated normal vectors. The graph on the right shows the points (numbered as in the plan) along with the normal vectors, indicating the distribution of points over each feature.

To see the image in a larger size, please follow the link: https://imgur.com/fkeGHu1

Time	Activity	Geo/ID	X	Y	Z	Tool	Total pts	I	J	K
34	ZeroZ	Plane1				Stylus1	8			
37	Point	1	68.07	15.38	30			0	0	1
39	Point	2	34.03	15.38	30			0	0	1
41	Point	3	15.01	36.76	30			0	0	1
43	Point	4	12.01	67.47	30			0	0	1
45	Point	5	30.01	86.54	30			0	0	1
47	Point	6	68.07	87.5	30			0	0	1
48	Point	7	88.09	69.5	30			0	0	1
51	Point	8	87.09	34.67	30			0	0	1
57	ZeroY	Plane2				Stylus1	4			
61	Point	9	10.93	0	24.02			0	-1	0
64	Point	10	90.05	0	23.02			0	-1	0
66	Point	11	91.04	0	8.007			0	-1	0
68	Point	12	10.93	0	5.004			0	-1	0
80	ZeroX	Plane3				Stylus1	4			
83	Point	13	0	11.92	24.02			-1	0	0
86	Point	14	0	91.04	25.02			-1	0	0
88	Point	15	0	93.02	10.01			-1	0	0
91	Point	16	0	12.91	6.005			-1	0	0
114	Tolerance	Position								
114	Datum	Plane2				Stylus1	4			
118	Datum	Plane3				Stylus1	4			
123	Inspection	Cylinder1				Stylus1	8			
127	Point	17	9.736	23.5	25.02			0.56514	-0.825	0
128	Point	18	21.74	22.39	24.02			-0.7071	-0.70711	0
130	Point	19	24.83	13.16	26.03			-0.9734	0.228951	0
132	Point	20	6.498	9.736	25.02			0.87362	0.486604	0
134	Point	21	6.498	9.736	7.006			0.87362	0.486604	0
136	Point	22	8.263	22.39	8.007			0.63885	-0.76933	0
138	Point	23	22.98	21.03	8.007			-0.7693	-0.63885	0
140	Point	24	22.98	8.974	6.005			-0.825	0.565135	0
152	Tolerance	Position								
160	Datum	Plane4				Stylus1	4			
163	Point	25	25	64.15	17			1	0	0
166	Point	26	25	66.1	26.01			1	0	0
169	Point	27	25	39.76	24.01			1	0	0
170	Point	28	25	38.78	19			1	0	0
175	Datum	Plane5				Stylus1	4			
178	Point	29	33.9	25	19			0	1	0
179	Point	30	35.85	25	25.01			0	1	0
182	Point	31	61.22	25	24.01			0	1	0
183	Point	32	64.15	25	19			0	1	0
189	Inspection	Cylinder2				Stylus1	8			
192	Point	33	45.54	58.95	4.003			0.40392	-0.91479	0
194	Point	34	57.39	56.74	5.004			-0.7693	-0.63885	0
195	Point	35	58.95	45.54	8.007			-0.8736	0.486606	0
197	Point	36	43.97	42.02	7.006			0.63885	0.769335	0
199	Point	37	42.02	43.97	26.03			0.76934	0.638845	0
201	Point	38	43.97	57.98	26.03			0.63885	-0.76934	0
203	Point	39	56.03	57.98	26.03			-0.5651	-0.825	0
204	Point	40	57.98	43.97	27.03			-0.7693	0.638845	0
239	Tolerance	Perpendicularity								
239	Datum	Plane5				Stylus1	4			
255	Inspection	Plane4				Stylus1	4			
284	Tolerance	Parallelism								
284	Datum	Plane5				Stylus1	4			
291	Inspection	Plane6				Stylus1	6			
295	Point	41	33.9	75	18			0	-1	0
297	Point	42	49.51	75	18			0	-1	0
298	Point	43	66.1	75	20			0	-1	0
300	Point	44	66.1	75	27.01			0	-1	0
301	Point	45	51.46	75	28.01			0	-1	0
303	Point	46	31.95	75	27.01			0	-1	0
335	Tolerance	Position								
335	Datum	Cylinder1				Stylus1	8			
345	Inspection	Cylinder3				Stylus1	8			
350	Point	47	78.26	22.39	3.002			0.63885	-0.76933	0
351	Point	48	92.98	21.03	4.003			-0.7693	-0.63885	0
353	Point	49	93.95	10.54	5.004			-0.8736	0.486599	0
354	Point	50	78.97	7.02	3.002			0.63885	0.769334	0
356	Point	51	78.26	7.61	25.02			0.7071	0.707109	0
357	Point	52	78.97	22.98	26.03			0.56514	-0.825	0
359	Point	53	92.39	21.74	25.02			-0.7071	-0.70711	0
361	Point	54	93.95	10.54	25.02			-0.9148	0.403924	0



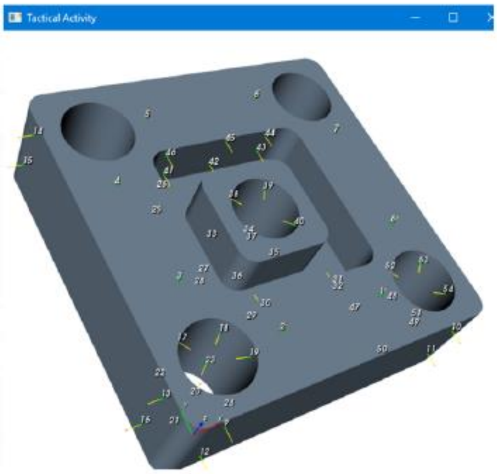
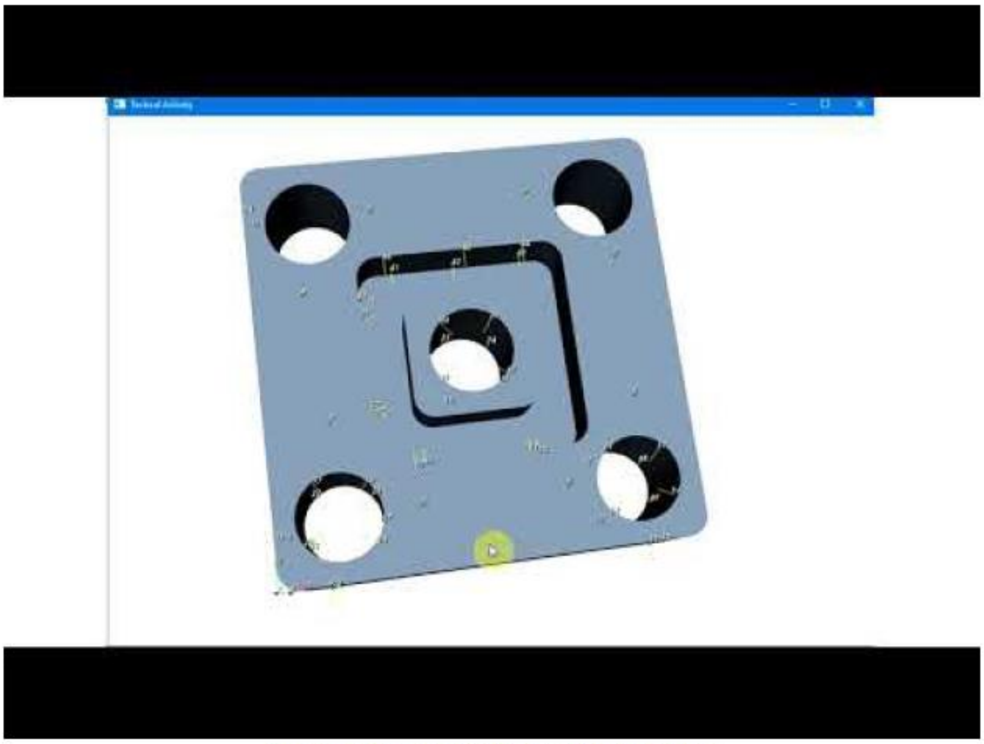


Figure 6.1 Sample of questionnaire on final knowledge representations evaluation



http://youtube.com/watch?v=WX6dVv6gvSc

In this video, the above digital model is shown in different angles, allowing the participant to have a better view of what is displayed. To watch the video in a larger window please follow the link: https://www.youtube.com/watch?v=WX6dVv6gvSc

2. **On a scale from 1 (lowest) to 5 (highest), please rate the format for each of the following aspects.** *

Mark only one oval per row.

	1	2	3	4	5
Ease of understanding	◯	◯	◯	◯	◯
Usefulness	◯	◯	◯	◯	◯
Overall	◯	◯	◯	◯	◯

3. **Please leave your comments for this format.** *

Figure 6.2 Sample of questionnaire on final knowledge representations evaluation (continued from Figure 6.1)

6.3 Knowledge representations evaluation and statistical analysis

6.3.1 Main groups comparison and statistical analysis

In the evaluation stage of IPaCK's outputs and knowledge representations, 10 novice planners and 62 experienced CMM planners responded. As in Chapter 5, participants' responses are divided into Set 1 (novice and experienced users) and Set 2 (five subgroups, Table 6.1).

Table 6.1 Classification of participants based on level of experience (Set 2)

CMM experience in years	Group of expertise
Basic training	Trial novice
0 < exp < 2	Online junior
2 ≤ exp < 5	Online intermediate
5 ≤ exp < 10	Online senior
≥ 10	Online expert

Figures 81-83 summarise the average scores of the Set 1 classification responses on the knowledge formats. The raw data for all main groups (Set 1) and subgroups (Set 2) can be found in Appendix E (Table E. 7, Table E. 8 for Set 1 and Table E. 9, Table E. 10Table E. 11, Table E. 12 for Set 2).

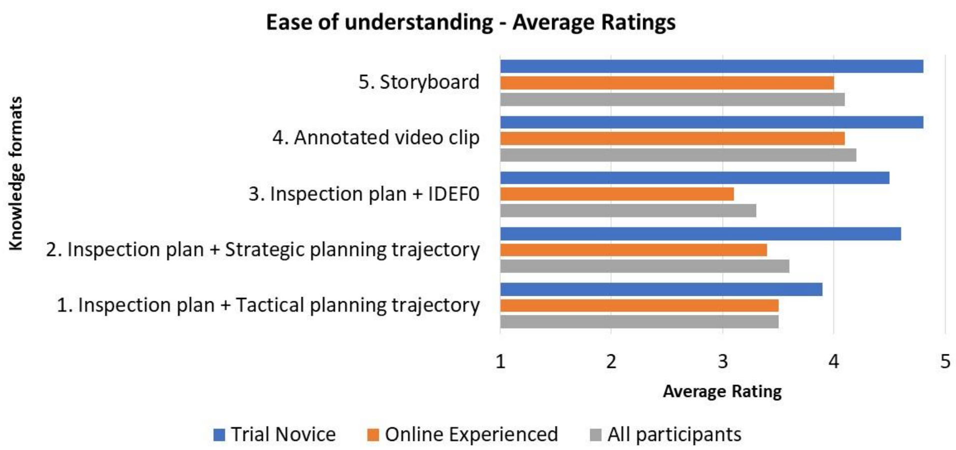


Figure 6.3 Ease of understanding average ratings - novice, experienced and all participants (Set 1)

On the aspect of ease of understanding (Figure 6.3), richer forms of representation, such as the Annotated Video clip and Storyboard (combined multiple forms), were rated highly (84% and 82% respectively) by all participants. The novice planners scored all the suggested formats higher compared to experienced group, showing the potential of these representations to support the training of inexperienced CMM planners. Additionally, the experienced planners gave scores ranging from mid to high (66% - 84%), showing the outputs acceptance and understanding from an industrial perspective, with a specific preference for the Annotated Video clip and Storyboard. Since all groups rated the formats highly, they were able to understand the embedded knowledge.

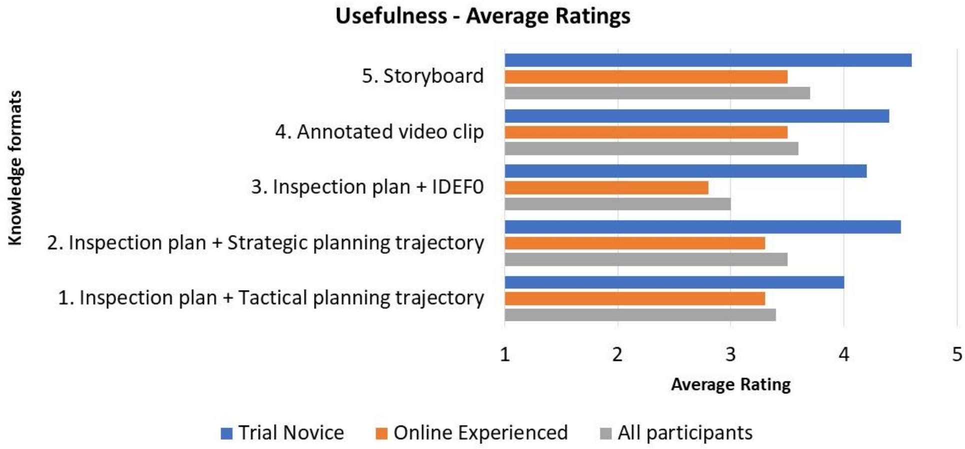


Figure 6.4 Usefulness average ratings - novice, experienced and all participants (Set 1)

As shown in Figure 6.4 the Storyboard and Annotated Video clip were rated with the highest scores (74% and 70% respectively) by all the participants in the aspect of usefulness. Novice users providing higher scores to all formats compared to experienced planners, found Storyboard and the combination Inspection Plan + Strategic Planning Trajectory more useful, while the experienced planners had the same preference as all the respondents, i.e. the Storyboard and Annotated Video-clip formats. The combination of Inspection Plan + IDEF0 diagram received the lowest score across all groups. In general, novice and experienced planners confirmed the usefulness of the proposed formats from which can be inferred that these could be beneficial for training purposes as well as a support in industrial CMM inspection planning needs.

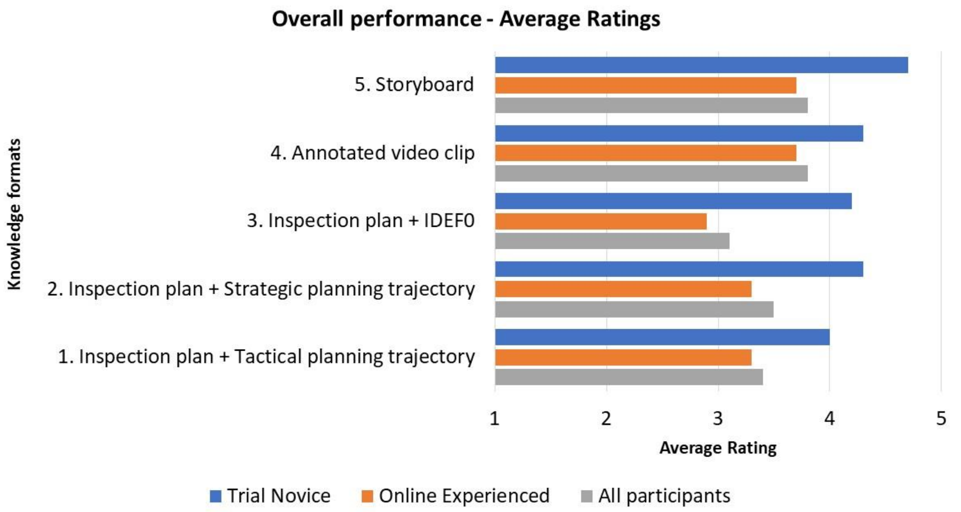


Figure 6.5 Overall performance average ratings - novice, experienced and all participants (Set 1)

Regarding the overall performance (Figure 6.5) all the formats received scores from mid to high from all participants and the two major groups in Set 1, i.e. the selected formats can successfully represent captured knowledge and inspection planning strategies. The Storyboard and Annotated Video-clip were again rated the highest (76%). The high scores show and validate the conclusion that the suggested formats can represent the captured CMM inspection knowledge and convey both the intended inspection plan and strategy they represent.

Comments on the representations by experienced planners include the following:

- Inspection Plan + Tactical Planning Trajectory:
  - ‘While this is a different software from what I use, the format is easily interpreted, and the information is clear and concise.’
  - ‘The first time is complicated understand this format as any new software, but on second time that you review is easy to use’
- Inspection Plan + Strategic Planning Trajectory
  - ‘Nice and easy to understand, very good.’
  - ‘Clear concise directions.’
- Inspection Plan + IDEF0
  - ‘It's useful in the sense that it establishes chronological order.’
  - ‘I understand what is being conveyed; the data on the left already makes that known anyway.’
- Annotated Video-clip
  - ‘It is much clearer what all of the points in the previous formats represent.’
  - Far the easiest to understand. This video will help a CMM programming beginner.’
- Storyboard

- ‘This diagram best explains the measurement strategy thus far. The combination of screenshots and diagrams creates a great visual representation.’
- ‘The explanations next to each diagram is very helpful.’

The positive comments and written feedback provided by experienced CMM planners showed they were able to reflect, interpret and therefore validate embedded knowledge, in line with Davenport and Prusak [126] who stated that *“Knowledge is information with the most value and is consequently the hardest form to manage. It is valuable precisely because somebody has given the information context, meaning, a particular interpretation; somebody has reflected on the knowledge, added their own wisdom to it, and considered its larger implications.”* This finding is also underpinned by Sung et al. [4, 165], as they employed experienced engineers to test similar knowledge representations and validated them in other engineering domains.

To compare these responses in a greater detail and detect statistically significant differences between the two main groups, the non-parametric Mann-Whitney U two-tailed test [189] for two unpaired samples was used as the acquired data are ordinal (Likert scale). The null and alternative hypotheses tested for the two groups comparison (Group 1: novice planners N_1=10 and Group 2: experienced planners N_2=62) with a significance level a=5% were as follows:

- H_0: The two groups’ ratings were the same (no statistically significant difference).
- H_1: The two groups’ ratings were not the same (existence of statistically significant difference).

The results summarised in Table 6.2 indicate that except for the format Inspection Plan + Tactical Planning Trajectory (all aspects) and the Annotated Video-clip’s overall performance, in most cases there is a statistically significant difference (highlighted results). That is, both novice and experienced planners perceive in the same way the ease of understanding, usefulness and overall performance of Inspection Plan + Tactical Planning Trajectory output and Annotated Video clip’s overall performance. Thus, both groups can benefit from these tested and confirmed outputs’ aspects at the same level.

Of the remaining representation formats, the median values of both groups (Figure 6.6), detected significant differences are in favour of novice planners’ group. That is, novice planners’ ratings were significantly higher compared to experienced planners’ responses. This outcome validates further that the proposed representations can be an important aid in training and supporting inexperienced CMM planners in generating a measurement strategy.

Table 6.2 Summary of statistical testing results for the two main groups' responses (Set 1) for all knowledge formats

Statistically significant difference testing (2-tailed) – Trial novice vs. Online Experienced. H_0: no difference - H_1: existence of difference											
N_1=10, N_2=62, a=0,05 (due to large samples, normal approximation is used)			1. Inspection plan + tactical plan. trajectory		2. Inspection plan + strategic plan. trajectory		3. Inspection plan + IDEF0		4. Annotated video-clip		5. Storyboard
Ease of understanding	U_m	Test-1	310	Test-4	310	Test-7	310	Test-10	310	Test-13	310
	U_{SD}		59.376		59.432		59.849		56.018		57.304
	z		1.0358		3.1044		3.2582		2.0083		2.4344
	p (2-tails)		0.3		0.0019		0.0011		0.0446		0.0149
	Result		H_0		H_1		H_1		H_1		H_1
Usefulness	U_m	Test-2	310	Test-5	310	Test-8	310	Test-11	310	Test-14	310
	U_{SD}		59.851		59.514		60.031		58.962		59.226
	z		1.7042		3.1001		3.0734		2.2896		2.7437
	p (2-tails)		0.0883		0.0019		0.0021		0.022		0.006
	Result		H_0		H_1		H_1		H_1		H_1
Overall performance	U_m	Test-3	310	Test-6	310	Test-9	310	Test-12	310	Test-15	310
	U_{SD}		59.593		59.383		60.043		58.829		58.72
	z		1.7787		2.6102		2.9063		1.5723		2.6567
	p (2-tails)		0.0752		0.009		0.0036		0.11587		0.0078
	Result		H_0		H_1		H_1		H_0		H_1

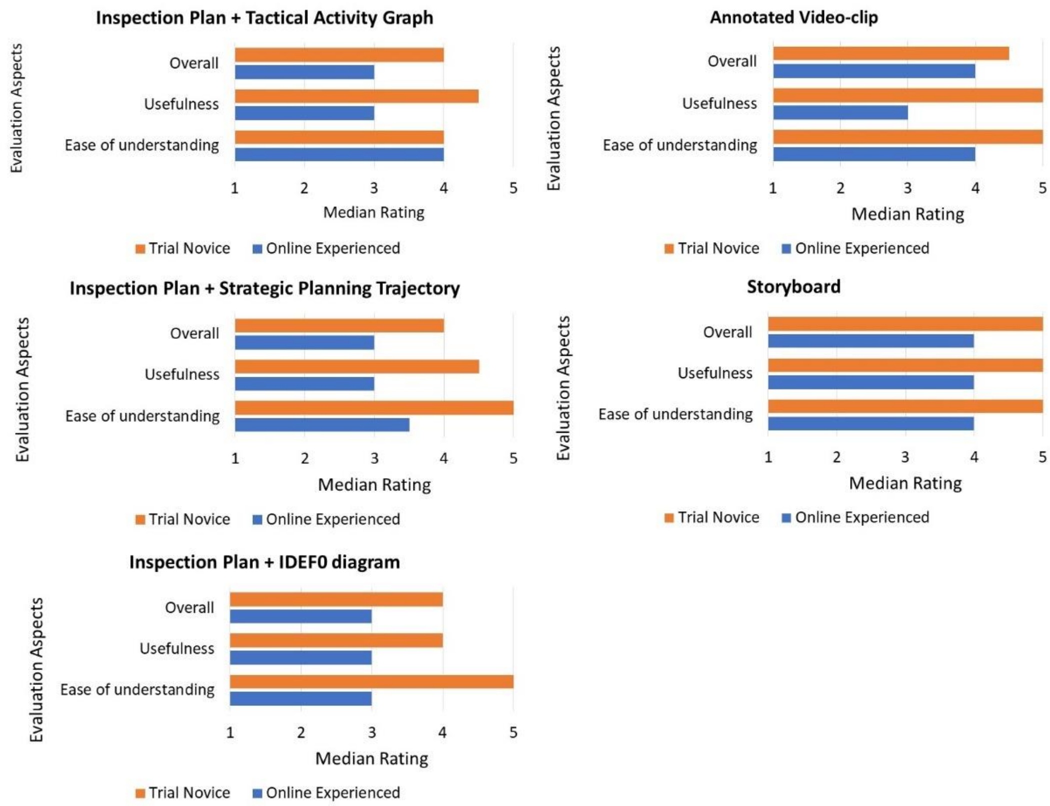


Figure 6.6 All aspects' median values of novice and experienced groups responses for all the knowledge formats

Some key conclusions can be drawn from these findings with respect to the research questions:

- All the proposed formats, studied and evaluated by novice and experienced planners with relatively high scores, were validated in the aspects of ease of understanding, usefulness and overall performance. Acceptance by the two groups is proven through the results obtained and associated written feedback (RQ2).

- With regards to the investigated aspects of ease of understanding, usefulness and overall performance, more visual outputs such as annotated video-clip and storyboard were preferred by all participants, novice and experienced, according to their ratings.
- Inspection Plan + Tactical Planning Trajectory was perceived to be equally understandable, useful and precise by novice and experienced planners. The same applies to annotated video-clip's overall performance.
- Novice planners found the rest outputs to be more easily understood, useful and precise compared to experienced planners. Therefore, the novice group could benefit more using the proposed formats, especially with regards to their development and training.
- In the perspective of different levels of picking up key information and relations due to experience level, statistically significant differences were found between novice and experienced planners' responses and ratings of different representation formats.
- The success of each representation format is that they could effectively convey the intended planned strategies and utilised knowledge into novice and experienced planners (RQ1-RQ2-RQ3). The novice participants were able to understand, reflect and interpret the planning strategy representations for a complex task that they were trained for only half an hour.
- More importantly, experienced planners' responses and ratings verified the structured knowledge formats in the defined perspectives of understanding, usefulness and performance (RQ3). This reveals the key contribution of the developed representations as support to industrial CMM inspection planning strategies.

Further analysis in the next sections will provide additional validation and insights through the following in-depth statistical analyses and comparisons.

6.3.2 Sub-groups' comparison and statistical analyses

Kellman and Massey [190] studied how experience level affects personal perception and information processing in executing complex tasks. Specifically, they noted that more experienced people show greater attention to the more relevant information, an increased level of observation and relationships detection, with easier and faster capability in picking up relevant information. In this perspective, it was worth investigating the perception and preferences of the participants on the suggested knowledge representations, depending on their level of exposure in CMM inspection planning. The results will provide the research domain with further insights on how the proposed representations can contribute to and support novice and experienced planners in planning a measurement strategy.

Using Set 2 classification, separate statistical tests were carried out on the knowledge format feedback data. To compare each sub-group against the others in order to detect statistically significant differences, the non-parametric Mann-Whitney U two-tailed test [189] for two unpaired samples was employed with a significance level a=5%. The results of the statistical testing and analysis will indicate the similarities and differences of experienced and non-experienced planners in perceiving and understanding the proposed knowledge formats.

Inspection Plan + Tactical Planning Trajectory

The statistical analysis (section 6.3.1) shows that no difference was detected between novice and experienced planners with regards to the first format (Inspection Plan + Tactical Planning Trajectory, section 4.4.2.1, Table 4.4, Figure 4.25). Therefore, there was no need to perform further comparisons among the formulated groups of experience.

The average scores across all sub-groups for the Inspection Plan + Tactical Planning Trajectory format are presented in Figure 6.7 with the raw data given in Table E. 13. The highest scores were given by novice planners for each of the three evaluation aspects: ease of understanding (78%), usefulness (78%), and overall performance (80%). The experienced planners' groups rated the representation with slight lower scores ranging from 56% to 74% for all aspects.

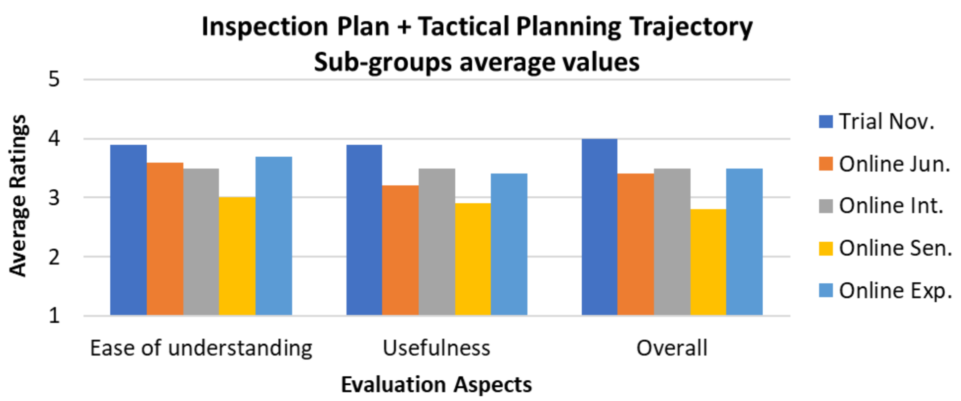


Figure 6.7 Average ratings of all sub-groups responses for inspection plan + tactical planning trajectory combined format

From Table 6.2, no statistically significant difference was found between the two main groups of novice and experienced planners, although novice participants appeared to rate this format slightly higher compared to the other sub-groups.

These differences are illustrated also in Figure 6.8, where the medians of each sub-group are presented; however no statistically significant differences were found according to Kruskal-Wallis test (proper test for comparing more than two unpaired ordinal data sets) results shown in Table 6.3 at 5% significance level. The null and alternative hypotheses tested for the comparison with a significance level a=5% were as follows:

- H_0: The groups' ratings were the same (no statistically significant difference).
- H_1: The groups' ratings were not the same (existence of statistically significant difference).

Table 6.3 Statistical testing results (Kruskal-Wallis test) of all sub-groups responses for the inspection plan + tactical planning trajectory combined format

Trial Novice – N_1=10 *Online Junior – N_2=5* *Online Intermediate – N_3=15* *Online Senior – N_4=17* *Online Expert – N_5=25*	**Statistically significant difference** (a=0.05) **H_0: no difference - H_1: existence of difference**					
	Ease of understanding		Usefulness		Overall performance	
	p (2-tail)	*Result*	*p (2-tail)*	*Result*	*p (2-tail)*	*Result*
	0.35312	H_0	0.25662	H_0	0.13495	H_0

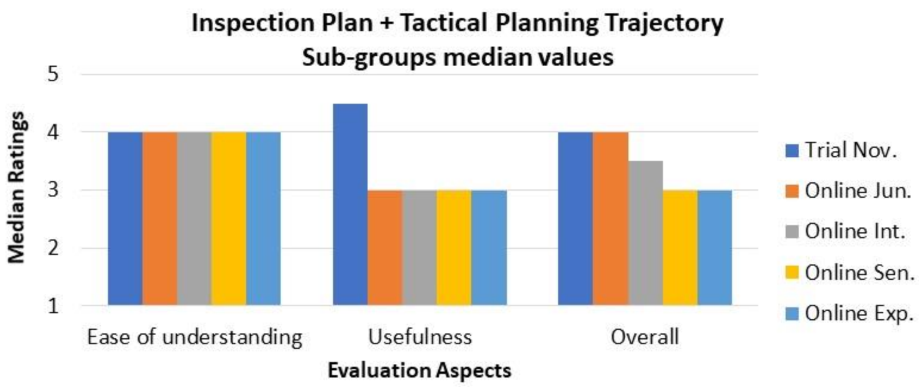


Figure 6.8 Median values of all sub-group's responses for the inspection plan + tactical planning trajectory combined format

The associated results in Table 6.3 confirm that all participants, independently from their level of experience in CMM inspection planning, perceive in the same way the ease of understanding, usefulness and overall performance of the inspection plan/tactical planning trajectory output. Thus, they could reflect and interpret it, while attributing the benefits of such a representation at the same satisfactory level. In addition, considering the different levels of expertise in terms of information processing and perception, the combination of an inspection plan and a tactical planning representation can successfully meet the needs and support any level of expertise a planner might have.

Inspection Plan + Strategic Planning Trajectory

Using the data in Table E.14, Figure 6.9 shows the average scores for the combined format Inspection Plan + Strategic Planning Trajectory (Table 4.4, Figure 4.26). As it can be seen, novice planners rated higher the format inspection plan/strategic planning trajectory in the perspectives of ease of understanding (92%), usefulness (90%) and overall performance

(86%) compared to the other more experienced groups. On average, the sub-groups of experienced participants rated at about the same lower level the inspection plan/strategic planning trajectory (62%-72%). In section's 6.3.1 analysis, significant differences were found between the novice and experienced planners' group.

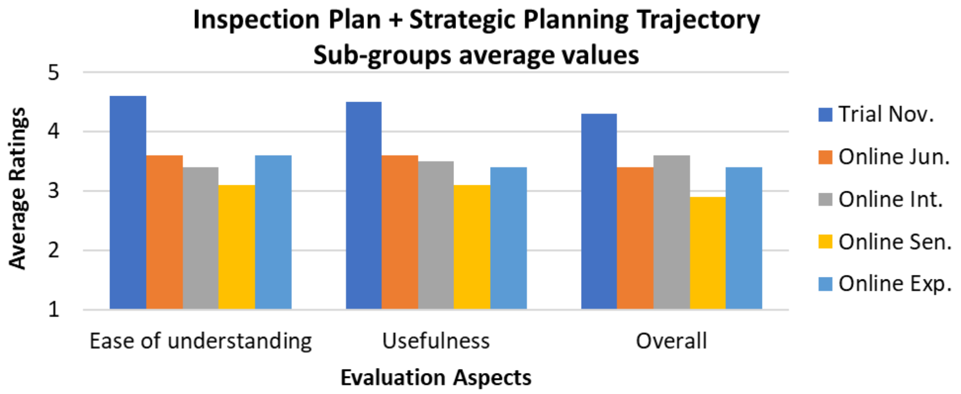


Figure 6.9 Average ratings of all sub-groups responses for inspection plan + strategic planning trajectory format

To investigate further the differences among the different levels of experienced participants, the non-parametric Mann-Whitney U two-tailed test for two unpaired samples was used as the acquired data are ordinal (Likert scale). The null and alternative hypotheses tested for each group's comparison with a significance level a=5% were as follows:

- H_0: The two groups' ratings were the same (no statistically significant difference).
- H_1: The two groups' ratings were not the same (existence of statistically significant difference).

Table 6.4 and Figure 6.10 confirmed that the novice planners rated inspection plan/strategic planning trajectory higher, with a significant difference when compared to all experienced sub-groups except for the junior planners' group. Another exception was the comparison between novices and intermediate planners, where it was found that both groups realised the inspection plan/strategic planning trajectory format's overall performance in the same manner. From the results obtained, it can be inferred that novice planners perceived higher the benefits of the inspection plan/strategic planning trajectory representation compared to the more experienced groups. On the other hand, the groups of experienced participants showed no significant difference among them. Thus, it can be stated that all experienced participants expressed the same preferences regarding the combination of inspection plan/strategic planning trajectory. It also shows that the level of expertise influenced the subjects' responses and results, highlighting the differences in personal perception and information processing as more experience is acquired.

Table 6.4 Statistical testing results of all sub-groups responses for the inspection plan + strategic planning trajectory combined format

$N_{Tr. Nov.}=10$ $N_{On. Jun.}=5$ $N_{On. Int.}=15$ $N_{On. Sen.}=17$ $N_{On. Exp.}=25$	Statistically significant difference, H_0: no difference - H_1: existence of difference, a=5% * If $N_{total}<20$, the exact Mann-Whitney Ucrit value is used														
	Ease of understanding (a)					Usefulness (b)					Overall performance (c)				
	U_m	U_{SD}	z	p (2-tail)	Result	U_m	U_{SD}	z	p (2-tail)	Result	U_m	U_{SD}	z	p (2-tail)	Result
Tr. Nov. vs On. Jun. (Test 1)	$U_{crit}=8$, U=11				H_0	$U_{crit}=8$, U=10				H_0	$U_{crit}=8$, U=10				H_0
Tr. Nov. vs On. Int. (Test 2)	75	17.19	2.53	0.0114	H_1	75	17.23	2.147	0.03179	H_1	75	17.11	1.782	0.07471	H_0
Tr. Nov. vs On. Sen. (Test 3)	85	19.17	3.129	0.0017	H_1	85	19.24	3.091	0.00199	H_1	85	19.37	2.606	0.00914	H_1
Tr. Nov. vs On. Exp. (Test 4)	125	26.17	2.521	0.0116	H_1	125	26.15	2.753	0.00589	H_1	125	26.18	2.215	0.02673	H_1
On. Jun. vs On. Int. (Test 5)	$U_{crit}=14$, U=34.5				H_0	$U_{crit}=14$, U=34.5				H_0	$U_{crit}=14$, U=31.5				H_0
On. Jun. vs On. Sen. (Test 6)	42.5	12.29	0.772	0.4396	H_0	42.5	12.21	0.818	0.41298	H_0	42.5	12.08	0.703	0.48175	H_0
On. Jun. vs On. Exp. (Test 7)	62.5	17.32	0.001	0.9991	H_0	62.5	17.35	0.288	0.77323	H_0	62.5	17.30	0.173	0.86239	H_0
On. Int. vs On. Sen. (Test 8)	127.5	25.67	0.681	0.4954	H_0	127.5	25.71	0.816	0.41405	H_0	127.5	25.65	1.461	0.14383	H_0
On. Int. vs On. Exp. (Test 9)	187.5	34.62	0.447	0.6544	H_0	187.5	34.67	0.216	0.82877	H_0	187.5	34.44	0.449	0.65274	H_0
On. Sen. vs On. Exp. (Test 10)	212.5	37.65	1.314	0.1886	H_0	212.5	37.83	0.792	0.42778	H_0	212.5	37.97	1.158	0.24657	H_0

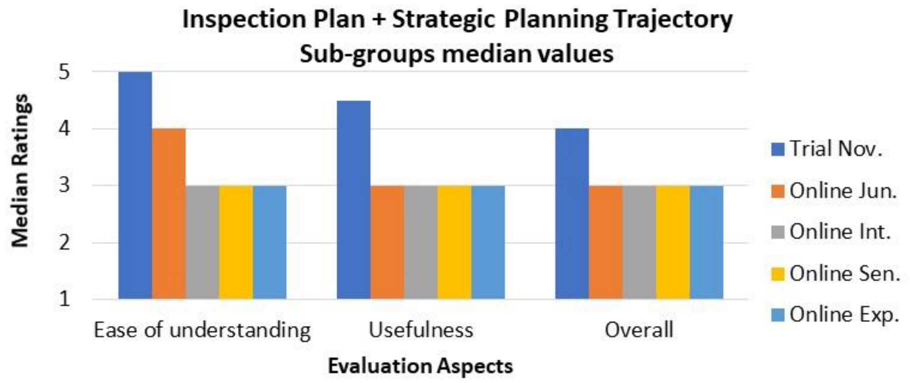


Figure 6.10 Median values of all sub-group's responses for Inspection Plan + Strategic Planning Trajectory

Inspection Plan + IDEF0 Diagram

The average scores of all sub-groups for the combined format of Inspection Plan + IDEF0 representations (Table 4.4, Figure 4.28) are shown in Figure 6.11 (Data: Table E. 15). As observed, novice group rated the format higher in the three studied aspects (understanding, usefulness, performance with 90%, 84%, 84% respectively) compared to the other groups of experienced planners (range of 52% - 72%).

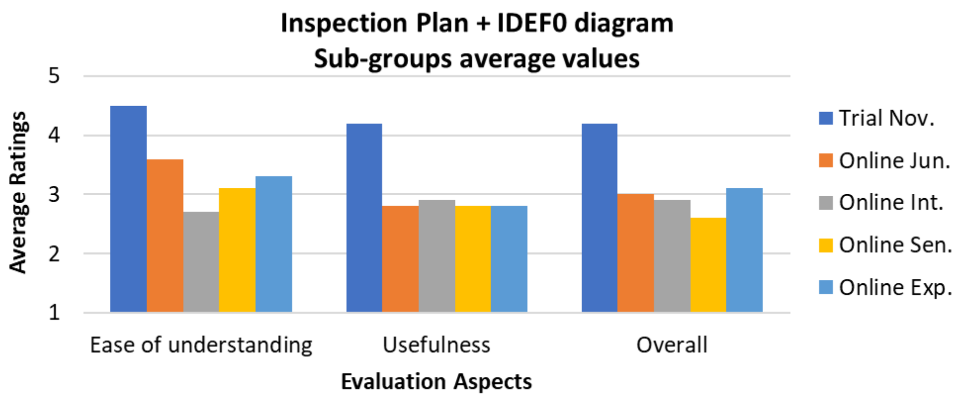


Figure 6.11 Average ratings of all sub-groups' responses for inspection plan + IDEF0 diagram format

According to initial statistical analysis (section 6.3.1), significant differences were noticed between the main novice and experienced groups. To study the differences with more detail, the non-parametric Mann-Whitney U two-tailed test for two unpaired samples was used for ordinal data sets. The null and alternative hypotheses tested for each group's comparison with a significance level a=5% were as follows:

- H_0: The two groups' ratings were the same (no statistically significant difference).
- H_1: The two groups' ratings were not the same (existence of statistically significant difference).

Table 6.5 presents the results and the sub-groups median values are shown in Figure 6.12 .

Table 6.5 Statistical testing results of all sub-groups responses for inspection plan + IDEF0 diagram combined format

$N_{Tr.\ Nov.}$=10 $N_{On.\ Jun.}$=5 $N_{On.\ Int.}$=15 $N_{On.\ Sen.}$=17 $N_{On.\ Exp.}$=25	**Statistically significant difference, H_0: no difference - H_1: existence of difference, a=5%** ** If N_{total}<20, the exact Mann-Whitney Ucrit value is used*														
	Ease of understanding (a)					**Usefulness (b)**					**Overall performance (c)**				
	U_m	U_{SD}	z	p (2-tail)	Result	U_m	U_{SD}	z	p (2-tail)	Result	U_m	U_{SD}	z	p (2-tail)	Result
Tr. Nov. vs On. Jun. (Test 1)	U_{crit}=8, U=11				H_0	U_{crit}=8, U=8.5				H_0	U_{crit}=8, U=10				H_0
Tr. Nov. vs On. Int. (Test 2)	75	17.54	3.049	0.0022	H_1	75	17.33	1.96	0.0498	H_1	75	17.55	2.079	0.037	H_1
Tr. Nov. vs On. Sen. (Test 3)	85	19.25	3.089	0.002	H_1	85	19.37	2.96	0.003	H_1	85	19.47	2.90	0.0037	H_1
Tr. Nov. vs On. Exp. (Test 4)	125	26.43	2.53	0.0112	H_1	125	26.75	2.82	0.0047	H_1	125	26.56	2.46	0.0136	H_1
On. Jun. vs On. Int. (Test 5)	U_{crit}=14, U=22				H_0	U_{crit}=14, U=35				H_0	U_{crit}=14, U=36				H_0
On. Jun. vs On. Sen. (Test 6)	42.5	12.06	0.994	0.3198	H_0	42.5	12.34	0.121	0.90	H_0	42.5	12.43	0.683	0.4941	H_0
On. Jun. vs On. Exp. (Test 7)	62.5	17.45	0.229	0.8187	H_0	62.5	17.49	0.001	0.9992	H_0	62.5	17.41	0.028	0.977	H_0
On. Int. vs On. Sen. (Test 8)	127.5	25.67	0.895	0.3704	H_0	127.5	25.89	0.27	0.7868	H_0	127.5	25.86	0.309	0.757	H_0
On. Int. vs On. Exp. (Test 9)	187.5	35.02	1.456	0.1453	H_0	187.5	35.04	0.156	0.8752	H_0	187.5	35.01	0.442	0.6579	H_0
On. Sen. vs On. Exp. (Test 10)	212.5	37.97	0.816	0.4142	H_0	212.5	37.77	0.145	0.8842	H_0	212.5	38.04	1.16	0.242	H_0

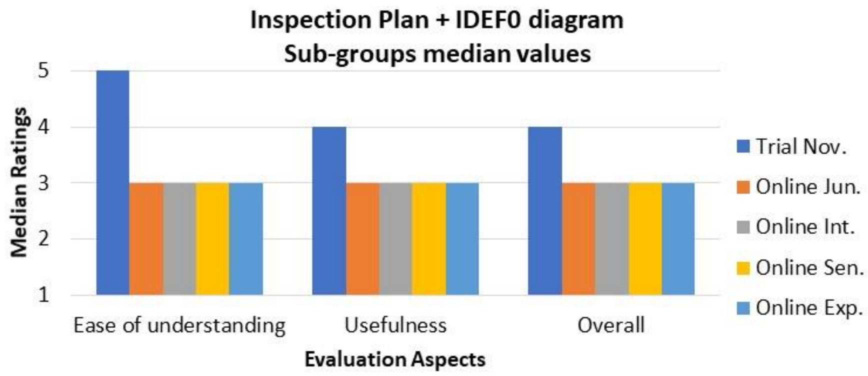


Figure 6.12 Median values of all sub-group's responses for inspection plan + IDEF0 diagram combined format

From comparisons, novice planners' ratings were significantly higher compared to experienced groups other than the junior group. No other statistically significant differences were revealed through the testing of the remaining groups. From the comparison of novice planners against each experienced sub-group, it was found that participants with less than two years' experience (novice and junior planners) had the same perception regarding understanding, usefulness and overall performance of the Inspection Plan + IDEF0 representation. Similarly, this applies to the more experienced planners' groups (intermediate, senior and expert planners). From the perspective of planner's perception and understanding in relation to the level of expertise, the sub-groups of experienced participants showed no significant differences in scoring and therefore they perceived inspection plan/IDEF0 format in a similar manner.

Annotated Video-clip

The average scores for Annotated Video clip (example screenshots shown in Figure 4.30), are presented in Figure 6.13 with the raw data given in Table E. 16. The format received very high scores with novice planners rating it with 96%, 88% and 86% for the characteristics of ease of understanding, usefulness and overall performance respectively. From the experienced groups, Annotated Video clip was rated lower but with relatively high scores, in the range of 68%-96% for each of the aspects.

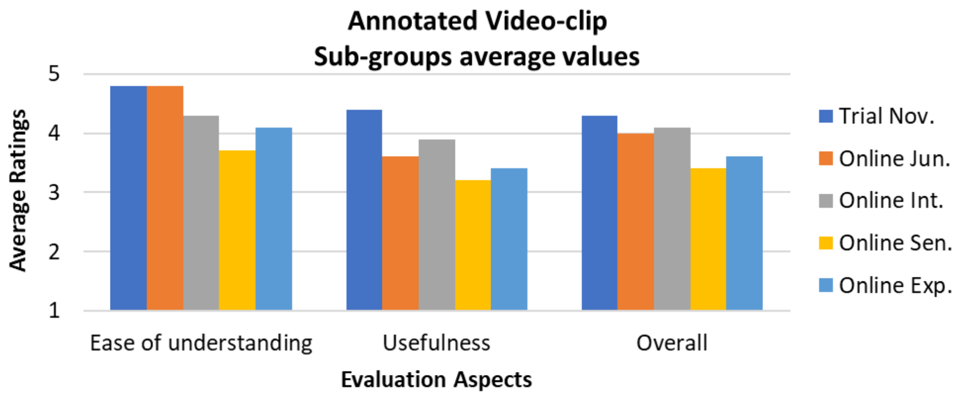


Figure 6.13 Average ratings of all sub-groups responses for Annotated Video clip format

From the previous results (section 6.3.1), statistically significant differences were detected between novice and experienced planners for the ratings in the aspects of ease of understanding and usefulness, while no difference was observed for the overall performance of the format. Additional statistical testing was performed as follows.

The non-parametric Mann-Whitney U two-tailed test for two unpaired samples was used as the acquired data are ordinal (Likert scale). The null and alternative hypotheses tested for this comparison with a significance level a=5% were as follows:

- H_0: The two groups' ratings were the same (no statistically significant difference).
- H_1: The two groups' ratings were not the same (existence of statistically significant difference).

Table 6.6 Statistical testing results of all sub-groups responses for annotated video clip format

$N_{Tr. Nov.}=10$ $N_{On. Jun.}=5$ $N_{On. Int.}=15$ $N_{On. Sen.}=17$ $N_{On. Exp.}=25$	Statistically significant difference, H_0: no difference - H_1: existence of difference, a=5% * If $N_{total}<20$, the exact Mann-Whitney Ucrit value is used														
	Ease of understanding (a)					Usefulness (b)					Overall performance (c)				
	U_m	U_{SD}	z	p (2-tail)	Result	U_m	U_{SD}	z	p (2-tail)	Result	U_m	U_{SD}	z	p (2-tail)	Result
Tr. Nov. vs On. Jun. (Test 1)	U_{crit}=8, U=25				H_0	U_{crit}=8, U=13.5				H_0	U_{crit}=8, U=20.5				H_0
Tr. Nov. vs On. Int. (Test 2)	75	15.26	1.408	0.1589	H_0	75	16.59	1.205	0.228	H_0	75	16.77	0.387	0.698	H_0
Tr. Nov. vs On. Sen. (Test 3)	85	18.29	2.432	0.0150	H_1	85	19.08	2.384	0.017	H_1	85	19.05	1.941	0.052	H_0
Tr. Nov. vs On. Exp. (Test 4)	125	24.42	1.862	0.0624	H_0	125	26.16	2.178	0.029	H_1	125	26.19	1.66	0.096	H_0
On. Jun. vs On. Int. (Test 5)	U_{crit}=14, U=26.5				H_0	U_{crit}=14, U=29.5				H_0	U_{crit}=14, U=34				H_0
On. Jun. vs On. Sen. (Test 6)	42.5	11.99	1.833	0.0667	H_0	42.5	12.06	0.621	0.534	H_0	42.5	12.15	0.946	0.343	H_0
On. Jun. vs On. Exp. (Test 7)	62.5	16.35	1.376	0.1687	H_0	62.5	17.03	0.146	0.883	H_0	62.5	17.21	0.580	0.561	H_0
On. Int. vs On. Sen. (Test 8)	127.5	24.95	1.422	0.1548	H_0	127.5	25.59	1.66	0.096	H_0	127.5	25.46	1.806	0.0709	H_0
On. Int. vs On. Exp. (Test 9)	187.5	32.93	0.516	0.6057	H_0	187.5	34.45	1.247	0.212	H_0	187.5	34.23	1.460	0.144	H_0
On. Sen. vs On. Exp. (Test 10)	212.5	36.89	1.057	0.290	H_0	212.5	37.33	0.629	0.529	H_0	212.5	37.48	0.680	0.496	H_0

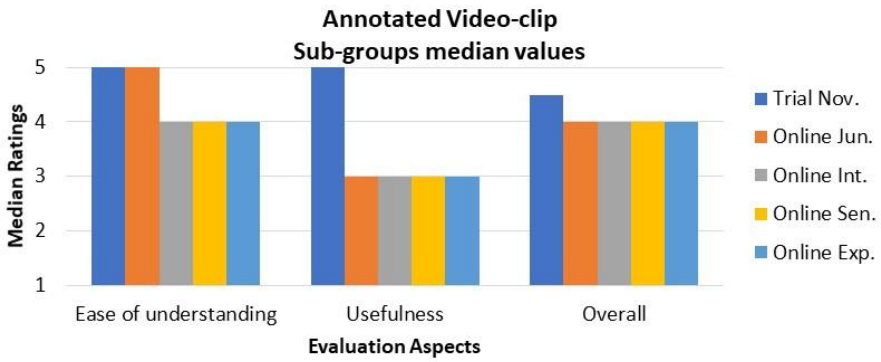


Figure 6.14 Median values of all sub-group's responses for Annotated Video-clip

Statistical results in Table 6.6 reveal primarily that Annotated Video clip is the format with the least detected significant differences among the sub-groups' responses. Although differences are shown in Figure 6.14, with regards to the sub-groups median values for the investigated aspects (understanding, usefulness, performance), these were not statistically significant as the results indicate (Table 6.6). Exceptions to this observation are the significant differences found between novice and senior planners in ease of understanding and usefulness ratings and between novice and expert planners' groups for the Annotated Video-clip's usefulness.

The only different perception in the format's usefulness may be due to the opinion of the more experienced planners that a video needs some time to watch as the complete planning strategy is studied. However, through their comments, experienced planners emphasized that such an output is useful, especially for training purposes. In the aspect of ease of understanding, the significant difference probably refers to the level of detail provided in the annotations (subtitles) and the single view angle of the video as it was recorded using only one device.

In general, the high ratings given by all participants and the smallest number of significant differences highlight a common acceptance of the Annotated Video-clip, both as a support to the industrial needs of CMM inspection planning and as a training aid for inexperienced planners.

Storyboard

Finally, the average ratings by all sub-groups for the Storyboard representation (Figure 4.31) are shown in Figure 6.15 with the raw data given in Table E. 17. All groups rated the storyboard with high scores for each of the defined aspects (ease of understanding, usefulness and overall performance); novice planners rated it with 96%, 92% and 94%% respectively. Experienced planners gave lower ratings with a range 58%-96%, but high enough to indicate the approval of Storyboard from the perspective of experienced participants. As shown in section 6.3.1, significant differences were found between novice and experienced planners.

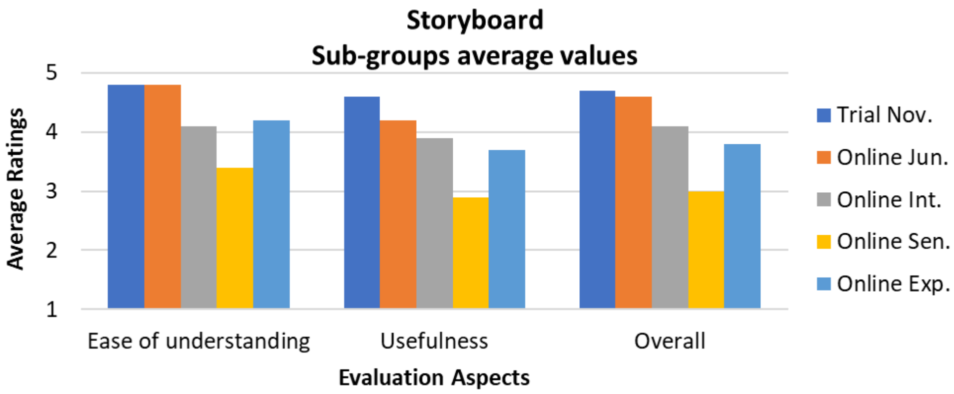


Figure 6.15 Average ratings of all sub-groups' responses for storyboard format

A deeper analysis was carried out to study these differences across the difference levels of experience. The non-parametric Mann-Whitney U two-tailed test for two unpaired samples was used as the acquired data are ordinal (Likert scale). The null and alternative hypotheses tested for each groups comparison with a significance level a=5% were as follows:

- H_0: The two groups' ratings were the same (no statistically significant difference).
- H_1: The two groups' ratings were not the same (existence of statistically significant difference).

Table 6.7 presents a summary of the statistical testing results; the related median values of each sub-group are shown in Figure 6.16.

Table 6.7 Statistical testing results of all sub-groups responses for annotated storyboard format

$N_{Tr. Nov.}=10$ $N_{On. Jun.}=5$ $N_{On. Int.}=15$ $N_{On. Sen.}=17$ $N_{On. Exp.}=25$	Statistically significant difference, H_0: no difference - H_1: existence of difference, a=5% * If $N_{total}<20$, the exact Mann-Whitney Ucrit value is used														
	Ease of understanding (a)					Usefulness (b)					Overall performance (c)				
	U_m	U_{SD}	z	p (2-tail)	Result	U_m	U_{SD}	z	p (2-tail)	Result	U_m	U_{SD}	z	p (2-tail)	Result
Tr. Nov. vs On. Jun. (Test 1)	$U_{crit}=8$, U=25				H_0	$U_{crit}=8$, U=25				H_0	$U_{crit}=8$, U=21				H_0
Tr. Nov. vs On. Int. (Test 2)	75	15.74	1.746	0.08	H_0	75	16.27	1.781	0.074	H_0	75	16.2	1.82	0.068	H_0
Tr. Nov. vs On. Sen. (Test 3)	85	18.94	3.246	0.0012	H_1	85	19.15	3.158	0.0015	H_1	85	18.81	2.975	0.0029	H_1
Tr. Nov. vs On. Exp. (Test 4)	125	24.61	2.010	0.044	H_1	125	25.90	2.431	0.015	H_1	125	25.78	2.540	0.011	H_1
On. Jun. vs On. Int. (Test 5)	$U_{crit}=14$, U=23.5				H_0	$U_{crit}=14$, U=33.5				H_0	$U_{crit}=14$, U=26				H_0
On. Jun. vs On. Sen. (Test 6)	42.5	12.29	2.48	0.013	H_1	42.5	12.34	2.147	0.031	H_1	42.5	12.38	2.179	0.029	H_1
On. Jun. vs On. Exp. (Test 7)	62.5	16.43	1.49	0.136	H_0	62.5	17.2	0.784	0.432	H_0	62.5	17.00	1.617	0.105	H_0
On. Int. vs On. Sen. (Test 8)	127.5	25.45	1.984	0.047	H_1	127.5	25.72	2.235	0.025	H_1	127.5	25.65	2.182	0.029	H_1
On. Int. vs On. Exp. (Test 9)	187.5	33.25	0.060	0.952	H_0	187.5	34.39	0.537	0.59	H_0	187.5	34.07	0.763	0.445	H_0
On. Sen. vs On. Exp. (Test 10)	212.5	37.28	2.33	0.019	H_1	212.5	37.94	2.174	0.029	H_1	212.5	37.95	1.87	0.061	H_0

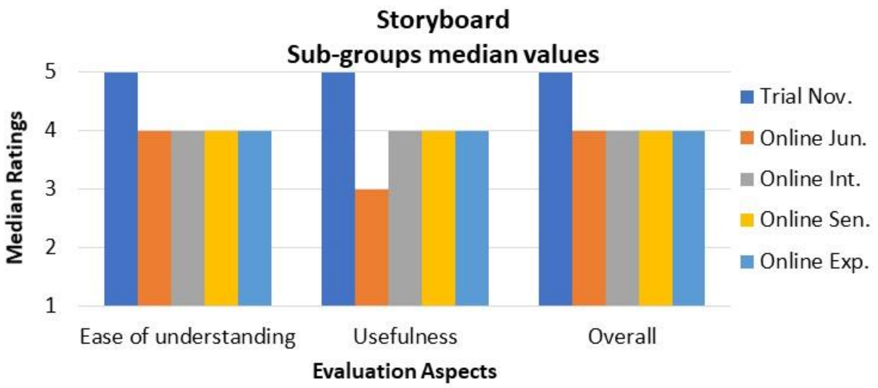


Figure 6.16 Median values of all sub-group's responses for storyboard representation

In the cases where significant differences were detected across all three comparison categories, the Storyboard received higher ratings from less experienced groups compared to the more experienced participants. That is, planners with less experience perceived the format as more easily understood, useful and performing well. Consequently, Storyboard can be more beneficial and contributory to less experienced planners either as training material or to support planning new inspection strategies. An exception to this was the comparison of senior group against experts where the latter provided higher scores to the format in relation to ease of understanding and usefulness.

Those differences not only emphasize the critical reflection of experienced participants but also highlight they also how differently the Storyboard is perceived across different levels of expertise. As in the previous format, Annotated Video clip, the Storyboard received high ratings in the aspects of ease of understanding, usefulness and overall performance. This reveals the high acceptance of the format across every level of experience, although significant differences were detected.

6.4 Summary

In the second stage of the main study, the primary goal was to evaluate the final proposed CMM inspection planning knowledge representations and obtain feedback by the participants regarding how easily they can understand each format, how useful they are and how well these represent the intended strategy and inferred knowledge. This stage was also related to the research objective (RO4) requiring "testing and validation of knowledge outputs and representations."

From the analysis of the two main group's average scores, it was found that novice participants rated the formats higher than other experienced groups, showing that even those with very little or no hands-on experience in inspection planning were able to understand the strategies in the suggested formats. Their first preference was the Storyboard, rating it the highest in ease of understanding (96%), usefulness (92%) and overall performance (94%); Annotated Video clip was the second preferred and rated very close to the storyboard. Therefore, the proposed representations could potentially enhance the understanding of measurement planning strategies and facilitate training of inexperienced CMM operators. From the responses of experienced planners, they were found to prefer the same two formats (Storyboard and Annotated Video clip) by rating them with the same average scores in the three defined aspects (82%, 70%, 74%).

A statistical analysis was carried out, revealing significant differences across the derived sub-groups with different experience levels (Set 2). In almost every comparison it was found that groups with less experience rated the formats significantly higher when compared to the more experienced groups. The main reason of this observation, is that understanding, processing and extracting information is influenced by the level of expertise according to Kellman and Massey [190]. The filtering and fluency in picking up important features and key relationships, and consequently, the level of interpretation and reflection varies across the different experience levels. From this perspective and considering that both novice and experienced participants (Set 1) rated two knowledge outputs the highest (Storyboard and Annotated Video clips), it is proven these two specific formats were structured properly to represent the associated strategy and knowledge in a way that can meet and address the different requirements of perception and processing for both experienced and inexperienced planners.

Considering the average ratings of novice and experienced participants, the proposed knowledge outputs were validated and accepted at a sufficiently high level. All participants were able to understand, reflect and interpret the combined knowledge formalisations verifying their capability to convert the inspection planning activity logged data into explicit, understandable and useful formats. The high scores obtained on the knowledge formats not only do highlight their acceptance within industry but also illustrate that the recommended representations can successfully be used as an aid to CMM planners in future tasks. More importantly, by having experienced engineers evaluating and reflecting on the suggested formats, they confirmed they could understand each of the formats, follow the planning strategies and validated the embedded knowledge and the way this is formalised as suggested by Sung et al. [4, 165] and Ritchie et al. [191].

Thus, not only associated research objective (RO4) was met but also a key contribution to the specific domain knowledge was made, since the research presented comprises the first known paradigm in capturing and formalising CMM inspection planning strategies and knowledge with the aid of a physical interactive inspection planning user logging system. With the outcomes and underpinning technology presented, it is demonstrated that human expertise and knowledge in inspection planning can be captured (RQ1), formalised and represented in multiple outputs (RQ2) and validated by experienced CMM planners (RQ3). These entail a range of key benefits for industrial CMM inspection planning:

- Rapid digitisation of CMM inspection planning strategies for storing and reuse.
- Support in CMM inspection planning tasks as future reference.
- Formulation of training material and guidance for novice planners.

Chapter 7 Discussion

The hypothesis of this thesis states that a novel CMM inspection planning prototype will enable implicit engineering knowledge to be made explicit and reusable, with the aid of user logging and motion tracking tools. This was defined after a study of past research work as well as industrial needs due to the lack of a methodology and proper tools for capturing, formalising and validating CMM inspection planning strategies and knowledge. Indeed, it became apparent that this fundamental CMM inspection planning gap had not been addressed.

Lowe et al. [192] has shown that about 30% of an engineer's working time is spent in searching and retrieving information necessary for task completion, slowing down product development and adding to costs. By capturing and storing human expertise, decision making and problem solving will be improved, leading to higher quality outputs with shorter lead times, giving a competitive advantage to any kind of industry [193].

To deal with the identified technological challenges in the CMM inspection planning area, an integrated knowledge capture and dissemination approach [118] was employed in the development of the proposed solutions as illustrated in Figure 7.1.

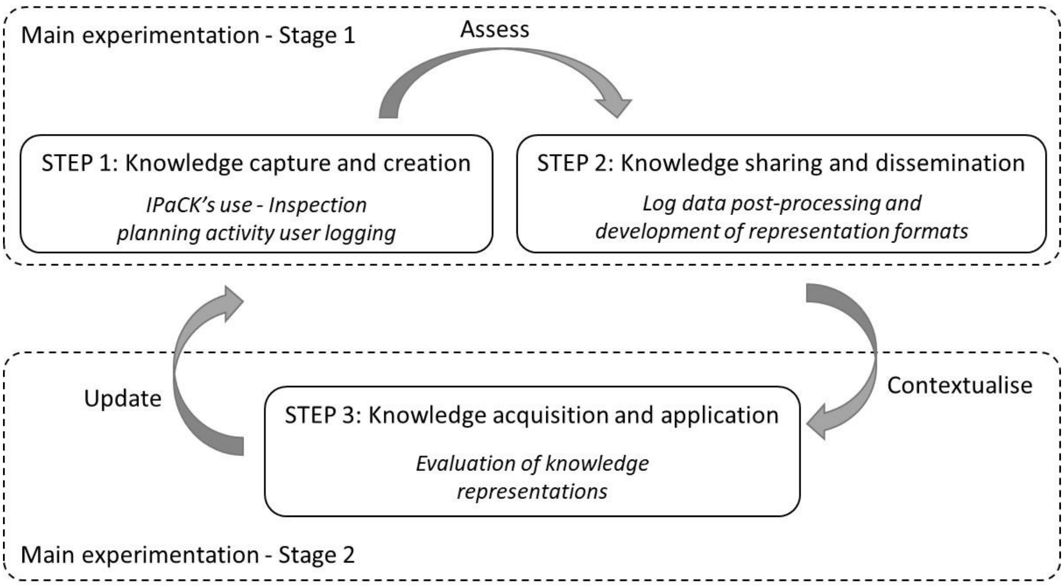


Figure 7.1, Integrated knowledge capture and dissemination cycle followed within the thesis [118]

The key steps involved in this approach were:

- Step 1 - Knowledge capture and creation: codification and storing of internal knowledge and know-how.
- Step 2 - Knowledge sharing and dissemination: knowledge is contextualised to be understood and used.

- Step 3 - Knowledge acquisition and application: knowledge is accessed and used in order to be updated.

A two-stage experimental study was carried out, following the knowledge management cycle as described, in order to address the identified gaps in the related knowledge domain:

Stage 1: focusing on logging inspection planning activity and knowledge capture, codification and storing and dissemination of logged data into understandable and usable knowledge formats (Steps 1-2).

Stage 2: central to this, was the knowledge acquisition and application of the developed representation outputs through the evaluation and validation from experienced CMM planners (Step 3).

The first knowledge gap identified through the reviewed research papers highlighted that, although presented intelligent and expert inspection planning systems utilising knowledge, there was no report of a methodology to capture this human expertise and associated knowledge to be integrated in the proposed systems. This led to the first research objective requiring "design and development of a novel user logging prototype for planning and capturing CMM inspection planning strategies" (RO1).

To meet this initially, a technical framework was established in Chapter 4 (4.2) and a modular prototype was developed for CMM inspection planning tool (IPaCK) incorporating user activity logging. This used a camera-based motion tracking system following user movements within a real-world environment that emulates – via a hand-held probe – the operation of a CMM. Inspection planning tasks could be simulated and captured with the aid of a stylus and a tablet-analogue as the main the user inputs. After conducting a pilot study on IPaCK's functionality and operation, the full study prototype was improved to include the integration of a real-time plan editing and display capability, as well as the rebuilding of the stylus for improving the motion tracking accuracy and conditions. Thus, research objective (RO1) was more rigorously addressed in Chapter 5 (5.3) along with meeting part of the objective (RO3) related to testing and evaluating IPaCK's usability, through the main experimentation study (stage 1).

High scores were given in the usability evaluation, while no statistically significant differences were found between the two major groups of participants, characterising it as "high OK" in the acceptability scale. This highlights the developed prototype can be easily used for planning measurements by CMM planners of any experience level. Although experienced participants validated the IPaCK's usability, novices were able to learn and use it directly, after having only just a short introduction in its operation and the related metrology principles and CMM inspection. This further confirms the system's functionality and simplicity allowing quick familiarisation with and training of inexperienced planners in the requirements of CMM inspection planning.

From the comparison of usability results between novice planners and those with mid-level of experience it can be inferred that CMM planners with lower level of experience are keener to adopt and use a new method for measurement planning compared to those with more years in the field. The latter may not feel confident enough to change the system they are used to and be trained on a new one. From the expert group usability results, the IPaCK was rated very highly on their average. Relative to this, it can be stated that due to their high level of expertise and exposure to various metrology and measurement planning systems, they were able to understand and appreciate the potential of IPaCK and its associated benefits. No previous research was found to support this correlation, therefore this should be further studied and analysed in future work.

Research objective (RO3) was fully achieved as presented in Chapter 5 (5.5) with performing an additional practical comparison of the task completion times for two planning tasks using the prototype against the use of a real CMM. The results showed that IPaCK facilitates faster generation of CMM part programs while offering the capability of logging user activity and capturing the intended planning strategy and decision making.

Another key research gap identified through the literature survey was the absence of an approach and associated tools to formalise automatically CMM inspection planning knowledge and strategies in multiple representation outputs. Driven from this, research objective (RO2) was formulated, necessitating design of knowledge representation structures and development of a tool for automatic generation of them. Closely linked to this, it was the research objective (RO4) requiring testing and validation of the generated knowledge outputs and representations. To achieve both objectives, a series of formalisation outputs were developed, as presented in Chapter 4 (4.2.2), based on previous research paradigms [133,167,168] proven successful in representing engineering knowledge. By carrying out a pilot study, significant feedback was obtained by experienced CMM planners on the recommended representations. The aspects that pilot study's participants were asked to assess were: ease of understanding, usefulness and overall performance. These aspects were considered also as key parameters for monitoring IPaCK's maturity level and capability to capture and represent CMM inspection planning knowledge. The results and written feedback obtained from the pilot study informed the main evaluation study (Stage 2) and led to further refinements, by reducing the number of knowledge formats considering planners' preferences, and their content was updated to be more compact by incorporating suggestions and input comments. With these modifications applied, it was also aimed to study how the defined parameters were updated and led to improved knowledge representation formats.

To give a full evaluation of the recommended knowledge representations' practicality, they were subsequently studied and assessed by all the study's participants. The survey feedback high scores indicated the confirmation and validation of the knowledge embedded with the designed representation formats across all the categories, i.e. understanding, usefulness and performance. Therefore, an original contribution from this research is the adaptation of existing engineering knowledge formats for reuse in the CMM inspection planning domain. An additional novelty was the automatic generation of these formats and their subsequent validation by novice and experienced CMM planners. The most popular formats from both the two groups of participants' responses were the storyboard and annotated video-clips, backing up previous research with similar findings [4,167].

Another interesting outcome was that the knowledge formats highly rated by the inexperienced planners proved to be easily understood, useful and accurately represented the intended strategies; therefore, they could play a key role in supporting the training of novice or inexperienced CMM planners by capturing best practice from experienced users. The high ratings from the experienced planners, who were crucially from an industrial needs' perspective, highlighted the potential of IPaCK's outputs as a means of supporting and storing expert plans and knowledge automatically. By analysing these best practices, standardised methods could be obtained.

The results and feedback obtained proved that these formats were effective and could successfully represent the captured domain specific knowledge and expertise. Therefore, with regards to the related research questions, these outcomes proved that human centred inspection planning knowledge can be captured (RQ1), formalised automatically and represented in multiple formats (RQ2) as well as validated by experienced CMM planners (RQ3).

The last identified knowledge gap was regarding the lack of a methodology for comparing generated inspection plans, detection of repeated patterns of activity and formulation of best sequences for the evaluation of planning strategies (RO5-RO6). To address these issues, at Stage 1 of the main experimentation study and using the recommended output "strategic planning trajectory", it was easy to extract the strategic thinking and sequence of each user and quickly codify it for the required comparison. Then, repeated patterns of planning activity were detected, and best sequences were created, considering the patterns resulted from the experienced planners' strategies. These best sequences were used as a benchmark for the evaluation of each suggested plan by all participants. The results of this part of the experimental work provided grounded answers to the research questions (RQ4-RQ5) linked to the related gap and associated objectives.

Key finding of the evaluation process was that novices' inspection plans were found to be not far from the best sequences structured based on the experienced strategies. This highlights that the proposed methodology and IPaCK played a key role and supported novice participants to understand very quickly the principles of CMM operation and inspection planning, given that they were trained for only 30 minutes before the user trials. This work also illustrates the potential of this rapid method to capture and formalise human expertise and knowledge that facilitates and proposes a novel approach to quickly digitise and standardise planning strategies for CMM applications.

With the participation of novice and experienced CMM planners in the main experimentation study, the obtained results and findings were adequate to establish the maturity level of IPaCK system's and underpinning technology. Provided that the developed proof-of-concept prototype's critical functionalities and its outputs were tested experimentally and analytically, it was estimated that the Technology Readiness Level 3 has been achieved.

In summary, a series of novel contributions result from this research. As shown in the literature, existing computer aided inspection planning systems involve only digital models and simulations of a work piece with the interaction of the planner via a software interface [86,97,98]. However, IPaCK's uniqueness resides in its operation by providing an intuitive, real world set up for logging and monitoring of user activity and inputs whilst resembling a real CMM. This direct interaction and logging of user activity with the physical component not only makes this approach original but generates data that can be post-processed and formalised into multiple outputs regarding plans, knowledge formats and user behaviour. The intuitive nature of this system enables it to be identified by all the participants as a systematic approach which could be used for planning CMM inspections at both a strategic and tactical level. Moreover, compared to existing commercial CMM programming software packages, IPaCK's operation and interface do not interrupt the inspection planner's thought process, allowing the user to focus on the planning solution rather than operating a software interface.

The intuitive and usable IPaCK prototype demonstrated that it facilitates faster generation of inspection plans and CMM part programs although tested at a small scale. The knowledge formats designed and tested can formalise and explicitly represent implicit human centred knowledge. Besides that, the proposed formats can also contribute to the rapid digitisation of inspection planning strategies allowing to store them for post-processing and future reuse as well as comparing and identifying common patterns of activity. Thus, a novel capability is provided to the industrial domain of CMM inspection for structuring best practices and standardising planning strategies.

Ettlie and Kubarek [194] found out that 28% of new designs in manufacturing resulted from past cases in product development, while according to Rezayat [195] 80% of new products comes from complete reuse (40%) or the slight modification (40%) of existing designs. Therefore, it is apparent that by storing and making existing knowledge accessible for quick reuse in future tasks would save significant amounts of time and money for any business. The proposed methodology, tools and outputs validated by experienced CMM planners while the knowledge capture and formalisation techniques were verified, demonstrating the overall impact of this work as a novel contribution to industrial CMM inspection planning and programming.

Industries have already realised that capturing, storing and reusing knowledge saves money and prevents or reduces interruptions in knowledge intensive tasks, while it contributes to dealing with changes in personnel [121,196]. On the completion of this research, a detailed methodology as well as an effective digital engineering tool for CMM inspection planning knowledge capture and formalisation were designed, tested and validated, potentially setting a new direction for computer-aided inspection planning applications and systems in the future.

Chapter 8 Conclusions and future work

8.1 Main conclusion

The research presented provides a novel solution for knowledge capture and formalisation in the area of Computer Aided Inspection Planning. By developing an original user logging and CMM inspection planning system, automated capture and formalisation of human centred knowledge and expertise is feasible. IPaCK aims to support CMM planners and programmers, by enabling the rapid capture and storing for post-processing of domain specific expertise and making it easily accessible for future reference and reuse.

A unique motion tracking-based user logging system was built for creating a usable interface that allows a CMM planner to interact with a real component and plan a measurement strategy. This enables the intuitive expression of implicit human knowledge during a planning task along with the rapid and easy generation of inspection plans and CMM part programs as well as effective unobtrusive capturing of domain knowledge and decision making.

Moreover, the proposed novel representations being tested and validated, facilitate the formalisation of captured knowledge and expertise in the CMM inspection planning field. Both experienced and novice CMM planners can benefit from the proposed IPaCK's outputs, as a support in the development of new inspection plans and part programs, and for creating training material and procedural guides. Besides, by studying the verified representations, a deeper understanding can be achieved on how a measurement strategy is generated.

In addition, an original contribution is provided for the evaluation of inspection plans. With the use of the proposed formats, a series of strategies can be analysed, compared and repeated patterns of planning activity can be rapidly detected. These can eventually lead to formulation of best sequences and practices. Using these as benchmarks, an inspection plan can be evaluated. More importantly, the detected patterns and structured best sequences can result in best practices, rules and protocols facilitating the standardisation of planning strategies, addressing consequently a key industrial need.

Furthermore, a novel knowledge management approach was proposed in the field of CMM applications. IPaCK and its outputs were proven successful in the effort to address a key challenge with regards to capturing, formalising and reusing domain expert CMM inspection planning knowledge, while enabling intuitive CMM inspection planning. The results of this thesis have illustrated a new original paradigm in knowledge engineering and development of future expert CMM inspection planning systems; those that enable automated capture and formalisation of inspection planning knowledge and expertise in multiple outputs.

In conclusion, the overall outcomes of this research have met the defined research objectives and answered the associated questions. Therefore, the thesis' hypothesis can be confirmed: "A novel CMM inspection planning prototype using a combination of user logging and motion tracking tools will enable implicit engineering knowledge to be made explicit and reusable".

Therefore, the general aim of this research is fulfilled: To design and develop a solution for planning CMM measurements and logging user activity. IPaCK not only enables capturing of planning strategies and associated knowledge, but also offers a novel interface that replicates CMM's principal functioning, supporting planners in inspection planning tasks.

8.2 Limitations of research and future directions

This thesis has demonstrated a series of novelties and contributions as well as the great potential of IPaCK and its outputs in capturing and formalising CMM inspection planning strategies and knowledge. However, there are limitations to overcome in the current work, showing that there is a great deal of opportunity to take this further forward into the future.

Through the proof of principle experimental work presented, the IPaCK planning module's state and functionality was found to be successful and adequate for the case study conducted. A key caveat is the limited range and variety of participants in the trials. Only novice users were employed in actually using the system when capturing the generated knowledge. Having experienced CMM planners involved in the actual planning tasks using IPaCK would allow the capture of further elements and aspects of their expertise and knowledge. This may lead to more robust results and strategies when analysing and comparing the quality of the different planning approaches as well as identifying repeated patterns and sub-sequences of activity as well as advanced knowledge and rationale.

To increase IPaCK's employability in future applications, it can be further expanded to include more planning options, such as tolerance characteristics, geometrical features and inspection tools as well as tracking of different part orientations. The current experimental setup is limited to capturing knowledge and strategies when inspecting work pieces of relatively simple geometry. Although this approach was successful for the case studies covered and provides a foundation for future work, it is desirable to test IPaCK with more complicated parts if relevant conclusions were required to be reached for more complex conditions. Extending the capability of IPaCK's tools would enable its application in more complex inspection planning situations including a wider range of components with more features and different design characteristics along with further evaluation of the proposed methodology.

A key limitation of the current state of IPaCK is that through the knowledge capture process bad or inefficient practice or knowledge will also be elicited. Central to this is the level of experience of a CMM programmer and their current level of expertise. Although, the proposed approach has partially considered and addressed this issue, a more sophisticated methodology could facilitate differentiating good knowledge from bad. In this aspect, it is recommended that, building on the current work, in the future the level of expertise of CMM programmers involved in relevant inspection planning knowledge capture experimentation should be more thoroughly investigated and classified into sub-categories considering further aspects such as the percentage of daily CMM programming workload. Moreover, another parameter to be taken into account could be the range of different measuring systems and CMM inspection planning software systems and experience of the participants.

In the vein of the abovementioned limitations, the presented research could be significantly improved in future work. Primarily, a more thorough comparison of the developed IPaCK prototype against using a CMM would be ideal. This will allow to identify the key differences between the traditional and novel approaches. That is, a full replication of each measurement strategy carried out with the IPaCK to be produced and contrasted on the CMM use. In this aspect, with the use of such comparison and analysis IPaCK could be further enhanced and improved much more so that it aligns with the requirements of CMM part programming.

For further advancing the current version of IPaCK, a significant technical advancement would be the integration of user video and voice recording devices or other user inputs. This will facilitate the enhanced capture of decision making and rationale along with the basic knowledge capture as offered by the current system. By using and capturing all these inputs would generate much richer data sets for comparison and analysis purposes that will eventually contribute to considerably improved knowledge representations.

On the aspect of improving the current IPaCK apparatus, the stylus' structure can be modified to allow greater motion tracking precision; adjusting tracking IR cameras' settings can contribute to even more accurate results. This would lead to enhanced outputs both in the digital user interface displayed on screen in real-time and the generated knowledge representation formats.

Another future direction would be the integration of IPaCK with virtual reality technologies in order to structure novel cyber-physical systems or digital twins, in the case coupling with a real CMM would be achieved. Such an implementation would greatly influence and improve knowledge capture as well as training novice CMM planners and support more experienced engineers. Furthermore, with the development of a mixed/virtual reality based IPaCK system, the already captured and formalised knowledge could be pushed to the user during planning tasks for providing help and guidance. In addition, the use of a digital motion tracking system would possibly offer higher precision than IPaCK's current state, while improving significantly its portability.

By evolving the current IPaCK's tools and adapting them in a real-world engineering environment, a series of case studies will be enabled. Engaging multiple components with similar geometries or sets of features, inspection plans can be quickly produced using IPaCK and best practices-to-inspect can be formulated for specific product designs or part families. By having a wider range of expert CMM planners to carry out measurement planning routines, extended analyses and comparisons would be carried out and repeated patterns can be detected leading to ideal probing sequences.

The scope of this thesis was to capture and formalise human expertise and knowledge in formats understandable to and useful for human CMM planners. However, part of the proposed and validated knowledge representations, such as IDEF0, could be integrated with and operate on computer-based applications and algorithms, i.e. ontologies. The current work's findings highlighted that it is feasible to generate various representations by post-processing the user logging data file. Therefore, it is recommended to extend further the formalised knowledge outputs to include other formats such as XML, STEP compliant or any other structures that could facilitate data integration with PLM systems or other CAIP systems. In this extent, another direction could be the utilisation of the logged user activity and captured planning strategies and their introduction into machine learning tools and algorithms aiming potentially at the automated detection of key relationships between large volumes of CMM inspection planning data.

Moreover, investigating the use of chronocyclegraphs could provide indications for user's learning curve when undergoing training as well as determining their confidence; therefore, testing IPaCK's learnability extensively. In addition, planner's behaviour and strategy would be more effectively analysed and studied, helping in detecting areas of inefficient activity and therefore improving the strategy. Besides that, the user activity and behaviour analyses' findings can contribute to tailoring existing CAIP systems and CMM programming packages to improve inspection planning options and capabilities. In combination with chronocyclegraphs, Therblig symbols would provide an easy and quickly reviewed form of representing the followed planning strategy, enabling in this way more efficient analyses and comparisons so that repeated patterns of activity are recognisable. Consequently, another approach would be available in future efforts for optimising inspection planning strategies and formulating best practices.

Finally, a future direction of the proposed IPaCK solution could potentially be its suitable modification and application for capturing and formalising knowledge in other non-inspection related tasks, i.e. surgical planning, assembly planning, maintenance tasks. This will provide a basis for testing and validating the knowledge capture and training capabilities offered by the proposed prototype.

References

[1] Groover, M. P., 2007, *Automation, Production Systems, and Computer Integrated Manufacturing*, Prentice Hall Press, London, UK.

[2] Ferreira, F., and Guerra, H., 2018, “The Coordinate Measuring Machines, Essential Tools for Quality Control of Dimensional and Geometrical Specifications of Technical Components, in the Context of the Industry 4.0,” J. Phys. Conf. Ser., **1044**(1).

[3] Ye, C., Fuzhi, C., and Linchang, H., 1996, “Integration of Computer Aided Inspection Planning with CAD Using STEP,” Tsinghua Sci. Technol., **1**(2), pp. 67–171.

[4] Sung, R. C. ., Ritchie, J. M., Lim, T., Liu, Y., and Kosmadoudi, Z., 2012, “The Automated Generation Of Engineering Knowledge Using A Digital Engineering Tool: An Industrial Evaluation Case Study,” Int. J. Innov. Technol. Manag., **09**(06).

[5] Kweon, S., and Medeiros, D. J., 1998, “Part Orientations for CMM Inspection Using Dimensioned Visibility Maps,” Comput. Des., **30**(9), pp. 741–749.

[6] Cho, M. W., Lee, H., Yoon, G. S., and Choi, J., 2005, “A Feature-Based Inspection Planning System for Coordinate Measuring Machines,” Int. J. Adv. Manuf. Technol., **26**, pp. 1078–1087.

[7] International Standards Organisation (ISO), 2017, *ISO 14253-1:2017, Geometrical Product Specifications (GPS) — Inspection by Measurement of Workpieces and Measuring Equipment — Part 1: Decision Rules for Verifying Conformity or Nonconformity with Specifications*.

[8] British Standards Institution (BSI), 1989, *BS 7172:1989 - Guide to Assessment of Position, Size and Departure from Nominal Form of Geometric Features*.

[9] Drake, P. J., 2009, *ASME Y14.5-2009 Dimensioning and Tolerancing*, American Society of Mechanical Engineers.

[10] Al-Ahmari, A., Nasr, E. A., and Abdulhameed, O., 2016, *Computer-Aided Inspection Planning: Theory and Practice*, CRC Press, Boca Raton.

[11] Corrigall, M. J., and Bell, R., 1991, “Probe and Component Set-up Planning for Coordinate Measuring Machines,” Int. J. Comput. Integr. Manuf., **4**(1), pp. 34–44.

[12] Ziemian, C. W., and Medeiros, D. J., 1998, “Automating Probe Selection Planning for Inspection on Measuring Machine and Part Setup a Coordinate,” Int. J. Comput. Integr.

Manuf., **11**, pp. 448–460.

[13] Beg, J., and Shunmugam, M. S., 2003, "Application of Fuzzy Logic in the Selection of Part Orientation and Probe Orientation Sequencing for Prismatic Parts," Int. J. Prod. Res., **41**(12), pp. 2799–2815.

[14] Spyridi, a. J., and Requicha, A. a. G., 1990, "Accessibility Analysis for the Automatic Inspection of Mechanical Parts by Coordinate Measuring Machines," Proceedings., IEEE Int. Conf. Robot. Autom., pp. 1284–1289.

[15] Lim, C. P., and Menq, C.-H., 1994, "CMM Feature Accessibility and Path Generation," Int. J. Prod. Res., **32**(3), pp. 597–618.

[16] Ziemian, C. W., and Medeiros, D. J., 1997, "Automated Feature Accessibility Algorithm for Inspection on a Coordinate Measuring Machine," Int. J. Prod. Res., **35**(10), pp. 2839–2856.

[17] Spitz, S. N., Spyridi, A. J., and Requicha, a. a G., 1999, "Accessibility Analysis for Planning of Dimensional Inspection with Coordinate Measuring Machines," IEEE Trans. Robot. Autom., **15**(4), pp. 714–727.

[18] Wu, Y., Liu, S., and Zhang, G., 2004, "Improvement of Coordinate Measuring Machine Probing Accessibility," Precis. Eng., **28**, pp. 89–94.

[19] Álvarez, B. J., Fernández, P., Mateos, S., Rico, J. C., and Suárez, C. M., 2006, "Accessibility Analysis for Automatic Inspection Using Bounding Volume Hierarchies," IEEE Int. Conf. Emerg. Technol. Fact. Autom. ETFA, **46**(20), pp. 515–522.

[20] Wang, Y., Nan, Z., Chen, Y., and Hu, Y., 2006, "Accessibility Analysis for CMM Inspection Planning Using Haptic Device," 2006 IEEE Int. Conf. Robot. Biomimetics, ROBIO 2006, pp. 1239–1243.

[21] Wang, Y., Chen, Y., Zhang, W., Liu, D., and Zhang, R., 2009, "Accessibility Analysis for CMM Inspection Planning by Means of Haptic Device and STL Representation," 2009 IEEE Int. Conf. Virtual Environ. Human-Computer Interfaces, Meas. Syst. VECIMS 2009 - Proc., pp. 174–178.

[22] Flack, D., 2014, *Measurement Good Practice Guide No. 41, CMM Measurement Strategies*, National Physical Laboratory, Teddington, Middlesex.

[23] International Organisation for Standardisation (ISO), 2017, *ISO 1101:2017 - Geometrical Product Specifications (GPS) – Geometrical Tolerancing – Tolerances of*

Form, Orientation, Location and Run-Out, International Organization for Standardization.

[24] Woo, T. C., Liang, R., Hsieh, C. C., and Lee, N. K., 1995, "Efficient Sampling for Surface Measurements," J. Manuf. Syst., **14**(5), pp. 345–354.

[25] Chan, F. M. M., King, T. G., and Stout, K. J., 1997, "The Influence of Sampling Strategy on a Circular Feature in Coordinate Measurements," **19**(2), pp. 73–81.

[26] Lee, G., Mou, J., and Shen, Y., 1997, "Sampling Strategy Design for Dimensional Measurement of Geometric Features Using Coordinate Measuring Machine," Int. J. Mach. Tools Manuf., **13**(7), pp. 917–934.

[27] Kim, W. S., and Raman, S., 2000, "On the Selection of Flatness Measurement Points in Coordinate Measuring Machine Inspection," Int. J. Mach. Tools Manuf., **40**, pp. 427–443.

[28] Edgeworth, R., and Wilhelm, R. G., 1999, "Adaptive Sampling for Coordinate Metrology," Precis. Eng., **23**(3), pp. 144–154.

[29] Elkott, D. F., Elmaraghy, H. A., and Elmaraghy, W. H., 2002, "Automatic Sampling for CMM Inspection Planning of Free-Form Surfaces," Int. J. Prod. Res., **40**(11), pp. 2653–2676.

[30] ElKott, D. F., and Veldhuis, S. C., 2007, "CAD-Based Sampling for CMM Inspection of Models with Sculptured Features," Eng. Comput., **23**, pp. 187–206.

[31] Mu, L., Yin, Z., and Xiong, Y., 2011, "Sampling Method for Similar Section Surface Inspection," *2011 First International Conference on Instrumentation, Measurement, Computer, Communication and Control*, IEEE, pp. 137–140.

[32] Obeidat, S. M., and Raman, S., 2009, "An Intelligent Sampling Method for Inspecting Free-Form Surfaces," Int. J. Adv. Manuf. Technol., **40**(11–12), pp. 1125–1136.

[33] Jiang, R. S., Wang, W. H., Zhang, D. H., and Wang, Z. Q., 2016, "A Practical Sampling Method for Profile Measurement of Complex Blades," Meas. J. Int. Meas. Confed., **81**, pp. 57–65.

[34] Zahmati, J., Amirabadi, H., and Mehrad, V., 2018, "A Hybrid Measurement Sampling Method for Accurate Inspection of Geometric Errors on Freeform Surfaces," Measurement, **122**(March), pp. 155–167.

[35] He, G., Sang, Y., Pang, K., and Sun, G., 2018, "An Improved Adaptive Sampling Strategy

for Freeform Surface Inspection on CMM," Int. J. Adv. Manuf. Technol., **96**(1–4), pp. 1521–1535.

[36] Lin, Z. C., and Lin, W. S., 2001, "Measurement Point Prediction of Flatness Geometric Tolerance by Using Grey Theory," Precis. Eng., **25**(3), pp. 171–184.

[37] Raghunandan, R., and Rao, P. V., 2007, "Selection of an Optimum Sample Size for Flatness Error Estimation While Using Coordinate Measuring Machine," Int. J. Mach. Tools Manuf., **47**, pp. 477–482.

[38] Raghunandan, R., and Venkateswara Rao, P., 2008, "Selection of Sampling Points for Accurate Evaluation of Flatness Error Using Coordinate Measuring Machine," J. Mater. Process. Technol., **202**, pp. 240–245.

[39] Raffaele, R., and Rosa, R., 2011, "An Extracting Points Strategy for Flatness Measuement on Components by Means of CMM," *International Conferennce on Innovative Methods in Product Design*, Venice, Italy, pp. 495–498.

[40] Pedone, P., and Romano, D., 2011, "Designing Small Samples for Form Error Estimation with Coordinate Measuring Machines," Precis. Eng., **35**(2), pp. 262–270.

[41] Affan Badar, M., Raman, S., and Pulat, P. S., 2003, "Intelligent Search-Based Selection of Sample Points for Straightness and Flatness Estimation," J. Manuf. Sci. Eng., **125**(2), pp. 263–271.

[42] Affan Badar, M., Raman, S., Simin Pulat, P., and Shehab, R. L., 2005, "Experimental Analysis of Search-Based Selection of Sample Points for Straightness and Flatness Estimation," J. Manuf. Sci. Eng., **127**(1), pp. 96–103.

[43] Jiang, B. C., and Chiu, S. D., 2002, "Form Tolerance-Based Measurement Points Determination with CMM," J. Intell. Manuf., **13**(2), pp. 101–108.

[44] Moroni, G., Polini, W., Rasella, M., Meccanica, D., Milano, P., and Biasio, G., 2003, "Manufacturing Signatures and CMM Sampling Strategies," *Proceedings of the ASPE Summer Topical Meeting on Coordinate Measuring Machines*, pp. 57–62.

[45] Colosimo, B. M., Moroni, G., and Petrò, S., 2010, "A Tolerance Interval Based Criterion for Optimizing Discrete Point Sampling Strategies," Precis. Eng., **34**(4), pp. 745–754.

[46] Vrba, I., Palencar, R., Hadzistevic, M., Strbac, B., and Hodolic, J., 2013, "The Influence of the Sampling Strategy and the Evaluation Method On The Cylindricity Error On A Coordinate Measurement Machine," J. Prod. Eng., **16**(2).

[47] Obeidat, S., Mandahawi, N., Fouad, R. H., and Jadayil, W. A., 2013, "Intelligent Sampling for Inspecting Cylindrical Surfaces," Int. J. Adv. Inf. Sci. Serv. Sci., **5**(July), pp. 46–55.

[48] Albuquerque, V. A., Liou, F. W., and Mitchell, O. R., 2000, "Inspection Point Placement and Path Planning Algorithms for Automatic CMM Inspection," Int. J. Comput. Integr. Manuf., **13**(February 2015), pp. 107–120.

[49] Duan, G., and Zhang, P., 2015, "Research on Measurement Points Planning Based on Structural Features of Parts," *International Industrial Informatics and Computer Engineering Conference (IIICEC 2015)*, Atlantis Press, pp. 1343–1346.

[50] Yau, H.-T., and Menq, C.-H., 1991, "Path Planning for Automated Dimensional Inspection Using Coordinate Measuring Machines," *Proceedings. 1991 IEEE International Conference on Robotics and Automation*, IEEE Comput. Soc. Press, pp. 1934–1939.

[51] Qu, L., Xu, G., and Wang, G., 1998, "Optimization of the Measuring Path on a Coordinate Measuring Machine Using Genetic Algorithms," Measurement, **23**, pp. 159–170.

[52] Han, Z., Liu, S., Li, X., Wang, Y., Zhang, X., and Zhang, G., 2018, "Path Planning Method for Intelligent CMMs Based on Safety and the High-Efficiency Principle," Int. J. Adv. Manuf. Technol., **95**(9–12), pp. 4003–4012.

[53] Yau, H.-T., and Menq, C.-H., 1995, "Automated CMM Path Planning for Dimensional Inspection of Dies and Molds Having Complex Surfaces," Int. J. Mach. Tools Manuf., **35**(6), pp. 861–876.

[54] Spitz, S., and Requicha, A. a G., 2000, "Multiple-Goals Path Planning for Coordinate Measuring Machines," *Proceedings of the 2000 IEEE International Conference on Robotlcs & Automation*, IEEE, San Francisco, CA, pp. 2322–2327.

[55] Buchal, R. O., and Wang, A., 2006, "CMM Sequence Optimisation with Collision Detection," Int. J. Comput. Appl. Technol., **26**(1/2), p. 65.

[56] Bai, Y., Wei, S., Liu, K., and Wang, X., 2010, "A Strategy to Automatically Planning Measuring Path with CMM Offline," 2010 Int. Conf. Mech. Autom. Control Eng. MACE2010, pp. 3064–3067.

[57] Lin, Z., and Chen, C., 1997, "Measuring-Sequence Planning by the Nearest Neighbour Method and the Refinement Method," Int. J. Adv. Manuf. Technol., **13**(4), pp. 271–281.

[58] Schmitt, R., Zheng, H., Zhao, X., König, N., and Coelho, R. R., 2009, "Application of Ant Colony Optimization to Inspection Planning," 2009 IEEE Int. Conf. Comput. Intell. Meas. Syst. Appl. CIMSA 2009, (1), pp. 71–75.

[59] Stojadinovic, S. M., Majstorovic, V. D., Durakbasa, N. M., and Sibalija, T. V, 2016, "Ants Colony Optimisation of a Measuring Path of Prismatic Parts on a CMM," Metrol. Meas. Syst., **23**(1), pp. 119–132.

[60] Han, Z., Liu, S., Yu, F., Zhang, X., and Zhang, G., 2017, "A 3D Measuring Path Planning Strategy for Intelligent CMMs Based on an Improved Ant Colony Algorithm," Int. J. Adv. Manuf. Technol.

[61] Zeqing, Y., Libing, L., and Weidong, Y., 2008, "Flexible Inspection Path Planning Based on Adaptive Genetic Algorithm," *Chinese Control and Decision Conference, 2008, CCDC 2008*, pp. 1558–1563.

[62] Lu, C. G., Morton, D., Wu, M. H., and Myler, P., 1999, "Genetic Algorithm Modelling and Solution of Inspection Path Planning on a Coordinate Measuring Machine (CMM)," Int. J. Adv. Manuf. Technol., **15**, pp. 409–416.

[63] Lu, C. G., Morton, D., Myler, P., and Wu, M. H., 1995, "An Artificial Intelligent (AI) Inspection Path Management for Multiple Tasks Measurement on Co-Ordinate Measuring Machine (CMM): An Application of Neural Network Technology," *Proceedings for Operating Research and the Management Sciences*, IEEE, pp. 353–357.

[64] Lin, Y. J., and Murugappan, P., 1999, "New Algorithm for Determining a Collision-Free Path for a CMM Probe," Int. J. Mach. Tools Manuf., **39**, pp. 1397–1408.

[65] Ainsworth, I., Ristic, M., and Brujic, D., 2000, "CAD-Based Measurement Path Planning for Free-Form Shapes Using Contact Probes," Int. J. Adv. Manuf. Technol., **16**, pp. 23–31.

[66] Lin, Y.-J., Mahabaleshwarkar, R., and Massina, E., 2001, "CAD-Based CMM Dimensional Inspection Path Planning – a Generic Algorithm," Robotica, **19**(2), pp. 137–148.

[67] Jia, Z. Y., Ma, J. W., Wang, F. J., and Ding, Y. M., 2014, "Investigation of a Measurement Scheme Based on IGES," Meas. J. Int. Meas. Confed., **47**, pp. 658–668.

[68] Lin, X., Jiang, S., Liu, X., and Yang, K., 2011, "The CMM Measurement Path Planning for Blade Surface Based on the Contour Measurement," Proc. 2011 2nd Int. Conf. Digit. Manuf. Autom. ICDMA 2011, pp. 1228–1232.

[69] Wang, F. J., Jia, Z. Y., Li, M. X., Ma, J. W., and Ding, L., 2013, "Generation of Geometric Measurement Collision-Free Path for Curved Part," Appl. Mech. Mater., **421**, pp. 427–432.

[70] ElMaraghy, H. A., and ElMaraghy, W. H., 1994, "Computer-Aided Inspection Planning (CAIP)," *Manufacturing Research and Technology*, pp. 363–396.

[71] Li, Y., and Gu, P., 2004, "Free-Form Surface Inspection Techniques State of the Art Review," CAD Comput. Aided Des., **36**, pp. 1395–1417.

[72] Zhao, F., Xu, X., and Xie, S. Q., 2009, "Computer-Aided Inspection Planning-The State of the Art," Comput. Ind., **60**, pp. 453–466.

[73] Stojadinović, S. M., Majstorović, V. D., Stojadinović, S. M., and Majstorović, V. D., 2019, "Introduction and Review of Inspection Planning Methods," *An Intelligent Inspection Planning System for Prismatic Parts on CMMs*, Springer International Publishing, Cham, pp. 1–31.

[74] Anagnostakis, D., Ritchie, J., Lim, T., Sivanathan, A., Dewar, R., Sung, R., Bosché, F., and Carozza, L., 2016, "Knowledge Capture in CMM Inspection Planning: Barriers and Challenges," Procedia CIRP, **52**, pp. 216–221.

[75] Negnevitsky, M., 2005, *Artificial Intelligence: A Guide to Intelligent Systems*, Pearson education.

[76] ElMaraghy, H., and Gu, P., 1987, "Expert Inspection Planning System," Ann. CIRP, **36**, pp. 85–89.

[77] Chan, K., and Gu, P., 1993, "An Object-Oriented Knowledge-Based Inspection Planner," Proc. IEEE Pacific Rim Conf. Commun. Comput. Signal Process., **2**, pp. 646–649.

[78] Gu, P., and Chan, K., 1996, "Generative Inspection Process and Probe Path Planning for Coordinate Measuring Machines," J. Manuf. Syst., **15**(4), pp. 240–255.

[79] Gu, P., 1994, "A Knowledge-Based Inspection Process Planning System for Coordinate Measuring Machines," J. Intell. Manuf., **5**(5), pp. 351–363.

[80] Abbasi, G. Y., 2005, "Integrating Design and Production Planning With Knowledge-Based Inspection Planning," Arab. J. Sci. Eng., **30**(2B), pp. 245–260.

[81] Ketan, H. S., Al-Bassam, M. a., Adel, M. B., and Rawabdeh, I., 2002, "Modelling Integration of CAD and Inspection Planning of Simple Element Features," Integr. Manuf. Syst., **13**(7), pp. 498–511.

[82] Pei, S. H., and Ma, Y. M., 2011, "The Expert System for Auto Programming in Coordinate Measuring Machines," Appl. Mech. Mater., **120**, pp. 254–257.

[83] Nasr, E. S. A., 2012, "A Methodology for Integrating CAD and Automatic Inspection of Standard Manufactured Features," Int. J. Rapid Manuf., **3**(1), p. 70.

[84] Messina, E., Horst, J., Kramer, T., Huang, H., Tsai, T., and Amatucci, E., 1999, "A Knowledge-Based Inspection Workstation," Proc. - 1999 Int. Conf. Inf. Intell. Syst. ICIIS 1999, pp. 216–222.

[85] Stojadinovic, S. M., Majstorovic, V. D., Durakbasa, N. M., and Sibalija, T. V., 2016, "Towards an Intelligent Approach for CMM Inspection Planning of Prismatic Parts," J. Meas., **92**, pp. 326–339.

[86] Stojadinović, S. M., Majstorović, V. D., Stojadinović, S. M., and Majstorović, V. D., 2019, "The Model for Inspection Planning of PMPs on a CMM," An Intell. Insp. Plan. Syst. Prism. Parts C., pp. 55–74.

[87] Zhang, Y., Nee, a. Y. C., Fuh, J. Y. H., Neo, K., and Loy, H., 1996, "A Neural Network Approach to Determining Optimal Inspection Sampling Size for CMM," Comput. Integr. Manuf. Syst., **9**(3), pp. 161–169.

[88] Hwang, C.-Y., Tsai, C.-Y., and Chang, C. a., 2004, "Efficient Inspection Planning for Coordinate Measuring Machines," Int. J. Adv. Manuf. Technol., **23**, pp. 732–742.

[89] Kamrani, A., Abouel Nasr, E., Al-Ahmari, A., Abdulhameed, O., and Mian, S. H., 2015, "Feature-Based Design Approach for Integrated CAD and Computer-Aided Inspection Planning," Int. J. Adv. Manuf. Technol., **76**(9–12), pp. 2159–2183.

[90] Kovacic, M., and Brezocnik, M., 2003, "Genetic Algorithm Method for Computer Aided Quality Control," *Proceedings of the 3rd Research Expert Conference with International Participation Quality 2003*, Zenica, B&H, pp. 125–130.

[91] Hwang, I., Lee, H., and Ha, S., 2002, "Hybrid Neuro-Fuzzy Approach to the Generation of Measuring Points for Knowledge-Based Inspection Planning," Int. J. Prod. Res., **40**, pp. 2507–2520.

[92] Beg, J., and Shunmugam, M. S., 2002, "An Object Oriented Planner for Inspection of Prismatic Parts - OOPIPP," Int. J. Adv. Manuf. Technol., **19**, pp. 905–916.

[93] Limaiem, A., 1999, "CATIP: A Computer-Aided Tactile Inspection Planning System," Int. J. Prod. Res., **37**(2), pp. 447–465.

[94] Zhang, G. X., Liu, S. G., Ma, X. H., Wang, J. L., Wu, Y. Q., and Li, Z., 2002, “Towards the Intelligent CMM,” CIRP Ann. - Manuf. Technol., **51**, pp. 437–442.

[95] Zhou, A., Guo, J., and Shao, W., 2011, “Automated Inspection Planning of Freeform Surfaces for Manufacturing Applications,” *2011 IEEE International Conference on Mechatronics and Automation*, IEEE, pp. 2264–2269.

[96] Hussien, H. A., Youssef, A. M., and Shoukry, M. K., 2012, “Automated Inspection Planning System for CMMs,” *International Conference on Engineering and Technology, ICET 2012 - Conference Booklet*.

[97] Stojadinovic, S. M., Majstorovic, V., and Durakbasa, N. M., 2017, “An Advanced CAI Model for Inspection Planning on CMM,” Lect. Notes Mech. Eng., pp. 57–65.

[98] Polini, W., and Moroni, G., 2015, “A Frame for a Computer Aided Inspection Planning System,” Int. J. Eng. Technol., **4**(1), pp. 125–138.

[99] Khan, A. A., Nasr, E. A., Al-ahmari, A., Abdulhameed, O., and Abidi, M. H., 2014, “An Integrated CAPP / CAFD / CAIP System for Prismatic Parts,” *Proceedings of the 2014 Industrial and Systems Engineering Research Conference*, Y. Guanand, and H. Liao, eds., pp. 1–10.

[100] Mohib, A., Azab, A., and ElMaraghy, H., 2009, “Feature-Based Hybrid Inspection Planning: A Mathematical Programming Approach,” Int. J. Comput. Integr. Manuf., **22**(1), pp. 13–29.

[101] Fan, K. C., and Leu, M. C., 1998, “Intelligent Planning of CAD-Directed Inspection for Coordinate Measuring Machines,” Comput. Integr. Manuf. Syst., **11**(1–2), pp. 43–51.

[102] Zhang, S., Ajmal, A., Wootton, J., and Chisholm, A., 2001, “An Automated Inspection Planning System for Coordinate Measuring Machines,” Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., **215**(3), pp. 419–424.

[103] Stouffer, K., and Horst, J., 2001, “Controller Driven VRML Animation of the Next Generation Inspection System (NGIS) Real-Time Controller,” Intell. Syst. Smart Manuf., pp. 31–37.

[104] Calonego, N., Kirner, C., Kirner, T., and Abackerli, A. J., 2004, “Implementation of a Virtual Environment for Interacting with a Coordinate Measuring Machine,” *VECIMS 2004 - IEEE International Conference on Virtual Environments, Human Computer Interface and Measurement Systems*, IEEE, Boston.

[105] Zhao, L., and Peng, Q., 2010, "Development of a CMM Training System in Virtual Environments," Vol. 6 15th Des. Manuf. Lifecycle Conf. 7th Symp. Int. Des. Des. Educ., pp. 537–544.

[106] Hu, Y., Yang, Q., and Sun, X., 2012, "Design, Implementation, and Testing of Advanced Virtual Coordinate-Measuring Machines," IEEE Trans. Instrum. Meas., **61**(5), pp. 1368–1376.

[107] Wang, Y., Guo, X., Sun, K., and Chen, Y., 2012, "Study on Virtual Coordinate Measuring Machine Based on Augmented Virtuality," *2012 IEEE International Conference on Virtual Environments Human-Computer Interfaces and Measurement Systems (VECIMS)*, IEEE, pp. 97–102.

[108] Chen, Y. H., Wang, Y. Z., and Yang, Z. Y., 2004, "Towards a Haptic Virtual Coordinate Measuring Machine," Int. J. Mach. Tools Manuf., **44**, pp. 1009–1017.

[109] Chen, Y. H., Yang, Z. Y., and Wang, Y. Z., 2005, "Haptic Modeling for a Virtual Coordinate Measuring Machine," Int. J. Prod. Res., **43**(9), pp. 1861–1878.

[110] Yang, Z., and Chen, Y., 2005, "Inspection Path Generation in Haptic Virtual CMM," Comput. Aided. Des. Appl., **2**, pp. 273–282.

[111] "ZEISS CALYPSO - Measuring Software for Geometry" [Online]. Available: https://www.zeiss.co.uk/metrology/products/software/calypso-overview/calypso.html. [Accessed: 28-Feb-2020].

[112] "PC-DMIS for Bridge and Gantry CMMs | Hexagon Manufacturing Intelligence" [Online]. Available: https://www.hexagonmi.com/products/software/pc-dmis/pcdmis-cmm-388. [Accessed: 28-Feb-2020].

[113] "OpenDMIS CMM Software | Wenzel America" [Online]. Available: https://www.wenzelamerica.com/product/opendmis-cmm-software/. [Accessed: 28-Feb-2020].

[114] "MCOSMOS Coordinate Measuring Machine Software" [Online]. Available: https://ecatalog.mitutoyo.com/MCOSMOS-Coordinate-Measuring-Machine-Software-C1019.aspx. [Accessed: 28-Feb-2020].

[115] "PolyWorks|Inspector™ Packages | InnovMetric Software" [Online]. Available: https://www.innovmetric.com/en/polyworksinspectortm-packages. [Accessed: 28-Feb-2020].

[116] "New MODUS^{TM} CMM Software Supports Powerful 5-Axis Measurement" [Online]. Available: https://www.renishaw.com/en/new-modus-cmm-software-supports-powerful-5-axis-measurement--10513. [Accessed: 28-Feb-2020].

[117] Becerra-Fernandez, I., and Rajiv Sabherwal, 2010, *Knowledge Management Systems and Processes*, M.E. Sharpe, Inc., Armonk, New York.

[118] Dalkir, K., 2005, *Knowledge Management in Theory and Practice*, Elsevier.

[119] Sainter, P., Oldham, K., Larkin, A., Murton, A., and Brimble, R., 2000, "Product Knowledge Management Within Knowledge-Based Engineering Systems," *Proceedings of DETC'00 ASME 2000 Design Engineering Technical Conference And Computers and Information in Engineering Conference*, Baltimore, Maryland, pp. 1–8.

[120] Ameri, F., and Dutta, D., 2005, "Product Lifecycle Management: Closing the Knowledge Loops," Comput. Aided. Des. Appl., **2**(5), pp. 577–590.

[121] Serban, A. M., and Luan, J., 2004, "Overview of Knowledge Management," Am. Product. Qual. Center, **2002**(113), pp. 5–16.

[122] Frost, A., 2017, "Defining Knowledge, Information, Data," Knowl. Manag. Tools [Online]. Available: https://www.knowledge-management-tools.net/knowledge-information-data.php. [Accessed: 17-Sep-2018].

[123] Du, J., and Liu, J., 2011, "Knowledge Management for Product Development: A Review," 2011 12th Int. Conf. Comput. Des. Comput. Graph., pp. 38–43.

[124] Lundvall, B.-äke, and Johnson, B., 1994, "The Learning Economy," J. Ind. Stud., **1**(2), pp. 23–42.

[125] Shadbolt, N. R., and Milton, N., 1999, "From Knowledge Engineering to Knowledge Management," Inf. Sci. (Ny)., **177**(19), pp. 4072–4094.

[126] Davenport, T. ., and Prusak, L., 1997, *Information Ecology: Mastering the Information and Knowledge Environment*, Oxford University Press.

[127] Lockwood, K., 2009, "Using Analogy to Model Spatial Language Use and Multimodal Knowledge Capture," NorthWestern University.

[128] Kendal, S. L., and Creen, M., 2007, "An Introduction to Knowledge Engineering," *An Introduction to Knowledge Engineering*, Springer London, London, pp. 1–25.

[129] Hayes-Roth, F., Waterman, D. A., and Lenat, D. B., 1983, *Building Expert System*, Addison-Wesley, Reading, MA.

[130] Jin, Y., and Ishino, Y., 2006, “DAKA: Design Activity Knowledge Acquisition through Data-Mining,” Int. J. Prod. Res., **44**(14), pp. 2813–2837.

[131] Rea, H. J., Ritchie, J. M., and Corney, J. R., 2007, “Automating Digital Capture of Engineering Knowledge,” *Proceedings of DET2007 - 4th International Conference on Digital Enterprise Technology*, Bath, UK.

[132] “Extensible Markup Language (XML)” [Online]. Available: https://www.w3.org/XML/. [Accessed: 16-Feb-2020].

[133] Sung, R. C. W., Ritchie, J. M., Robinson, G., Day, P. N., Corney, J. R., and Lim, T., 2009, “Automated Design Process Modelling and Analysis Using Immersive Virtual Reality,” Comput. Des., **41**(12), pp. 1082–1094.

[134] Sung, R., Ritchie, J. M., Rea, H. J., and Corney, J., 2011, “Automated Design Knowledge Capture and Representation in Single-User CAD Environments,” J. Eng. Des., **22**(7), pp. 487–503.

[135] Sivanathan, A., Lim, T., Ritchie, J., Sung, R., Kosmadoudi, Z., and Liu, Y., 2013, “The Application of Ubiquitous Multimodal Synchronous Data Capture in CAD,” CAD Comput. Aided Des., **59**, pp. 176–191.

[136] Sivanathan, A., Ritchie, J. M., and Lim, T., 2017, “A Novel Design Engineering Review System with Searchable Content: Knowledge Engineering via Real-Time Multimodal Recording,” J. Eng. Des., **28**(10–12), pp. 681–708.

[137] Park, S. C., 2003, “Knowledge Capturing Methodology in Process Planning,” CAD Comput. Aided Des., **35**(12), pp. 1109–1117.

[138] Sung, R. C. W., Ritchie, J. M., Lim, T., Dewar, R., and Weston, N., 2011, “Knowledge Capture inside a Haptic Soldering Environment,” *The 6th International Conference on Virtual Learning ICVL*, pp. 39–44.

[139] Zhang, X., Nassehi, A., Safaieh, M., and Newman, S. T., 2013, “Process Comprehension for Shopfloor Manufacturing Knowledge Reuse,” Int. J. Prod. Res., **51**(23–24), pp. 7405–7419.

[140] Fletcher, C., Ritchie, J., Lim, T., and Sung, R., 2013, “The Development of an Integrated Haptic VR Machining Environment for the Automatic Generation of Process Plans,” Comput. Ind., **64**(8), pp. 1045–1060.

[141] Ritchie, J. M., Lim, T., Sung, R. S., Corney, J. R., and Rea, H., 2008, “The Analysis of

Design and Manufacturing Tasks Using Haptic and Immersive VR - Some Case Studies',” *Product Engineering*, Springer Science, pp. 507–522.

[142] Sung, R., Ritchie, J., Lim, T., and Medellin, H., 2009, “Assembly Planning and Motion Study Using Virtual Reality,” *ASME/AFM World Conference on Innovative Virtual Reality 2009*, pp. 31–38.

[143] Read, A., Ritchie, J., and Lim, T., 2017, “Haptic Virtual Reality DFMA - A Case Study,” *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, Springer International Publishing, Cham, pp. 24–38.

[144] Owen, R., and Horváth, I., 2002, “Towards Product-Related Knowledge Asset Warehousing in Enterprises,” *International Symposium on Tools and Methods of Competitive Engineering*, Wuhan, China, pp. 155–170.

[145] “IDEF0 Function Modeling Method” [Online]. Available: http://www.idef.com/idefo-function_modeling_method/. [Accessed: 23-Jun-2019].

[146] Feng, S., 2003, “A Machining Process Planning Activity Model for Systems Integration,” J. Intell. Manuf., **14**(6), pp. 527–539.

[147] Bracewell, R., Wallace, K., Moss, M., and Knott, D., 2009, “Capturing Design Rationale,” CAD Comput. Aided Des., **41**(3), pp. 173–186.

[148] Barreiro, J., Martinez-Pellitero, S., Cuesta, E., Patino, H., and Telenti, A., 2015, “Implementation of Rules into a KBE Model for Improving Reliability in AACMM Measurement,” *International Conference on Innovative Technologies, IN-TECH 2015,* Dubrovnik.

[149] Barreiro, J., Labarga, J. ., Vizán, a, and Ríos, J., 2003, “Functional Model for the Development of an Inspection Integration Framework,” Int. J. Mach. Tools Manuf., **43**(15), pp. 1621–1632.

[150] Martinez, S., Barreiro, J., Cuesta, E., and Alvarez, B., 2009, “Moka Ontology Variant To Apply To the Inspection Planning Process in a Kbe System.,” *Annals of DAAAM for 2009 & Proceedings of the 20th International DAAAM Symposium*, B. Katalinic, ed., Vienna, Austria, pp. 1471–1472.

[151] Barreiro, J., Martinez, S., Cuesta, E., Alvarez, B., and Fernandez, P., 2009, “High Level Diagrams for Identification of Knowledge as a Basis for a KBE Implementation of Inspection Planning Process,” *III Manufacturing Engineering Society International*

Congress, pp. 272–278.

[152] Martínez, S., Barreiro, J., Cuesta, E., Álvarez, B. J., and González, D., 2012, “Methodology for Identifying and Representing Knowledge in the Scope of CMM Inspection Resource Selection,” AIP Conf. Proc., **1431**, pp. 250–257.

[153] Martínez-Pellitero, S., Barreiro, J., Cuesta, E., and Fernández-Abia, A. I., 2015, “KBE Rules Oriented to Resources Management in Coordinates Inspection by Contact,” J. Manuf. Syst., **37**, pp. 149–163.

[154] Barreiro, J., Martínez, S., Cuesta, E., and Alvarez, B., 2010, “Conceptual Principles and Ontology for a KBE Implementation in Inspection Planning,” Int. J. Mechatronics Manuf. Syst., **3**(5–6), pp. 451–465.

[155] Barreiro, J., Martinez Pellitero, S., Gonzalez Madruga, M., Gonzalez-Madruga, D., and Gonzalez, J., 2011, “Framework for an Integrated Ontology Definition in the Scope of CMM Inspection Planning Using CBR,” *Annals of DAAAM and Proceedings of the International DAAAM Symposium*, B. Katalinic, ed., DAAAM International, Vienna, Austria, pp. 69–70.

[156] Majstorovic, V. D., and Stojadinovic, S. M., 2013, “Research and Development of Knowledge Base for Inspection Planning Prismatic Parts on CMM,” *11th IMEKO TC14 International Symposium on Measurement and Quality Control, ISMQC 2013*, Paolo Carbone, ed., Cracow-Kielce, pp. 327–330.

[157] Majstorovic, V., Stojadinovic, S., and Sibalija, T., 2015, “Development Of Knowledge Base For Inspection Planning Prismatic Parts On CMM,” *Acta IMEKO*, Paolo Carbone, ed., pp. 11–14.

[158] Stojadinovic, S., and Majstorovic, V., 2014, “Developing Engineering Ontology for Domain Coordinate Metrology,” FME Trans., **42**(3), pp. 249–255.

[159] Stojadinović, S. M., and Majstorović, V. D., 2019, “Ontological Knowledge Base for Integrating Geometry and Tolerance of PMPs,” *An Intelligent Inspection Planning System for Prismatic Parts on CMMs*, Springer International Publishing, Cham, pp. 33–54.

[160] Martínez-Pellitero, S., Barreiro, J., Cuesta, E., and Fernández-Abia, A. I., 2018, “Knowledge Base Model for Automatic Probe Orientation and Configuration Planning with CMMs,” Robot. Comput. Integr. Manuf., **49**, pp. 285–300.

[161] Michalczuk, A., Pęszor, D., Josiński, H., Świtoński, A., Mucha, R., and Wojciechowski, K.,

2015, "Precision of Gait Indices Approximation by Kinect Based Motion Acquisition," *Studies in Computational Intelligence*, pp. 53–60.

[162] Moeslund, T. B., Hilton, A., and Krüger, V., 2006, "A Survey of Advances in Vision-Based Human Motion Capture and Analysis," Comput. Vis. Image Underst., **104**, pp. 90–126.

[163] Qiu, S., Fan, X., Wu, D., He, Q., and Zhou, D., 2013, "Virtual Human Modeling for Interactive Assembly and Disassembly Operation in Virtual Reality Environment," Int. J. Adv. Manuf. Technol., **69**(9–12), pp. 2355–2372.

[164] Sivanathan, A., Abdel-Wahab, M., Bosche, F., and Lim, T., 2014, "Towards a Cyber-Physical Gaming System for Training in the Construction and Engineering Industry," *Proceedings of the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, ASME, Buffalo, New York, pp. 1–9.

[165] Geiselhart, F., Otto, M., and Rukzio, E., 2016, "On the Use of Multi-Depth-Camera Based Motion Tracking Systems in Production Planning Environments," *Procedia CIRP - 48th CIRP Conference on Manufacturing Systems - CIRP CMS 2015*, pp. 759–764.

[166] Ritchie, J. M., Sung, R. C. W., and Lim, T., 2011, "Using VR as a Tool for the Automated Capture and Formalisation of Engineering Knowledge," *ASME 2011 World Conference on Innovative Virtual Reality, WINVR 2011*, pp. 235–242.

[167] Sung, R. C. W., Ritchie, J. M., Lim, T., and Kosmadoudi, Z., 2012, "Automated Generation of Engineering Rationale, Knowledge and Intent Representations during the Product Life Cycle," Virtual Real., **16**(1), pp. 69–85.

[168] Ritchie, J. M., Lim, T., Sung, R., Sivanathan, A., Fletcher, C., Liu, Y., Kosmadoudi, Z., Gonzalez, G., and Medellin, H., 2016, "Knowledge Capture in Virtual Reality and Beyond," *Advances in Computers and Information in Engineering Research*, John G. Michopoulos, C.J.J. Paredis, D.W. Rosen, and Judy M. Vance, eds., ASME Press, pp. 531–555.

[169] Martínez-Pellitero, S., Barreiro, J., Cuesta, E., and Álvarez, B. J., 2011, "A New Process-Based Ontology for KBE System Implementation: Application to Inspection Process Planning," Int. J. Adv. Manuf. Technol., **57**(1–4), pp. 325–339.

[170] Martínez-Pellitero, S., Barreiro, J., Cuesta, E., and Raya, F., 2015, "Categorization of Inspection Elements in Coordinates Measurement for a KBE Implementation," *Proceedings of the 6th Manufacturing Engineering Society International Conference*,

Barcelona, pp. 1037–1044.

[171] Schroeder, W., Martin, K., and Lorensen, B., 2006, *The Visualization Toolkit : An Object-Oriented Approach to 3D Graphics*, Kitware, Inc.

[172] Ritchie, J. M., Sung, R. C. W., Rea, H., Lim, T., Corney, J. R., and Howley, I., 2008, "The Use of Non-Intrusive User Logging to Capture Engineering Rationale, Knowledge and Intent during the Product Life Cycle," *PICMET: Portland International Center for Management of Engineering and Technology, Proceedings*, pp. 981–989.

[173] "Visualisation Toolit (VTK Library), C++ Examples" [Online]. Available: https://lorensen.github.io/VTKExamples/site/Cxx/. [Accessed: 13-Apr-2020].

[174] Sung, R. C. W., Ritchie, J. M., Lim, T., Rea, H. J., and Corney, J. R., 2013, "Automated Capture of Design Knowledge Using a Virtual Creature Design Environment," Int. J. Innov. Technol. Manag., pp. 1–14.

[175] Ritchie, J. M., Sung, R., Rea, H., Lim, T., Corney, J. R., Salamon, C., and Howley, I., 2008, "Automated Knowledge Capture in 2D and 3D Design Environments," *2nd International Workshop Virtual Manufacturing VirMan 08 as Part of the 5th INTUITION International Conference: Virtual Reality in Industry and Society: From Research to Application.*

[176] "Google Forms: Free Online Surveys for Personal Use" [Online]. Available: https://www.google.co.uk/forms/about/. [Accessed: 16-Feb-2020].

[177] Shackleton, R., 2016, "An Examination of Different Measures of Work Experience, and the Relationship between Previous Experience and Safety," , MSc Dissertation, University of Canterbury.

[178] Park, J., and Jung, W., 2003, "The Operators' Non-Compliance Behavior to Conduct Emergency Operating Procedures - Comparing with the Work Experience and the Complexity of Procedural Steps," Reliab. Eng. Syst. Saf., **82**(2), pp. 115–131.

[179] "CMMGuys Forum" [Online]. Available: http://cmmguys.com/forum/index.php. [Accessed: 16-Feb-2020].

[180] "LinkedIn" [Online]. Available: https://www.linkedin.com/feed/. [Accessed: 16-Feb-2020].

[181] Qt Group, 2018, "Qt | Cross-Platform Software Development for Embedded & Desktop" [Online]. Available: https://www.qt.io/. [Accessed: 23-Nov-2018].

[182] Brooke, J., 1996, “SUS - A Quick and Dirty Usability Scale,” Usability Eval. Ind., **189**(194), pp. 4–7.

[183] Bangor, A., Kortum, P. T., and Miller, J. T., 2008, “An Empirical Evaluation of the System Usability Scale,” Int. J. Hum. Comput. Interact., **24**(6), pp. 574–594.

[184] Tullis, T. S., and Stetson, J. N., 2004, “A Comparison of Questionnaires for Assessing Website Usability,” *Usability Professional Association (UPA) 2004 Conference*, Minneapolis, Minnesota, pp. 1–12.

[185] Bangor, A., Kortum, P., and Miller, J., 2009, “Determining What Individual SUS Scores Mean: Adding an Adjective Rating Scale,” J. Usability Stud., **4**(3), pp. 114–123.

[186] Ghasemi, A., and Zahediasl, S., 2012, “Normality Tests for Statistical Analysis: A Guide for Non-Statisticians,” Int. J. Endocrinol. Metab., **10**(2), pp. 486–489.

[187] Razali, N. M., and Wah, Y. B., 2011, “Power Comparisons of Shapiro-Wilk , Kolmogorov-Smirnov, Lilliefors and Anderson-Darling Tests,” J. Stat. Model. Anal., **2**(1), pp. 21–33.

[188] Mankins, J., 1995, “Technology Readiness Levels - A White Paper.”

[189] Nachar, N., 2008, “The Mann-Whitney U: A Test for Assessing Whether Two Independent Samples Come from the Same Distribution,” Tutor. Quant. Methods Psychol., **4**(1), pp. 13–20.

[190] Kellman, P. J., and Massey, C. M., 2013, “Perceptual Learning, Cognition, and Expertise,” *Psychology of Learning and Motivation - Advances in Research and Theory*, pp. 117–165.

[191] Ritchie, J. M., Dewar, R. G., Robinson, G., Simmons, J. E. L., and Ng, F. M., 2006, “The Role of Non-Intrusive Operator Logging to Support the Analysis and Generation of Product Engineering Data Using Immersive VR,” Virtual Phys. Prototyp., **1**(2), pp. 117–134.

[192] Lowe, A., McMahon, C., and Culley, S., 2004, “Characterising the Requirements of Engineering Information Systems,” Int. J. Inf. Manage., **24**(5), pp. 401–422.

[193] Sun, W., Ma, Q. Y., Gao, T. Y., and Chen, S., 2010, “Knowledge-Intensive Support for Product Design with an Ontology-Based Approach,” Int. J. Adv. Manuf. Technol., **48**(5–8), pp. 421–434.

[194] Ettlie, J. E., and Kubarek, M., 2008, “Design Reuse in Manufacturing and Services,” J. Prod. Innov. Manag., **25**(5), pp. 457–472.

[195] Rezayat, M., 2000, "Knowledge-Based Product Development Using XML and KCs," CAD Comput. Aided Des., **32**(5), pp. 299–309.

[196] Hofer-Alfeis, J., 2008, "Knowledge Management Solutions for the Leaving Expert Issue," J. Knowl. Manag., **12**(4), pp. 44–54.

Appendix A

Appendix A.1 Early stage IPaCK – demo video

Demonstration video of the early stage IPaCK can be found in the link: https://youtu.be/BZagUv1B73g

Alternatively, it can be found on Youtube.com under the title:

“Early stage IPaCK prototype – demo”

Appendix A.2 Ray tracing algorithm for inspection path

```
  vtkSmartPointer<vtkPoints> intersectPoints =
      vtkSmartPointer<vtkPoints>::New();

    vtkSmartPointer<vtkIdList> intersectCells =
      vtkSmartPointer<vtkIdList>::New();

    vtkSmartPointer<vtkExtractCells> cellSource =
      vtkSmartPointer<vtkExtractCells>::New();
    cellSource->SetInputConnection(part->GetOutputPort());

      vtkSmartPointer<vtkPoints> test_points =
        vtkSmartPointer<vtkPoints>::New();

  double tol = 0;
  int j = 0;

  double o[3];
  double d[3];

  for (vtkIdType i = 0; i < pathLinePts->GetNumberOfPoints()-1; i++)
    {
  flag:
    pathLinePts->GetPoint(i, o);
    pathLinePts->GetPoint(i + 1, d);

    double lineP0[3] = { o[0],o[1],o[2] };
    double lineP1[3] = { d[0],d[1],d[2] };

    partOBBree->SetTolerance(tol);
    partOBBree->IntersectWithLine(lineP0, lineP1, intersectPoints, intersectCells);

    if (intersectPoints->GetNumberOfPoints() == 0)
      {
      test_points->InsertPoint(i, o[0], o[1], o[2]);
      test_points->InsertPoint(i + 1, d[0], d[1], d[2]);

      }
    else
      {
      if (o[2] < d[2])
        {
        o[2] = o[2] + 5;
        }
      else if (o[2] > d[2])
        {
        d[2] = d[2] + 5;
        }
      else
        {
        o[2] = o[2] + 5;
        d[2] = d[2] + 5;
        }
      pathLinePts->InsertPoint(i, o[0], o[1], o[2]);
      pathLinePts->InsertPoint(i + 1, d[0], d[1], d[2]);

      goto flag;

      double intersection[3];
      for (int i = 0; i < intersectPoints->GetNumberOfPoints(); i++)
        {
        intersectPoints->GetPoint(i, intersection);
        cout << "\tPoint Intersection " << i << ": " << intersection[0] << ", " << intersection[1]
<< ", " << intersection[2] << endl;
        }
```

```
vtkIdType cellId;
      for (vtkIdType i = 0; i < intersectCells->GetNumberOfIds(); i++)
        {
        cellId = intersectCells->GetId(i);
        cellSource->AddCellList(intersectCells);
        }
      }

    }

    vtkSmartPointer<vtkDataSetMapper> cellMapper =
      vtkSmartPointer<vtkDataSetMapper>::New();
    cellMapper->SetInputConnection(cellSource->GetOutputPort());

    vtkSmartPointer<vtkActor> cellActor =
      vtkSmartPointer<vtkActor>::New();
    cellActor->SetMapper(cellMapper);
    cellActor->GetProperty()->SetColor(0, 0.8, 0.9);

  // ========================================================

  // Create a polydata to store inspection path points and lines in


  vtkSmartPointer<vtkPolyData> pathLinePoly =
    vtkSmartPointer<vtkPolyData>::New();

  pathLinePoly->SetPoints(pathLinePts);

  vtkSmartPointer<vtkCellArray> pathCellArray =
    vtkSmartPointer<vtkCellArray>::New();

  for (vtkIdType i = 0; i < pathLinePts->GetNumberOfPoints()-1; i++)
    {
    vtkSmartPointer<vtkLine> pathLines =
      vtkSmartPointer<vtkLine>::New();
    pathLines->GetPointIds()->SetId(0, i);
    pathLines->GetPointIds()->SetId(1, i + 1);

    pathCellArray->InsertNextCell(pathLines);

    }

  // Add the lines to the dataset

  pathLinePoly->SetLines(pathCellArray);

  vtkSmartPointer<vtkPolyDataMapper> pathLineMap =
    vtkSmartPointer<vtkPolyDataMapper>::New();
  pathLineMap->SetInputData(pathLinePoly);

  vtkSmartPointer<vtkActor>  pathLineAct =
    vtkSmartPointer<vtkActor>::New();
  pathLineAct->SetMapper(pathLineMap);
  pathLineAct->GetProperty()->SetLineWidth(1);
  pathLineAct->GetProperty()->SetColor(1, 1, 0);

  vtkSmartPointer<vtkPolyData> pathPointspolydata =
    vtkSmartPointer<vtkPolyData>::New();
  pathPointspolydata->SetPoints(pathLinePts);

  vtkSmartPointer<vtkOctreePointLocator> pathPtOctree =
    vtkSmartPointer<vtkOctreePointLocator>::New();
  pathPtOctree->SetDataSet(pathPointspolydata);
  pathPtOctree->BuildLocator();
```

Appendix A.3 Code for CMM part program generation

```
ofstream myfile3("CMM_program.txt");
  if (myfile3.is_open())
    {
    myfile3 << "MODE/PROG,MAN" << endl;
    myfile3 << " " << endl;
    for (int i = 0; i < table2->GetNumberOfRows(); i++)
      {
      if  (table2->GetValue(i,  2).ToString().substr(0,  4)  ==  "Plan"  &&  table2->GetValue(i+1,
1).ToString()=="Point")
        {
        lab_tag = table2->GetValue(i, 2).ToString();
        geo_tag1 = "PLANE";
        geo_tag2 = "PLANE,CART";
        myfile3 << "$$<MEAS_" << geo_tag1 << " name = " << "\"" << lab_tag << "\"" << ">" <<
endl;
        myfile3 << "MODE/PROG,MAN" << endl;
                    int j = i+1;
                    Xsum = 0;
                    Ysum = 0;
                    Zsum = 0;
                    Xcount = 0;
                    Ycount = 0;
                    Zcount = 0;

                    while (table2->GetValue(j, 1).ToString() == "Point")
                      {
                      Xsum = Xsum + table2->GetValue(j, 3).ToDouble();
                      Ysum = Ysum + table2->GetValue(j, 4).ToDouble();
                      Zsum = Zsum + table2->GetValue(j, 5).ToDouble();
                      Xcount = Xcount + 1;
                      Ycount = Ycount + 1;
                      Zcount = Zcount + 1;
                      Xnor = table2->GetValue(j, 8).ToDouble();
                      Ynor = table2->GetValue(j, 9).ToDouble();
                      Znor = table2->GetValue(j, 10).ToDouble();
                      j++;
                      }

                    Xc = Xsum / Xcount;
                    Yc = Ysum / Ycount;
                    Zc = Zsum / Zcount;

        myfile3 << "F(" << lab_tag << ")=FEAT/" << geo_tag2 << "," << Xc << "," << Yc << "," <<
Zc << "," << Xnor <<  "," << Ynor << "," << Znor << endl;
        myfile3 << "MEAS/PLANE,F(" << lab_tag << ")," << Xcount << endl;
        int k = i + 1;
        while (table2->GetValue(k, 1).ToString() == "Point")
          {
          double Xpt, Ypt, Zpt;
          Xpt = table2->GetValue(k, 3).ToDouble();
          Ypt = table2->GetValue(k, 4).ToDouble();
          Zpt = table2->GetValue(k, 5).ToDouble() - ZzeroAxis;
          myfile3 << "PTMEAS/CART," << Xpt << "," << Ypt << "," << Zpt << endl;
          k++;
          }
        myfile3 << "ENDMES" << endl;
        myfile3 << "$$<\MEAS_PLANE = " << lab_tag << ">" << endl;
        myfile3 << " " << endl;
        }

      if (table2->GetValue(i, 2).ToString().substr(0, 4) == "Line" && table2->GetValue(i + 1,
1).ToString() == "Point")
        {
        lab_tag = table2->GetValue(i, 2).ToString();
        geo_tag1 = "LINE";
        geo_tag2 = "LINE,UNBND,CART";
        myfile3 << "$$<MEAS_" << geo_tag1 << " name = " << "\"" << lab_tag << "\"" << ">" <<
endl;
        myfile3 << "MODE/PROG,MAN" << endl;

        int j = i + 1;
```

```
        Xsum = 0;
        Ysum = 0;
        Zsum = 0;
        Xcount = 0;
        Ycount = 0;
        Zcount = 0;

        while (table2->GetValue(j, 1).ToString() == "Point")
          {
          Xsum = Xsum + table2->GetValue(j, 3).ToDouble();
          Ysum = Ysum + table2->GetValue(j, 4).ToDouble();
          Zsum = Zsum + table2->GetValue(j, 5).ToDouble();
          Xcount = Xcount + 1;
          Ycount = Ycount + 1;
          Zcount = Zcount + 1;
          Xnor = table2->GetValue(j, 8).ToDouble();
          Ynor = table2->GetValue(j, 9).ToDouble();
          Znor = table2->GetValue(j, 10).ToDouble();
          j++;
          }

        Xc = Xsum / Xcount;
        Yc = Ysum / Ycount;
        Zc = Zsum / Zcount;

        myfile3 << "F(" << lab_tag << ")=FEAT/" << geo_tag2 << "," << Xc << "," << Yc << "," <<
Zc << "," << Xnor << "," << Ynor << "," << Znor << endl;
        myfile3 << "MEAS/LINE,F(" << lab_tag << ")," << Xcount << endl;
        int k = i + 1;
        while (table2->GetValue(k, 1).ToString() == "Point")
          {
          double Xpt, Ypt, Zpt;
          Xpt = table2->GetValue(k, 3).ToDouble();
          Ypt = table2->GetValue(k, 4).ToDouble();
          Zpt = table2->GetValue(k, 5).ToDouble() - ZzeroAxis;
          myfile3 << "PTMEAS/CART," << Xpt << "," << Ypt << "," << Zpt << endl;
          k++;
          }
        myfile3 << "ENDMES" << endl;
        myfile3 << "$$<\MEAS_LINE = " << lab_tag << ">" << endl;
        myfile3 << " " << endl;
        }

      if (table2->GetValue(i, 2).ToString().substr(0, 4) == "Cyli" && table2->GetValue(i + 1,
1).ToString() == "Point")
        {
        lab_tag = table2->GetValue(i, 2).ToString();
        geo_tag1 = "CYLNDR";
        geo_tag2 = "CYLNDR,INNER,CART";
        myfile3 << "$$<MEAS_" << geo_tag1 << " name = " << "\"" << lab_tag << "\"" << ">" <<
endl;
        myfile3 << "MODE/PROG,MAN" << endl;

        int j = i + 1;
        Xsum = 0;
        Ysum = 0;
        Zsum = 0;
        Xcount = 0;
        Ycount = 0;
        Zcount = 0;

        while (table2->GetValue(j, 1).ToString() == "Point")
          {
          Xsum = Xsum + table2->GetValue(j, 3).ToDouble();
          Ysum = Ysum + table2->GetValue(j, 4).ToDouble();
          Zsum = Zsum + table2->GetValue(j, 5).ToDouble();
          Xcount = Xcount + 1;
          Ycount = Ycount + 1;
          Zcount = Zcount + 1;
          j++;
          }

        Xc = Xsum / Xcount;
        Yc = Ysum / Ycount;
```

```
        Zc = Zsum / Zcount;

        float ax, ay, bx, by, cx, cy;

        ax = table2->GetValue(i + 1, 3).ToFloat();
        ay = table2->GetValue(i + 1, 4).ToFloat();
        bx = table2->GetValue(i + 2, 3).ToFloat();
        by = table2->GetValue(i + 2, 4).ToFloat();
        cx = table2->GetValue(i + 3, 3).ToFloat();
        cy = table2->GetValue(i + 3, 4).ToFloat();

        myfunction(ax, ay, bx, by, cx, cy);

        myfile3 << "F(" << lab_tag << ")=FEAT/" << geo_tag2 << "," << Xc << "," << Yc << "," <<
Zc << ",0,0,1," << centdia[0] << endl;
        myfile3 << "MEAS/CYLNDR,F(" << lab_tag << ")," << Xcount << endl;
        int k = i + 1;
        while (table2->GetValue(k, 1).ToString() == "Point")
          {
          double Xpt, Ypt, Zpt;
          Xpt = table2->GetValue(k, 3).ToDouble();
          Ypt = table2->GetValue(k, 4).ToDouble();
          Zpt = table2->GetValue(k, 5).ToDouble() - ZzeroAxis;
          myfile3 << "PTMEAS/CART," << Xpt << "," << Ypt << "," << Zpt << endl;
          k++;
          }

        myfile3 << "ENDMES" << endl;
        myfile3 << "$$<\MEAS_CYLNDR = " << lab_tag << ">" << endl;
        myfile3 << " " << endl;
        }

      if (table2->GetValue(i, 2).ToString().substr(0, 4) == "Circ" && table2->GetValue(i + 1,
1).ToString() == "Point")
        {
        lab_tag = table2->GetValue(i, 2).ToString();
        geo_tag1 = "CIRCLE";
        geo_tag2 = "CIRCLE,INNER,CART";
        myfile3 << "$$<MEAS_" << geo_tag1 << " name = " << "\"" << lab_tag << "\"" << ">" <<
endl;
        myfile3 << "MODE/PROG,MAN" << endl;

        int j = i + 1;
        Xsum = 0;
        Ysum = 0;
        Zsum = 0;
        Xcount = 0;
        Ycount = 0;
        Zcount = 0;

        while (table2->GetValue(j, 1).ToString() == "Point")
          {
          Xsum = Xsum + table2->GetValue(j, 3).ToDouble();
          Ysum = Ysum + table2->GetValue(j, 4).ToDouble();
          Zsum = Zsum + table2->GetValue(j, 5).ToDouble();
          Xcount = Xcount + 1;
          Ycount = Ycount + 1;
          Zcount = Zcount + 1;
          j++;
          }

        Xc = Xsum / Xcount;
        Yc = Ysum / Ycount;
        Zc = Zsum / Zcount;

        float ax, ay, bx, by, cx, cy;

        ax = table2->GetValue(i + 1, 3).ToFloat();
        ay = table2->GetValue(i + 1, 4).ToFloat();
        bx = table2->GetValue(i + 2, 3).ToFloat();
        by = table2->GetValue(i + 2, 4).ToFloat();
        cx = table2->GetValue(i + 3, 3).ToFloat();
        cy = table2->GetValue(i + 3, 4).ToFloat();
```

```
        myfunction(ax, ay, bx, by, cx, cy);

        myfile3 << "F(" << lab_tag << ")=FEAT/" << geo_tag2 << "," << Xc << "," << Yc << "," <<
Zc << ",0,0,1," << centdia[0] << endl;
        myfile3 << "MEAS/CIRCLE,F(" << lab_tag << ")," << Xcount << endl;
        int k = i + 1;
        while (table2->GetValue(k, 1).ToString() == "Point")
          {
          double Xpt, Ypt, Zpt;
          Xpt = table2->GetValue(k, 3).ToDouble();
          Ypt = table2->GetValue(k, 4).ToDouble();
          Zpt = table2->GetValue(k, 5).ToDouble() - ZzeroAxis;
          myfile3 << "PTMEAS/CART," << Xpt << "," << Ypt << "," << Zpt << endl;
          k++;
          }

        myfile3 << "ENDMES" << endl;
        myfile3 << "$$<\MEAS_CIRCLE = " << lab_tag << ">" << endl;
        myfile3 << " " << endl;
        }

     // Adding GOTO points between features probing

      if (i < table2->GetNumberOfRows() - 1 && table2->GetValue(i, 1).ToString() == "Point" &&
table2->GetValue(i + 1, 1).ToString() != "Point")
        {
        lastpt[0] = table2->GetValue(i, 3).ToDouble();
        lastpt[1] = table2->GetValue(i, 4).ToDouble();
        lastpt[2] = table2->GetValue(i, 5).ToDouble();

        vtkIdType iD = pathPtOctree->FindClosestPoint(lastpt);
        pathPtOctree->GetDataSet()->GetPoint(iD, lastpt);

        pathPtOctree->GetDataSet()->GetPoint(iD + 1, goto1);
        pathPtOctree->GetDataSet()->GetPoint(iD + 2, goto2);

        myfile3 << "GOTO/CART," << goto1[0] << "," << goto1[1] << "," << goto1[2] - ZzeroAxis
<< endl;

        myfile3 << "GOTO/CART," << goto2[0] << "," << goto2[1] << "," << goto2[2] - ZzeroAxis
<< endl;
        myfile3 << " " << endl;
        }

      } // End of reading inspection plan file


    } // End of CMM part program file writing
```

Appendix A.4 VBA macro code for IDEF0 generation

```
Sub DrawIDEF0()

Dim Shp As Shape

Dim pts As Integer


Range("A1").Select

   Selection.CurrentRegion.Select

   row_num = Selection.Rows.count


s1 = "b2:b" & row_num

s2 = "h2:h" & row_num

s3 = "c2:c" & row_num

s4 = "g2:g" & row_num
```

```
Set a = Range(s1)
Set b = Range(s2)
Set c = Range(s3)
Set g = Range(s4)

'Count the number of rows in the log file
row_num = a.Rows.count

Dim s As Shape
Dim ws As Worksheet
Dim pbox As Shape
Dim sbox As Shape
Dim tbox As Shape
Dim conn As Shape
Dim ro As Integer

Set ws = ActiveSheet

lo = 700
ho = 100
 boxw = 100
 boxh = 50
 arrl = 50
Row = a(i).Value
fpts = 0
pts = 0
       'MsgBox Row

   For i = 1 To row_num
    'MsgBox a(i).Value

    If a(i).Value = "ZeroZ" Or a(i).Value = "ZeroY" Or a(i).Value = "ZeroX" Then
     text1 = "Part alignment" & vbCrLf & a(i).Value
     pttext = b(i).Value
     geo = c(i).Value
     toolID = g(i).Value
       Set pbox = ws.Shapes.AddShape(msoShapeRectangle, lo, ho, boxw, boxh)
       pbox.Fill.ForeColor.RGB = RGB(300, 300, 300)
       pbox.Line.ForeColor.RGB = RGB(0, 0, 0)
       pbox.TextFrame.Characters.Text = text1
       pbox.TextFrame.Characters.Font.ColorIndex = xlAutomatic
       pbox.TextFrame.HorizontalAlignment = xlCenter
```

```
pbox.TextFrame.VerticalAlignment = xlCenter
pbox.TextFrame.Characters.Font.Size = 10

'add input box before
Set s = ws.Shapes.AddShape(msoShapeRectangle, 10 + lo - 2 * arrl / 2, ho + boxh - 25, 60, 15)
s.Fill.ForeColor.RGB = RGB(300, 300, 300)
s.Line.ForeColor.RGB = RGB(300, 300, 300)
s.TextFrame.Characters.Text = pttext & " pts"
s.TextFrame.Characters.Font.ColorIndex = xlAutomatic
s.TextFrame.AutoSize = True
s.TextFrame.HorizontalAlignment = xlCenter
s.TextFrame.VerticalAlignment = xlCenter
s.TextFrame.Characters.Font.Size = 10

'add control box above
Set s = ws.Shapes.AddShape(msoShapeRectangle, lo, ho - arrl, 60, 30)
s.Fill.ForeColor.RGB = RGB(300, 300, 300)
s.Line.ForeColor.RGB = RGB(300, 300, 300)
s.TextFrame.Characters.Text = geo
s.TextFrame.Characters.Font.ColorIndex = xlAutomatic
s.TextFrame.AutoSize = True
s.TextFrame.HorizontalAlignment = xlCenter
s.TextFrame.VerticalAlignment = xlCenter
s.TextFrame.Characters.Font.Size = 10

'add mechanism box below
Set s = ws.Shapes.AddShape(msoShapeRectangle, lo + 5, ho + boxh + arrl / 2, 60, 30)
s.Fill.ForeColor.RGB = RGB(300, 300, 300)
s.Line.ForeColor.RGB = RGB(300, 300, 300)
s.TextFrame.Characters.Text = toolID
s.TextFrame.Characters.Font.ColorIndex = xlAutomatic
s.TextFrame.AutoSize = True
s.TextFrame.HorizontalAlignment = xlCenter
s.TextFrame.VerticalAlignment = xlCenter
s.TextFrame.Characters.Font.Size = 10

 'add input arrow before
ws.Shapes.AddLine(lo - arrl, ho + boxh / 2, lo, ho + boxh / 2).Select
Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

'add control arrow above
```

```
    ws.Shapes.AddLine(lo + boxw / 2, ho - boxh, lo + boxw / 2, ho).Select
    Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
    Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

    'add mechanism arrow below box
    ws.Shapes.AddLine(lo + boxw / 2, ho + boxh + arrl, lo + boxw / 2, ho + boxh).Select
    Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
    Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

    'add output arrow next to box
    ws.Shapes.AddLine(lo + boxw, ho + boxh / 2, lo + boxw + arrl, ho + boxh / 2).Select
    Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
    Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

    'ws.Shapes.AddLine(lo + 4 * boxw + 4 * arrl, ho + boxh / 2, lo + 4 * boxw + 4 * arrl, ho + 4 * boxh + 4 * arrl).Select
    'Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
    'Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)
     'add connector

    'ws.Shapes.AddConnector(msoConnectorElbow, lo + boxw, ho + boxh / 2, lo + 6 * boxw, ho + 6 * boxh).Select
    'Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
    'Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)
'MsgBox lo
lo = lo + 150
 'ho = ho + boxw


ElseIf a(i).Value = "Datum" Then
text2 = "Datum"
pttext = b(i).Value
geo = c(i).Value

    'add a box -
    Set sbox = ws.Shapes.AddShape(msoShapeRectangle, lo, ho, boxw, boxh)
    sbox.Fill.ForeColor.RGB = RGB(300, 300, 300)
    sbox.Line.ForeColor.RGB = RGB(0, 0, 0)
    sbox.TextFrame.Characters.Text = text2
    sbox.TextFrame.Characters.Font.ColorIndex = xlAutomatic
    sbox.TextFrame.HorizontalAlignment = xlCenter
    sbox.TextFrame.VerticalAlignment = xlCenter
    sbox.TextFrame.Characters.Font.Size = 10
```

```
'add input box before
 Set s = ws.Shapes.AddShape(msoShapeRectangle, 10 + lo - 2 * arrl / 2, ho + boxh - 25, 60, 15)
s.Fill.ForeColor.RGB = RGB(300, 300, 300)
s.Line.ForeColor.RGB = RGB(300, 300, 300)
s.TextFrame.Characters.Text = pttext & " pts"
s.TextFrame.Characters.Font.ColorIndex = xlAutomatic
s.TextFrame.AutoSize = True
s.TextFrame.HorizontalAlignment = xlCenter
s.TextFrame.VerticalAlignment = xlCenter
s.TextFrame.Characters.Font.Size = 10
s.ZOrder msoSendToBack

'add control box above
Set s = ws.Shapes.AddShape(msoShapeRectangle, lo, ho - boxh, 60, 30)
s.Fill.ForeColor.RGB = RGB(300, 300, 300)
s.Line.ForeColor.RGB = RGB(300, 300, 300)
s.TextFrame.Characters.Text = geo
s.TextFrame.Characters.Font.ColorIndex = xlAutomatic
s.TextFrame.AutoSize = True
s.TextFrame.HorizontalAlignment = xlCenter
s.TextFrame.VerticalAlignment = xlCenter
s.TextFrame.Characters.Font.Size = 10

'add mechanism box below
Set s = ws.Shapes.AddShape(msoShapeRectangle, lo + 5, ho + arrl / 2 + boxh, 60, 30)
s.Fill.ForeColor.RGB = RGB(300, 300, 300)
s.Line.ForeColor.RGB = RGB(300, 300, 300)
s.TextFrame.Characters.Text = toolID
s.TextFrame.Characters.Font.ColorIndex = xlAutomatic
s.TextFrame.AutoSize = True
s.TextFrame.HorizontalAlignment = xlCenter
s.TextFrame.VerticalAlignment = xlCenter
s.TextFrame.Characters.Font.Size = 10

' add input arrow
ws.Shapes.AddLine(lo - boxw / 2, ho + boxh / 2, lo, ho + boxh / 2).Select
Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

'add control arrow
```

```
    ws.Shapes.AddLine(lo + boxw / 2, ho - boxh, lo + boxw / 2, ho).Select
    Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
    Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

    'add mechanism arrow
    ws.Shapes.AddLine(lo + boxw / 2, ho + boxh + arrl, lo + boxw / 2, ho + boxh).Select
    Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
    Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

    'add output arrow
   ws.Shapes.AddLine(lo + boxw, ho + boxh / 2, lo + boxw + arrl, ho + boxh / 2).Select
    Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
    Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

lo = lo + 150

ElseIf a(i).Value = "Tolerance" Then
text3 = "Tolerance inspection"
 pttext = b(i).Value
geo = c(i).Value
ho = ho + 200

    'add a box / new IDEF0 block
    Set sbox = ws.Shapes.AddShape(msoShapeRectangle, lo, ho, boxw, boxh)
    sbox.Fill.ForeColor.RGB = RGB(300, 300, 300)
    sbox.Line.ForeColor.RGB = RGB(0, 0, 0)
    sbox.TextFrame.Characters.Text = text3
    sbox.TextFrame.Characters.Font.ColorIndex = xlAutomatic
    sbox.TextFrame.HorizontalAlignment = xlCenter
    sbox.TextFrame.VerticalAlignment = xlCenter
    sbox.TextFrame.Characters.Font.Size = 10


    'add input box before
     Set s = ws.Shapes.AddShape(msoShapeRectangle, lo - 2 * arrl / 2, ho + boxh, 60, 15)
    s.Fill.ForeColor.RGB = RGB(300, 300, 300)
    s.Line.ForeColor.RGB = RGB(300, 300, 300)
    s.TextFrame.Characters.Text = pttext & "  "
    s.TextFrame.Characters.Font.ColorIndex = xlAutomatic
    s.TextFrame.AutoSize = True
    s.TextFrame.HorizontalAlignment = xlCenter
    s.TextFrame.VerticalAlignment = xlCenter
```

```
s.TextFrame.Characters.Font.Size = 10
s.ZOrder msoSendToBack

'add control box above
Set s = ws.Shapes.AddShape(msoShapeRectangle, lo, ho - boxh, 60, 30)
s.Fill.ForeColor.RGB = RGB(300, 300, 300)
s.Line.ForeColor.RGB = RGB(300, 300, 300)
s.TextFrame.Characters.Text = geo
s.TextFrame.Characters.Font.ColorIndex = xlAutomatic
s.TextFrame.AutoSize = True
s.TextFrame.HorizontalAlignment = xlCenter
s.TextFrame.VerticalAlignment = xlCenter
s.TextFrame.Characters.Font.Size = 10

'add mechanism box below
Set s = ws.Shapes.AddShape(msoShapeRectangle, lo + 5, ho + arrl / 2 + boxh, 60, 30)
s.Fill.ForeColor.RGB = RGB(300, 300, 300)
s.Line.ForeColor.RGB = RGB(300, 300, 300)
s.TextFrame.Characters.Text = toolID
s.TextFrame.Characters.Font.ColorIndex = xlAutomatic
s.TextFrame.AutoSize = True
s.TextFrame.HorizontalAlignment = xlCenter
s.TextFrame.VerticalAlignment = xlCenter
s.TextFrame.Characters.Font.Size = 10

' add input arrow
ws.Shapes.AddLine(lo - boxw / 2, ho + boxh / 2, lo, ho + boxh / 2).Select
Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

'add control arrow

ws.Shapes.AddLine(lo + boxw / 2, ho - boxh, lo + boxw / 2, ho).Select
Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

'add mechanism arrow
ws.Shapes.AddLine(lo + boxw / 2, ho + boxh + arrl, lo + boxw / 2, ho + boxh).Select
Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

'add output arrow
```

```
  ws.Shapes.AddLine(lo + boxw, ho + boxh / 2, lo + boxw + arrl, ho + boxh / 2).Select
   Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
   Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

lo = lo + 150

ElseIf a(i).Value = "Inspection" Then
text3 = "Inspection feature"
 pttext = b(i).Value
geo = c(i).Value

   'add a box -
   Set sbox = ws.Shapes.AddShape(msoShapeRectangle, lo, ho, boxw, boxh)
   sbox.Fill.ForeColor.RGB = RGB(300, 300, 300)
   sbox.Line.ForeColor.RGB = RGB(0, 0, 0)
   sbox.TextFrame.Characters.Text = text3
   sbox.TextFrame.Characters.Font.ColorIndex = xlAutomatic
   sbox.TextFrame.HorizontalAlignment = xlCenter
   sbox.TextFrame.VerticalAlignment = xlCenter
   sbox.TextFrame.Characters.Font.Size = 10



   'add input box before
    Set s = ws.Shapes.AddShape(msoShapeRectangle, 10 + lo - 2 * arrl / 2, ho + boxh - 25, 60, 15)
   s.Fill.ForeColor.RGB = RGB(300, 300, 300)
   s.Line.ForeColor.RGB = RGB(300, 300, 300)
   s.TextFrame.Characters.Text = pttext & " pts"
   s.TextFrame.Characters.Font.ColorIndex = xlAutomatic
   s.TextFrame.AutoSize = True
   s.TextFrame.HorizontalAlignment = xlCenter
   s.TextFrame.VerticalAlignment = xlCenter
   s.TextFrame.Characters.Font.Size = 10
   s.ZOrder msoSendToBack

   'add control box above
   Set s = ws.Shapes.AddShape(msoShapeRectangle, lo, ho - boxh, 60, 30)
   s.Fill.ForeColor.RGB = RGB(300, 300, 300)
   s.Line.ForeColor.RGB = RGB(300, 300, 300)
   s.TextFrame.Characters.Text = geo
   s.TextFrame.Characters.Font.ColorIndex = xlAutomatic
   s.TextFrame.AutoSize = True
   s.TextFrame.HorizontalAlignment = xlCenter
```

```
    s.TextFrame.VerticalAlignment = xlCenter
    s.TextFrame.Characters.Font.Size = 10

    'add mechanism box below
    Set s = ws.Shapes.AddShape(msoShapeRectangle, lo, ho + arrl / 2 + boxh, 60, 30)
    s.Fill.ForeColor.RGB = RGB(300, 300, 300)
    s.Line.ForeColor.RGB = RGB(300, 300, 300)
    s.TextFrame.Characters.Text = toolID
    s.TextFrame.Characters.Font.ColorIndex = xlAutomatic
    s.TextFrame.AutoSize = True
    s.TextFrame.HorizontalAlignment = xlCenter
    s.TextFrame.VerticalAlignment = xlCenter
    s.TextFrame.Characters.Font.Size = 10

    ' add input arrow
    ws.Shapes.AddLine(lo - boxw / 2, ho + boxh / 2, lo, ho + boxh / 2).Select
    Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
    Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

    'add control arrow

    ws.Shapes.AddLine(lo + boxw / 2, ho - boxh, lo + boxw / 2, ho).Select
    Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
    Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

    'add mechanism arrow
    ws.Shapes.AddLine(lo + boxw / 2, ho + boxh + arrl, lo + boxw / 2, ho + boxh).Select
    Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
    Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

    'add output arrow
   ws.Shapes.AddLine(lo + boxw, ho + boxh / 2, lo + boxw + arrl, ho + boxh / 2).Select
    Selection.ShapeRange.Line.EndArrowheadStyle = msoArrowheadTriangle
    Selection.ShapeRange.Line.ForeColor.RGB = RGB(0, 0, 0)

lo = lo + 150

ElseIf i = row_num Then
text4 = "end of session"

    Set s = ws.Shapes.AddShape(msoShapeRectangle, lo, ho, 100, 50)
    s.Fill.ForeColor.RGB = RGB(300, 300, 300)
```

```
    s.TextFrame.Characters.Text = text4
    s.TextFrame.Characters.Font.ColorIndex = xlAutomatic
    s.TextFrame.HorizontalAlignment = xlCenter
    s.TextFrame.VerticalAlignment = xlCenter
    s.TextFrame.Characters.Font.Size = 10
        s.Line.ForeColor.RGB = RGB(0, 0, 0)

  lo = lo + 150
  End If

Next i

 ActiveSheet.Shapes.SelectAll
Selection.ShapeRange.Group
End Sub
```

Appendix A.5 VBA macro code for subtitles generation

```
Sub GenerateSubs()

Dim count As Integer
Dim tol As String
Dim fso As Object
  Set fso = CreateObject("Scripting.FileSystemObject")

  Dim Fileout As Object
  Set Fileout = fso.CreateTextFile("C:\Users\Dimitrios\OneDrive - Heriot-Watt
University\PhD\Experimentation\Trials\Results\video.sub", True, True)

'create a message box in the beginning
'MsgBox "Create IDEF0" OR InputBox ("Create IDEF0")

Range("A1").Select
  Selection.CurrentRegion.Select
  row_num = Selection.Rows.count

  s1 = "b2:b" & row_num
  s2 = "h2:h" & row_num
  s3 = "c2:c" & row_num
  s4 = "g2:g" & row_num
  s5 = "a2:a" & row_num
  s6 = "l2:l" & row_num
```

```
Set a = Range(s1)
Set b = Range(s2)
Set c = Range(s3)
Set g = Range(s4)
Set e = Range(s5)
Set d = Range(s6)

count = 0

For i = 1 To row_num - 1
text1 = a(i).Value           'Activity
text2 = b(i).Value           'Total points
text3 = c(i).Value           'Geometry
text4 = g(i).Value           'Tool
step_time = e(i).Value
Repeat = d(i).Value

If text1 = "ZeroZ" Or text1 = "ZeroY" Or text1 = "ZeroX" Then
count = count + 1
  Fileout.Write count & vbCrLf
  Fileout.Write "00:00:" & step_time & " --> " & "00:00:" & step_time + 5 & vbCrLf
  Fileout.Write "Probe " & text2 & " points on " & text3 & " with " & text4 & ". Set as " & text1 & vbCrLf
  Fileout.Write "" & vbCrLf

ElseIf text1 = "Datum" Then
count = count + 1
  Fileout.Write count & vbCrLf
  Fileout.Write "00:00:" & step_time & " --> " & "00:00:" & step_time + 5 & vbCrLf
  If Repeat = 0 Then
  Fileout.Write "Probe " & text2 & " points on " & text3 & " with " & text4 & ". Set as " & text1 & vbCrLf
  ElseIf Repeat = 1 Then
  Fileout.Write "Reuse " & text3 & ". Set as " & text1 & vbCrLf
  End If

  Fileout.Write "" & vbCrLf

ElseIf text1 = "Inspection" Then
count = count + 1
  Fileout.Write count & vbCrLf
  Fileout.Write "00:00:" & step_time & " --> " & "00:00:" & step_time + 5 & vbCrLf
  If Repeat = 0 Then
```

```
    Fileout.Write "Probe " & text2 & " points on " & text3 & " with " & text4 & ". Check " & tol & " of " & text3 &
vbCrLf
    ElseIf Repeat = 1 Then
    Fileout.Write "Reuse " & text3 & ". Check " & tol & " of " & text3 & vbCrLf
    End If
    Fileout.Write "" & vbCrLf

  ElseIf text1 = "Tolerance" Then
  count = count + 1
    Fileout.Write count & vbCrLf
    Fileout.Write "00:00:" & step_time & " --> " & "00:00:" & step_time + 5 & vbCrLf
    Fileout.Write "Inspection of " & text3 & " tolerance" & vbCrLf
    Fileout.Write "" & vbCrLf

    tol = text3

    End If

  Next i

End Sub
```

Appendix A.6 VBA macro code for text instructions generation

```
Sub GenerateInstructions()

Dim count As Integer
Dim tol As String

Dim fso2 As Object

  Set fso2 = CreateObject("Scripting.FileSystemObject")

 Dim Fileout2 As Object
 Set Fileout2 = fso2.CreateTextFile("C:\Users\Dimitrios\OneDrive - Heriot-Watt
University\PhD\Experimentation\Trials\Results\instructions.txt", True, True)

Range("A1").Select
  Selection.CurrentRegion.Select
  row_num = Selection.Rows.count

  s1 = "b2:b" & row_num
  s2 = "h2:h" & row_num
```

```
s3 = "c2:c" & row_num
s4 = "g2:g" & row_num
s5 = "a2:a" & row_num
s6 = "l2:l" & row_num

Set a = Range(s1)
Set b = Range(s2)
Set c = Range(s3)
Set g = Range(s4)
Set e = Range(s5)
Set d = Range(s6)

 Fileout2.Write "Step    " & "      Instruction" & vbCrLf
 Fileout2.Write "====    " & "     ==========" & vbCrLf

count = 0

For i = 1 To row_num - 1
text1 = a(i).Value            'Activity
text2 = b(i).Value            'Total points
text3 = c(i).Value            'Geometry
text4 = g(i).Value            'Tool
step_time = e(i).Value
Repeat = d(i).Value

If text1 = "ZeroZ" Or text1 = "ZeroY" Or text1 = "ZeroX" Then
count = count + 1

   Fileout2.Write count & "    " & "        Probe " & text2 & " points on " & text3 & " with " & text4 & ". Set as " &
text1 & vbCrLf

ElseIf text1 = "Datum" Then
count = count + 1
   If Repeat = 0 Then
   Fileout2.Write count & "    " & "        Probe " & text2 & " points on " & text3 & " with " & text4 & ". Set as " &
text1 & vbCrLf
   ElseIf Repeat = 1 Then
   Fileout2.Write count & "    " & "       Reuse " & text3 & ". Set as " & text1 & vbCrLf
   End If
ElseIf text1 = "Inspection" Then
count = count + 1
```

```
    If Repeat = 0 Then
    Fileout2.Write count & "    " & "       Probe " & text2 & " points on " & text3 & " with " & text4 & ". Check " &
tol & " of " & text3 & vbCrLf
    ElseIf Repeat = 1 Then
    Fileout2.Write count & "    " & "       Reuse " & text3 & " for " & text1 & ". Check " & tol & " of " & text3 & vbCrLf
    End If

  ElseIf text1 = "Tolerance" Then
  count = count + 1

   Fileout2.Write count & "    " & "       Inspection of " & text3 & " tolerance" & vbCrLf
    tol = text3

    End If
  Next i
End Sub
```

Appendix A.7 Example of Annotated Video-clip – pilot study

Example of Annotated video clip format in the pilot study stage can be found in the link:

https://youtu.be/DOM8DxrQZrk

Alternatively, can it be found on Youtube.com under the title:

'Pilot study - annotated video clip format'

Appendix A.8 Final IPaCK – demo video

Demonstration video of the final prototype IPaCK can be found in the link:

https://youtu.be/nYeYllOTSTI

Alternatively, can it be found on Youtube.com under the title:

'Final IPaCK functionality demo'

Appendix A.9 Example of Annotated Video-clip – main experimental study

Example of Annotated video clip format in the final experimental study can be found in the link: https://youtu.be/g_WEHi9c7b0

Alternatively, it can be found on Youtube.com under the title:

'Annotated Video-clip sample'

Appendix B

Appendix B.1 Knowledge representations evaluation – Pilot study questionnaire

The questionnaire employed in the pilot study for evaluating the designed knowledge formats and outputs.

Pilot study - Knowledge formats evaluation

The aim of this survey is to evaluate different forms for representing a CMM inspection planning strategy and associated knowledge.

In your answers, please bear in mind that the following formats were developed so they can potentially be used for understanding the planned strategy, for training purposes and as using as guides for future reference.

A measurement strategy has been planned for inspecting a true position tolerance of a work-piece. Below you can see the production design of the test component.

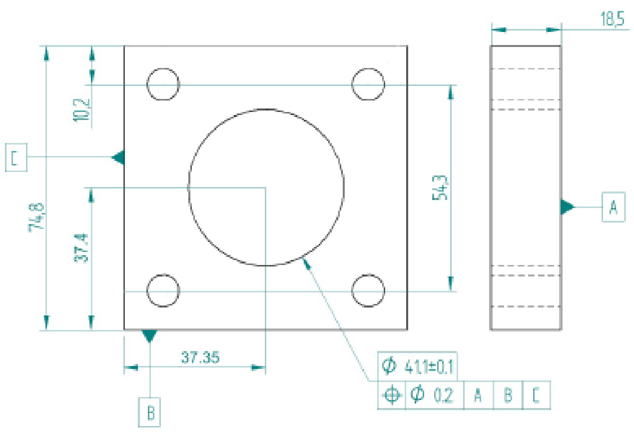
*Required

1. **How many years of CMM programming experience do you have?** *

Mark only one oval.

- 0 - 2 years
- 2 - 5 years
- 5 - 10 years
- over 10 years

Production design of component



Inspection plan

In this format the followed strategy is displayed as a list of steps (inspection plan) in a chronological order with details on how the part is aligned on the CMM, how the tolerances are inspected, what geometrical features are used and the number of points with XYZ coordinates.

Instruction	Time (sec)	XYZ coordinates			ID	tool	Points
part alignment feature	22.14	4.51	-84.25	0.92	plane1	tool1	3
touch	27.13	10.005	23.658	18.5	0		
touch	28.25	35.03	66.286	18.5	1		
touch	29.37	65.06	32.837	18.5	2		
part alignment feature	31.17	6.62	-87.32	1.07	line1	tool1	2
touch	33.53	9.96	0	10	3		
touch	35.13	64.74	0	10	4		
part alignment feature	37.06	10	-86.65	0.87	touch	tool1	1
touch	38.92	0	34.907	8.5	5		
true position	42.00	92.55	-164.78	0.92	tolerance	tool1	
datum feature	43.71	7.08	-104.59	0.97	plane2	tool1	8
touch	46.47	10.005	23.658	18.5	6		
touch	47.58	10.005	51.245	18.5	7		
touch	48.58	20.015	61.603	18.5	8		
touch	49.62	55.05	65.774	18.5	9		
touch	51.10	60.055	49.867	18.5	10		
touch	52.45	65.06	23.613	18.5	11		
touch	53.90	50.045	8.5657	18.5	12		
touch	55.05	20.015	8.8319	18.5	13		
datum feature	57.30	5.14	-106.27	1.05	plane3	tool1	4
touch	59.62	9.96	0	15	14		
touch	61.47	64.74	0	10	15		
touch	62.88	69.72	0	5	16		
touch	64.47	10.005	0	5	17		
datum feature	66.93	7.42	-104.4	1.03	plane4	tool1	4
touch	70.43	0	69.813	13.5	18		
touch	72.18	0	9.9733	13.5	19		
touch	74.61	0	9.9733	8.5	20		
touch	76.28	0	64.827	8.5	21		
inspection feature	79.42	28.5	-104.75	0.93	cylinder1	tool1	8
touch	83.26	39.246	57.912	13.5	22		
touch	84.99	57.9	37.45	13.5	23		
touch	86.76	39.246	16.988	13.5	24		
touch	88.41	18.188	44.874	13.5	25		
touch	90.08	39.246	57.912	8.5	26		
touch	91.49	57.55	33.674	8.5	27		
touch	93.06	42.974	17.685	8.5	28		
touch	94.49	16.8	37.45	8.5	29		

2. **On a scale from 1(lowest) - 5 (highest), please rate the format for each of the following aspects.** *

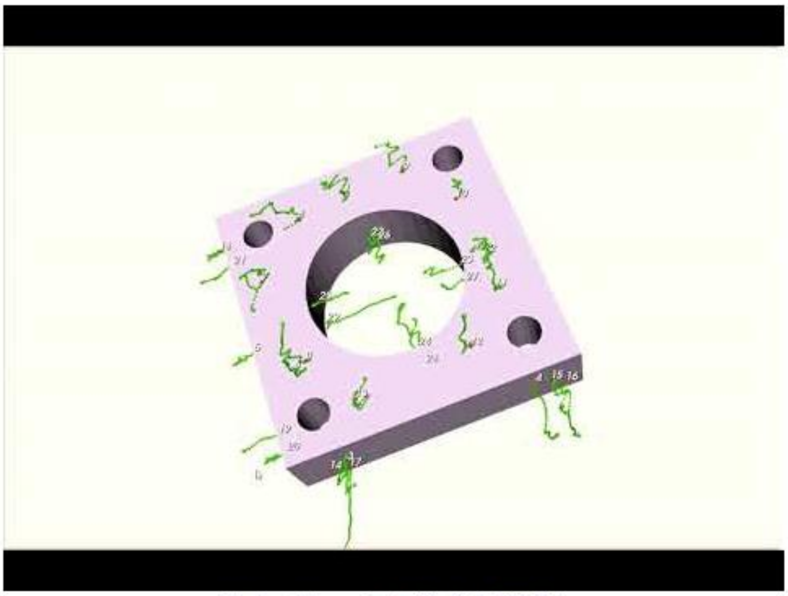
Mark only one oval per row.

	1	2	3	4	5
Ease of understanding					
Usefulness					
Overall score					

Tactical planning trajectory

This trajectory graph presents the specific tactical planning activity consisting of: a large green ball showing the beginning point for each segment, a set of smaller green balls indicating the approaching path and direction and a red ball for the recorded point of contact.

If the video display is too small, please follow the link: https://www.youtube.com/watch?v=Vx4oNfMLNyA



http://youtube.com/watch?v=Vx4oNfMLNyA

3. **On a scale from 1(lowest) - 5 (highest), please rate the format for each of the following aspects.** *

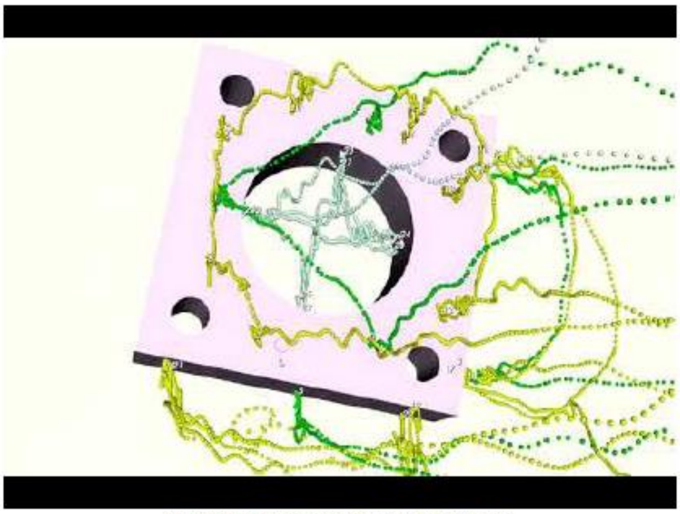
Mark only one oval per row.

	1	2	3	4	5
Ease of understanding	◯	◯	◯	◯	◯
Usefulness	◯	◯	◯	◯	◯
Overall score	◯	◯	◯	◯	◯

Groups of planning activity trajectory

This graph shows the groups of planning activity highlighting the different sub-actions with different colors: green segments relate to the part alignment features, yellow segments concern the probing of datum features and the white segment shows the strategy for a feature under test.

If the video display is too small, please follow the link: https://www.youtube.com/watch?v=knLgzglVy8Q



http://youtube.com/watch?v=knLgzglVy8Q

4. **On a scale from 1(lowest) - 5 (highest), please rate the format for each of the following aspects.** *

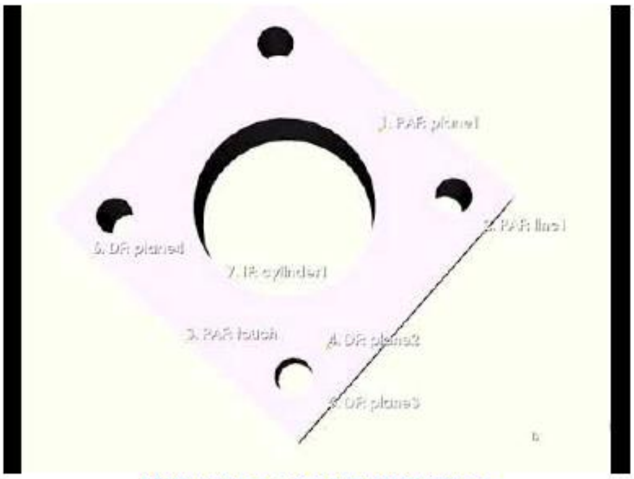
Mark only one oval per row.

	1	2	3	4	5
Ease of understanding	◯	◯	◯	◯	◯
Usefulness	◯	◯	◯	◯	◯
Overall score	◯	◯	◯	◯	◯

Strategic planning sequence

This output presents the strategic planning activity as a sequence of features to probe, numbered and labelled with the following IDs: PAF for part alignment features, DF for datum features and IF for inspection features.

If the video display is too small, please follow the link: https://www.youtube.com/watch?v=hV3NJC2gcoc



http://youtube.com/watch?v=hV3NJC2gcoc

5. **On a scale from 1(lowest) - 5 (highest), please rate the format for each of the following aspects.** *

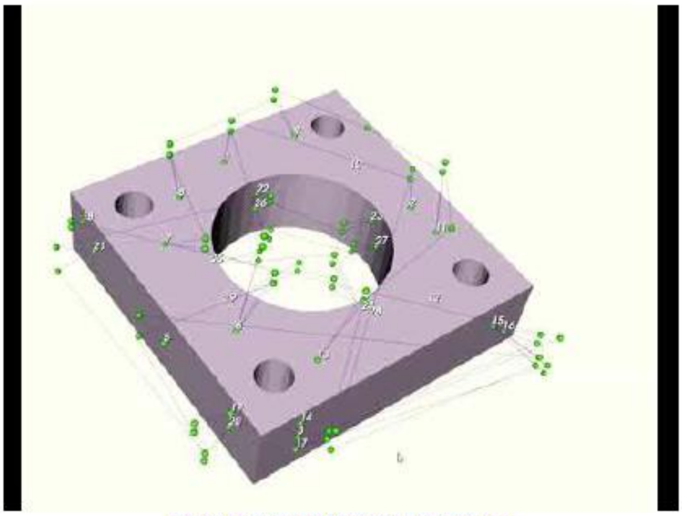
   Mark only one oval per row.

	1	2	3	4	5
Ease of understanding	⬭	⬭	⬭	⬭	⬭
Usefulness	⬭	⬭	⬭	⬭	⬭
Overall score	⬭	⬭	⬭	⬭	⬭

Inspection path

This output shows the inspection path as designed during the planning task.

If the video display is too small, please follow the link: https://www.youtube.com/watch?v=DiH-j1ANV-w



http://youtube.com/watch?v=DiH-j1ANV-w

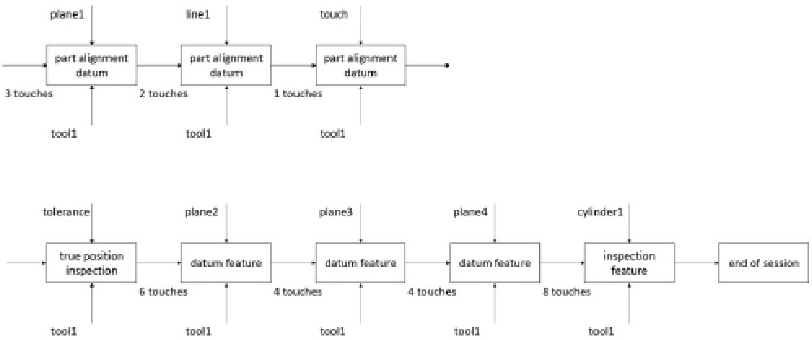
6. **On a scale from 1(lowest) - 5 (highest), please rate the format for each of the following aspects.** *

Mark only one oval per row.

	1	2	3	4	5
Ease of understanding	◯	◯	◯	◯	◯
Usefulness	◯	◯	◯	◯	◯
Overall score	◯	◯	◯	◯	◯

IDEF0 diagram

In the following format, the followed strategy is displayed in a procedural manner. Each main step is shown in a separate set of diagrams.



7. **On a scale from 1(lowest) - 5 (highest), please rate the format for each of the following aspects.** *

Mark only one oval per row.

	1	2	3	4	5
Ease of understanding	◯	◯	◯	◯	◯
Usefulness	◯	◯	◯	◯	◯
Overall score	◯	◯	◯	◯	◯

Plain text instructions

This format presents the strategy in a textual description using plain English syntax.

Time (sec)	Description
22.1417	The user is probing plane1 as part alignment feature using tool1 with 3 points
31.15	The user is probing line1 as part alignment feature using tool1 with 2 points
37.0583	The user is probing a touch as part alignment feature using tool1 with 1 point
42	The user is going to test a true position tolerance
43.7083	The user is probing plane2 as datum feature using tool1 with 8 points
57.2917	The user is probing plane3 as datum feature using tool1 with 4 points
66.925	The user is probing plane4 as datum feature using tool1 with 4 points
79.4167	The user is probing cylinder1 as inspection feature using tool1 with 8 points

8. **On a scale from 1(lowest) - 5 (highest), please rate the format for each of the following aspects.** *

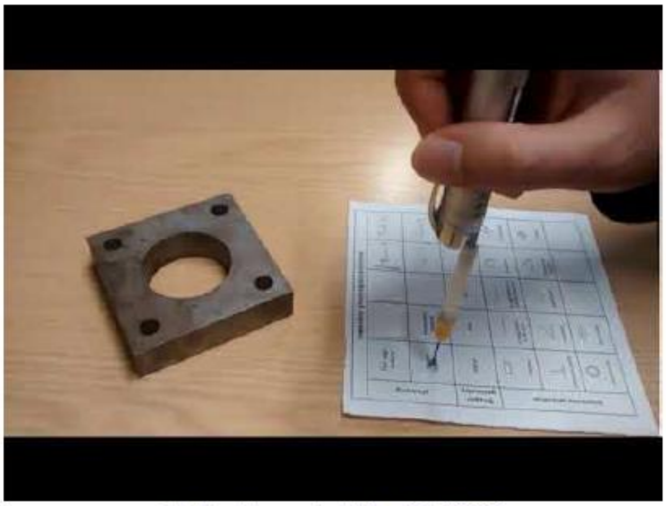
Mark only one oval per row.

	1	2	3	4	5
Ease of understanding	◯	◯	◯	◯	◯
Usefulness	◯	◯	◯	◯	◯
Overall score	◯	◯	◯	◯	◯

Annotated video clip

Annotated video clip presents the intended strategy as recorded during the planning task.

If the video display is too small, please follow the link: https://www.youtube.com/watch?v=-6t4bcY2f4M



http://youtube.com/watch?v=-6t4bcY2f4M

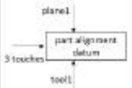
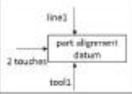
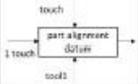
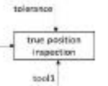
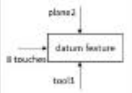
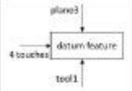
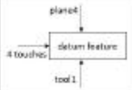
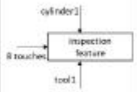
9. **On a scale from 1(lowest) - 5 (highest), please rate the format for each of the following aspects.** *

Mark only one oval per row.

	1	2	3	4	5
Ease of understanding	◯	◯	◯	◯	◯
Usefulness	◯	◯	◯	◯	◯
Overall score	◯	◯	◯	◯	◯

9. Storyboard

In the storyboard, a combination of representation formats is employed, formulating a step by step guide for the specific inspection planning task.

Time (sec)	IDEF	Inspection plan	Text instructions	Screenshot
22		part alignment feature,plane1,4.51,-84.25,0.92,22.1417,3,tool1 touch, 0, 10.005, 23.6583, 18.5, 0, 0, 1, 27.1333 touch, 1, 35.03, 66.2862, 18.5, 0, 0, 1, 28.25 touch, 2, 65.06, 32.8371, 18.5, 0, 0, 1, 29.3667	Probe plane1 as part alignment feature using tool1 with 3 points	
31		part alignment feature,line1, 4.62,-87.32,1.07,31.1667,2,tool1 touch, 3, 9.96, 0, 10.005, 0, -1, 0, 33.5333 touch, 4, 64.74, 0, 10.005, 0, -1, 0, 35.1333	Probe line1 as part alignment feature using tool1 with 2 points	
37		part alignment feature,touch,10,-86.65,0.87,37.0583,1,tool1 touch, 5, 0, 34.9067, 8.495, -1, 0, 0, 38.9167	Probe a touch as part alignment feature using tool1 with 1 point	
42		true position, tolerance,92.55,-164.78,0.92,42,tool1	A true position tolerance is under test	
43		datum feature,plane2,7.08,-104.59,0.97,43.7083,8,tool1 touch, 6, 10.005, 23.6583, 18.5, 0, 0, 1, 46.4667 touch, 7, 10.005, 51.2649, 18.5, 0, 0, 1, 47.5833 touch, 8, 20.015, 61.603, 18.5, 0, 0, 1, 48.5833 touch, 9, 55.05, 65.7739, 18.5, 0, 0, 1, 49.6167 touch, 10, 60.055, 49.8667, 18.5, 0, 0, 1, 51.1 touch, 11, 65.06, 23.6125, 18.5, 0, 0, 1, 52.45 touch, 12, 50.045, 8.56567, 18.5, 0, 0, 1, 53.9 touch, 13, 20.015, 8.8319, 18.5, 0, 0, 1, 55.05	Probe plane2 as datum feature using tool1 with 8 points	
57		datum feature,plane3,5.14,-106.27,1.05,57.3,4,tool1 touch, 14, 9.96, 0, 15.01, 0, -1, 0, 59.8167 touch, 15, 64.74, 0, 10.005, 0, -1, 0, 61.4667 touch, 16, 69.72, 0, 5, 0, -1, 0, 62.8833 touch, 17, 10.005, 0, 5, 0, -1, 0, 64.4667	Probe plane3 as datum feature using tool1 with 4 points	
66		datum feature,plane4,7.42,-104.4,1.03,66.9333,4,tool1 touch, 18, 0, 69.8133, 13.5, -1, 0, 0, 70.4333 touch, 19, 0, 9.97333, 13.5, -1, 0, 0, 72.1833 touch, 20, 0, 9.97333, 8.495, -1, 0, 0, 74.6083 touch, 21, 0, 64.8267, 8.495, -1, 0, 0, 76.275	Probe plane4 as datum feature using tool1 with 4 points	
79		inspection feature,cylinder1,28.5,-104.75,0.93,79.4167,8,tool1 touch, 22, 39.2461, 57.9123, 13.5, 0, -1, 0, 83.2583 touch, 23, 57.9, 37.45, 13.5, -0.9955, -0.09225, 0.01737, 84.9917 touch, 24, 39.2461, 16.9877, 13.5, -0.1837, 0.9828, 0.01732, 86.7583 touch, 25, 18.1877, 44.8735, 13.5, 0.895163, -0.445738, 0, 88.4083 touch, 26, 39.2461, 57.9123, 8.495, -0.183749, -0.982973, 0, 90.075 touch, 27, 57.5501, 33.674, 8.495, -0.961825, 0.273664, 0, 91.4917 touch, 28, 42.9738, 17.6845, 8.495, -0.361241, 0.932472, 0, 93.0583 touch, 29, 16.8, 37.45, 8.495, 0.995734, 0.092368, 0, 94.4917	Probe cylinder1 as inspection feature using tool1 with 8 points	

10. **On a scale from 1(lowest) - 5 (highest), please rate the format for each of the following aspects.** *

Mark only one oval per row.

	1	2	3	4	5
Ease of understanding	◯	◯	◯	◯	◯
Usefulness	◯	◯	◯	◯	◯
Overall score	◯	◯	◯	◯	◯

Combination of formats

Please select just two of the following formats that you believe they could be combined together to provide the best representation of the planning strategy.

11. *

Tick all that apply.

- [ ] Inspection plan
- [ ] Tactical planning activity trajectory
- [ ] Groups of planning activity trajectory
- [ ] Strategic planning sequence
- [ ] Inspection path
- [ ] IDEF0 diagrams
- [ ] Text instructions
- [ ] Annotated video clip
- [ ] Storyboard

Feedback

Please provide your feedback and comments about the presented inspection planning strategy and knowledge formats.

Thank you for your participation.

12.

____
____
____
____
____

Appendix B.2 Inspection planning strategies questionnaire

CMM inspection planning survey

This survey constitutes part of a research project about CMM inspection planning and investigation of different formats to represent a strategy for analysis and comparison, future reuse as well as training of novice CMM planners.

In this survey, you will have to suggest two measurement strategies (inspection plans) for two components as if it would be to measure these on a computer controlled CMM. Major aim of this part is to identify and compare the different considerations and strategies followed by CMM programmers for inspecting a component.

*Required

1. **How many years of CMM programming experience do you have?** *

   Mark only one oval.

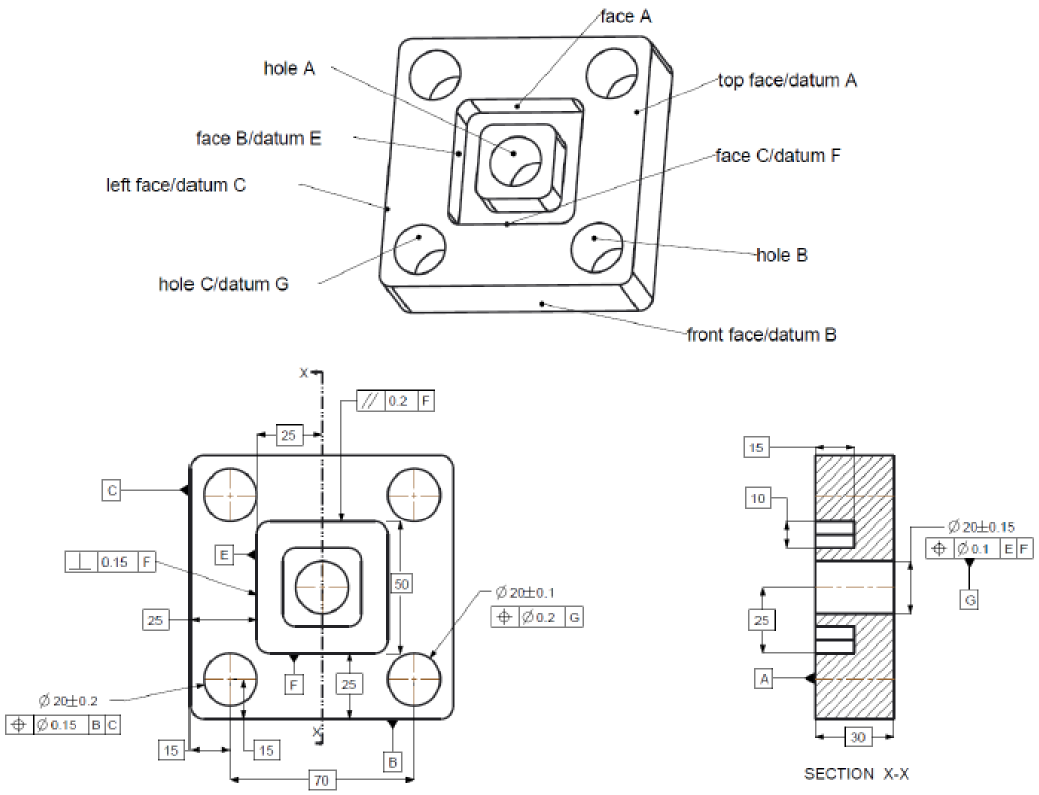
   - 0-2 years
   - 2-5 years
   - 5-10 years
   - over 10 years

1) Measurement strategy for component 1

Please describe shortly the steps you would follow in order to measure the following part with a CMM/touch trigger probing system, by stating the datums and features you would probe and in what order:

Please add also some reasoning for the strategy followed, for example (shortest measurement time, shortest probe travel distance, tightness of tolerances, etc.).

For image in larger size please follow the link: http://imageupload.co.uk/image/4vuh



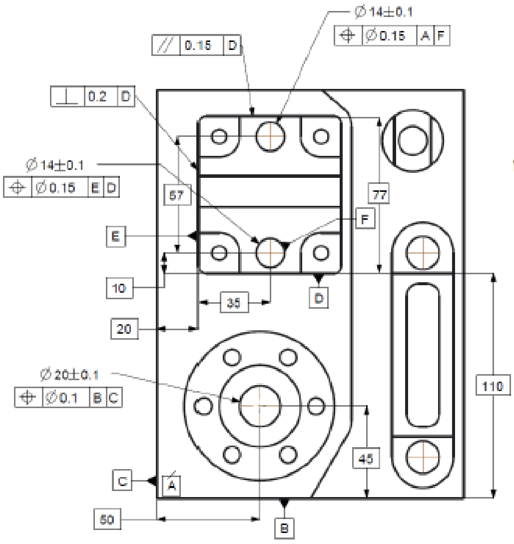
2. **Inspection plan** *

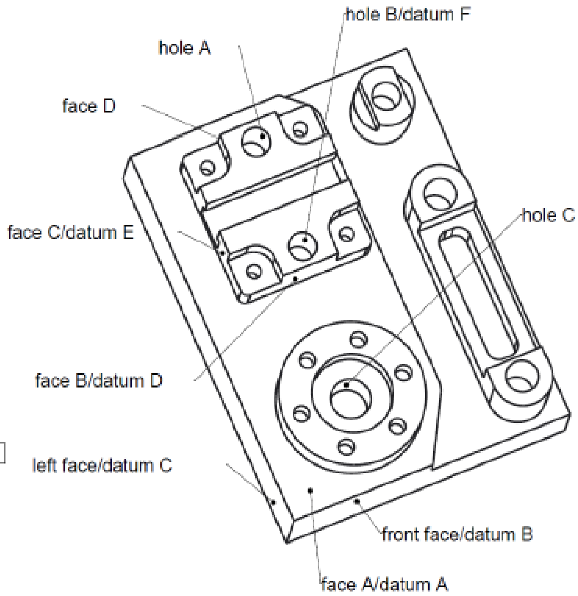
2) Measurement strategy for component 2

Please describe shortly the steps you would follow in order to measure the following part with a CMM/touch trigger probing system, by stating the datums and features you would probe and in what order:

Please add also some reasoning for the strategy followed, for example (shortest measurement time, shortest probe travel distance, tightness of tolerances, etc.).

For image in larger size please follow the link: http://imageupload.co.uk/image/4vuh





3. **Inspection plan** *

Appendix B.3 Pattern Detection Tool (PADET) algorithm

```
function varargout = code(isRandomM, N, ignoreOrder, minAppear)
%% Handling inputs:
if nargin < 1
  % Should we generate a random matrix, or use a hardcoded default?
  isRandomM = false;
end
if isRandomM && nargin < 2
  % Number of columns.
  N = 9;
end
if nargin < 3
  % When this flag is true, [1 2 3] is considered the same as [3 1 2] etc.
  ignoreOrder = true;
end
if nargin < 4
  % The minimal frequancy needed to be plotted in the histogram.
  minAppear = 4;
end
%% Definitions:
R = 9;
MIN_LEN = 4;
%% Setup:
if isRandomM
  M = zeros(R,N);
  for ind1 = 1:R
    M(ind1,:) = randperm(N,N);
  end
else % the example from the question:

    % Below strategies for component 1 - simple / experts

%   M = uint8([
% 1 4 2 3 6 5 8 7 9
% 1 2 3 8 5 6 9 4 7
% 1 2 3 4 9 7 5 6 8
% 1 2 3 4 9 6 5 8 7
% 1 2 3 4 9 5 6 7 8
% 1 2 3 4 9 5 6 8 7
% 1 7 8 5 6 9 4 3 2
% 1 2 7 4 9 3 8 5 6
% 1 2 7 6 8 5 3 4 9
% 1 3 2 4 9 5 6 7 8
% 1 2 3 7 5 6 8 4 9
% 1 3 2 4 9 5 6 8 7
% 1 2 3 4 9 6 5 8 7
% ]);

% Below strategies for component 2 - complex / experts

M = uint8([
1 2 3 4 5 8 6 7 9
1 2 3 6 7 9 8 5 4
1 2 3 4 5 6 8 7 9
1 2 3 4 9 8 6 5 7
1 2 3 4 5 6 7 8 9
1 4 2 3 5 6 8 9 7
1 2 3 4 5 6 9 7 8
1 2 3 4 7 8 6 9 5
1 2 4 5 7 6 8 3 9
1 5 8 6 7 9 2 3 4
1 2 3 8 9 5 7 6 4
1 2 3 4 5 6 8 9 7
1 2 3 4 5 6 7 8 9
]);
```

```
[R,N] = size(M);
end
%% Populate the "row-chopping" indices:
allIdx = cell(N-MIN_LEN+1,1);
for ind1 = MIN_LEN:N
  allIdx{ind1-1} = (1:ind1) + (0:N-ind1).';
end
%% Extract sequences from every row according to the indices:
S = cell((N-1)*R,1);
if ignoreOrder
  for ind1 = 1:R
    idx = (1:N-1) + (N-1)*(ind1-1);
    S(idx) = cellfun(@(x){sort(reshape(M(ind1,x.'), size(x,2),[]).',2)}, allIdx);
  end
else
  for ind1 = 1:R
    idx = (1:N-1) + (N-1)*(ind1-1);
    S(idx) = cellfun(@(x){reshape(M(ind1,x.'), size(x,2),[]).'}, allIdx);
  end
end
S = cellfun(@(x)num2cell(x,2), S, 'UniformOutput', false); S = vertcat(S{:});
% S now contains all sequences **appearing in the array**.
%% Analyze the output:
md5 = string(cellfun(@GetMD5, S, 'UniformOutput', false));
[~,ia,ic] = unique(md5, 'stable'); uS = S(ia);
N = histcounts(ic,'BinMethod','integers');
%% Show chart:
f = find(N >= minAppear); % ignore combinations that appear less than a threshold
figure(); hB = bar(N(f)); hB.Parent.XTickLabelRotation = 45;
hB.Parent.XTickLabel = string(cellfun(@mat2str, uS(f), 'UniformOutput', false));
hB.Parent.XTickLabel
  xticks([1 2 3 4 5 6]); %7 8 9 10
title('Part 2 - Experienced patterns (4 app/4 length)');
saveas(gcf,'exp_part1_new 4 app 4 len.png')
%% Assign outputs:
if nargout > 0
  varargout{1} = M;
  varargout{2} = S;
  varargout{3} = ic;
end
```

Appendix B.4 Strategies comparison algorithm

```
function [V,v] = EditDistance(string1,string2)
% Edit Distance is a standard Dynamic Programming problem. Given two strings s1 and s2,
the edit distance between s1 and s2 is the minimum number of operations required to
convert string s1 to s2. The following operations are typically used:
% Replacing one character of string by another character.
% Deleting a character from string
% Adding a character to string
% Example:
% s1='article'
% s2='ardipo'
% EditDistance(s1,s2)
% > 4
% you need to do 4 actions to convert s1 to s2
% replace(t,d) , replace(c,p) , replace(l,o) , delete(e)
% using the other output, you can see the matrix solution to this problem
%

m=length(string1);
n=length(string2);
v=zeros(m+1,n+1);
for i=1:1:m
    v(i+1,1)=i;
end
for j=1:1:n
    v(1,j+1)=j;
end
for i=1:m
    for j=1:n
        if (string1(i) == string2(j))
            v(i+1,j+1)=v(i,j);
        else
            v(i+1,j+1)=1+min(min(v(i+1,j),v(i,j+1)),v(i,j));
        end
    end
end
V=v(m+1,n+1);
end
```

Appendix C

Appendix C.1 Knowledge representations Pilot study results - Raw data

	1. Inspection plan			2. Tactical activity graph			3. Groups planning activity			4. Strategic sequence of features		
years of CMM programming experience	Ease of understanding	Usefulness	Overall score	Ease of understanding	Usefulness	Overall score	Ease of understanding	Usefulness	Overall score	Ease of understanding	Usefulness	Overall score
5 - 10 years	3	3	3	3	3	3	3	3	3	4	4	4
5 - 10 years	1	1	1	5	2	3	3	1	2	3	2	3
over 10 years	2	1	1	1	1	1	1	1	1	2	1	1
over 10 years	2	3	2	1	1	1	1	1	1	1	2	1
over 10 years	1	1	1	1	1	1	1	1	1	3	3	3
2 - 5 years	4	4	4	5	5	5	4	4	4	4	3	3
over 10 years	3	3	3	2	2	2	1	1	1	3	3	3
over 10 years	3	3	3	3	3	3	2	3	2	4	4	4
over 10 years	4	2	3	1	1	1	1	1	1	3	3	3
over 10 years	4	3	3	3	2	2	4	2	3	5	3	3
over 10 years	4	2	2	1	1	1	1	1	1	2	2	2
over 10 years	3	2	2	4	4	4	3	3	3	4	2	2
over 10 years	1	1	1	3	3	3	4	4	4	4	3	4
over 10 years	2	2	2	2	3	3	2	3	3	3	2	3
over 10 years	4	2	3	3	1	2	2	1	1	2	2	2
5 - 10 years	4	4	4	4	4	4	4	4	4	4	4	4
over 10 years	1	1	1	1	1	1	1	1	1	2	2	2
0 - 2 years	3	3	3	3	3	3	3	3	3	3	3	3
over 10 years	1	1	1	2	1	2	3	2	2	2	2	2
over 10 years	2	2	2	1	1	1	1	1	1	3	2	2
average	2.6	2.2	2.25	2.45	2.15	2.3	2.25	2.05	2.1	3.05	2.6	2.7
standard deviation	1.187655807	1.0052494	1.01954582	1.35627198	1.26802789	1.21828179	1.208522	1.190975	1.165287	0.998683	0.820783	0.92338052

	5. Inspection path			6. IDEF0			7. Text instructions			8. Annotated video clip			9. Storyboard		
years of CMM programming experience	Ease of understanding	Usefulness	Overall score	Ease of understanding	Usefulness	Overall score	Ease of understanding	Usefulness	Overall score	Ease of understanding	Usefulness	Overall score	Ease of understanding	Usefulness	Overall score
5 - 10 years	3	3	3	4	2	3	4	3	3	4	4	4	3	3	3
5 - 10 years	2	2	1	1	1	1	4	3	3	3	2	2	2	2	2
over 10 years	1	1	1	1	1	1	2	1	1	3	3	3	1	1	1
over 10 years	1	1	1	1	1	1	3	2	2	1	1	1	1	1	1
over 10 years	2	2	2	1	1	1	1	1	1	1	1	1	3	3	3
2 - 5 years	5	5	5	3	3	3	5	5	5	5	5	5	3	4	4
over 10 years	2	2	2	4	4	4	4	4	4	4	2	3	4	4	4
over 10 years	3	4	3	2	3	3	3	2	3	3	2	3	3	4	4
over 10 years	3	1	2	1	1	1	4	4	4	3	3	3	2	2	2
over 10 years	5	4	4	3	2	2	3	1	1	2	1	1	4	2	3
over 10 years	1	2	1	2	1	1	5	4	4	5	5	5	5	4	4
over 10 years	3	3	3	4	3	3	3	2	2	4	3	3	4	4	4
over 10 years	5	4	4	1	2	1	1	4	3	4	1	2	4	4	4
over 10 years	4	3	3	3	3	3	4	4	4	3	2	2	4	3	4
over 10 years	2	2	2	4	2	2	4	1	2	3	1	1	3	1	1
5 - 10 years	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
over 10 years	1	1	1	1	1	1	3	3	3	2	2	2	2	2	2
0 - 2 years	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
over 10 years	2	3	2	2	2	2	2	2	2	2	2	2	2	2	2
over 10 years	1	1	1	1	1	1	2	2	2	2	2	2	3	3	3
average	2.65	2.55	2.4	2.3	2.05	2.05	3.2	2.75	2.8	3.05	2.45	2.6	3	2.8	2.9
standard deviation	1.386969	1.234376	1.231174	1.260743	1.050063	1.099043	1.151658	1.251315	1.151658	1.145931	1.276302	1.231174	1.076055	1.105013	1.11921

Appendix C.2 Usability study and SUS Ratings average and standard deviation

Table C 1 Average and Standard Deviation values – SUS Ratings, Sub-groups (Set 1)

Groups (Set 1)	N	Average	SD
Trial Novice	10	75	10.7819
Online Experienced	74	69	11.5411
All participants	84	70	11.6016

Table C 2 Average and Standard Deviation values – SUS Ratings, Sub-groups (Set 2)

Sub-groups (Set 2)	N	Average	SD
Trial Nov.	10	75	10.7819
Online Jun.	11	73	10.7949
Online Int.	20	66	11.0286
Online Sen.	18	65	11.3923
Online Exp.	25	73	11.6255

Appendix C.3 Part 1 – Part programs (Plan 7)

Part 1 - Plan 7 part programs:

IPaCK output

```
IPaCK_Plan7_Part_1_CMM_program.txt - Notepad
File Edit Format View Help
MODE/PROG,MAN

$$<MEAS_PLANE name = "Plane1">
MODE/PROG,MAN
F(Plane1)=FEAT/PLANE,CART,53.052,50.2274,30,0,0,1
MEAS/PLANE,F(Plane1),4
PTMEAS/CART,62.061,12.5,0
PTMEAS/CART,14.013,53.4382,0
PTMEAS/CART,49.048,89.4231,0
PTMEAS/CART,87.086,45.5483,0
ENDMES
$$<MEAS_PLANE = Plane1>

GOTO/CART,87.086,45.5483,2
GOTO/CART,49.5055,-4,0.0189991

$$<MEAS_PLANE name = "Plane2">
MODE/PROG,MAN
F(Plane2)=FEAT/PLANE,CART,48.5165,0,14.3467,0,-1,0
MEAS/PLANE,F(Plane2),3
PTMEAS/CART,49.5055,0,-9.981
PTMEAS/CART,84.1209,0,-17.989
PTMEAS/CART,11.9231,0,-18.99
ENDMES
$$<MEAS_PLANE = Plane2>

GOTO/CART,11.9231,-2,1.01
GOTO/CART,-4,78.1868,2.011

$$<MEAS_PLANE name = "Plane3">
MODE/PROG,MAN
F(Plane3)=FEAT/PLANE,CART,0,49.5055,12.011,-1,0,0
MEAS/PLANE,F(Plane3),3
PTMEAS/CART,0,78.1868,-17.989
PTMEAS/CART,0,48.5165,-9.981
PTMEAS/CART,0,21.8132,-25.997
ENDMES
$$<MEAS_PLANE = Plane3>

GOTO/CART,-2,21.8132,-25.997
GOTO/CART,15.738,20.9616,-25.997

$$<MEAS_CYLNDR name = "Cylinder1">
MODE/PROG,MAN
F(Cylinder1)=FEAT/CYLNDR,INNER,CART,15.6842,16.2445,14.1798,0,0,1,20
MEAS/CYLNDR,F(Cylinder1),6
PTMEAS/CART,15.9227,24.9573,-25.997
PTMEAS/CART,24.3247,11.3876,-22.994
PTMEAS/CART,5.17027,13.1625,-21.993
PTMEAS/CART,9.73568,23.5022,-8.98
PTMEAS/CART,23.9516,19.4574,-7.979
PTMEAS/CART,15,5,-6.978
ENDMES
$$<MEAS_CYLNDR = Cylinder1>

GOTO/CART,15.0924,6.99787,3.022
GOTO/CART,83.7151,20.8681,2.001
```

CE Johansson CMM – Modus 1.1

```
Part1_CMM_part_program.txt - Notepad
File Edit Format View Help
$$<MEAS_PLANE name = "PLN001">
MODE/AUTO,PROG,MAN
F(PLN001)=FEAT/PLANE,CART,39.62,53.973,-0.004,0,0,1
MEAS/PLANE,F(PLN001),4
PTMEAS/CART,59.722,13.28,-0.006,-0.0476,-0.0487,0.9977
PTMEAS/CART,12.196,57.331,0.006,-0,0.0006,1
PTMEAS/CART,46.992,91.356,-0.01,-0.0004,0.0006,1
PTMEAS/CART,85.884,51.953,0.009,0.0006,0.0002,1
ENDMES
$$<\MEAS_PLANE = PLN001>

GOTO/CART,52.678,-18.158,23.268

$$<MEAS_PLANE name = "PLN002">
MODE/AUTO,PROG,MAN
F(PLN002)=FEAT/PLANE,CART,52.632,-0.006,-17.081,0,-1,-0
MEAS/PLANE,F(PLN002),3
PTMEAS/CART,51.176,-0.014,-5.254,0.0977,-0.9952,0.0005
PTMEAS/CART,87.366,0.004,-22.984,-0.019,-0.9998,0.0005
PTMEAS/CART,19.179,-0.018,-23.009,0.0996,-0.995,0.0008
ENDMES
$$<\MEAS_PLANE = PLN002>

GOTO/CART,22.187,-16.471,16.453
GOTO/CART,-18.461,19.948,16.427

$$<MEAS_PLANE name = "PLN003">
MODE/AUTO,PROG,MAN
F(PLN003)=FEAT/PLANE,CART,0.002,47.214,-16.719,-1,-0,0.001
MEAS/PLANE,F(PLN003),3
PTMEAS/CART,0.002,12.935,-21.715,-0.9998,0.0187,-0.0003
PTMEAS/CART,0.014,47.11,-6.185,-0.9998,0.0184,0
PTMEAS/CART,-0.011,81.542,-22.255,-0.9998,0.0187,0.0003
ENDMES
$$<\MEAS_PLANE = PLN003>

GOTO/CART,-15.845,9.349,25.058

DATDEF/FA(PLN002), DAT(A)
DATDEF/FA(PLN003), DAT(B)
DATDEF/FA(PLN004), DAT(C)
D(PartAlign)=DATSET/DAT(A),ZDIR,ZORIG,DAT(B),-YDIR,YORIG,DAT(C),XORIG

GOTO/CART,15.465,14.888,13.298

$$<MEAS_CYLNDR name = "CYL001">
MODE/AUTO,PROG,MAN
F(CYL001)=FEAT/CYLNDR,INNER,CART,14.997,15.009,-14.061,-0.001,-0.001,-1,20.003
MEAS/CYLNDR,F(CYL001),6
PTMEAS/CART,15.672,24.976,-23.513,-0.0189,-0.9998,-0.0005
PTMEAS/CART,21.017,7.147,-23.508,-0.2339,0.9722,-0.0009
PTMEAS/CART,7.114,8.835,-23.513,0.7866,0.6174,0.0011
PTMEAS/CART,11.276,24.296,-4.621,0.3846,-0.9231,0.0019
PTMEAS/CART,23.724,10.648,-4.602,-0.3898,0.9209,0.0007
PTMEAS/CART,6.184,10.31,-4.61,0.9158,0.4015,0.0025
ENDMES
$$<\MEAS_CYLNDR = CYL001>


T(CYL001TruePos)=TOL/POS,2D,0.15,RFS,DAT(B),RFS,DAT(C),RFS
OUTPUT/FA(CYL001),TA(CYL001TruePos)

GOTO/CART,13.009,14.494,18.657
GOTO/CART,87.15,13.262,18.683
```

```
$$<MEAS_CYLNDR name = "Cylinder2">
MODE/PROG,MAN
F(Cylinder2)=FEAT/CYLNDR,INNER,CART,84.9262,14.5241,14.299,0,0,1,20
MEAS/CYLNDR,F(Cylinder2),7
PTMEAS/CART,83.1625,24.8297,-27.999
PTMEAS/CART,77.6099,8.26304,-19.991
PTMEAS/CART,91.0263,7.01983,-18.99
PTMEAS/CART,91.0263,22.9802,-13.985
PTMEAS/CART,76.4978,20.2643,-11.983
PTMEAS/CART,80.5426,6.04837,-10.982
PTMEAS/CART,94.6183,12.2634,-5.977
ENDMES
$$<MEAS_CYLNDR = Cylinder2>

GOTO/CART,92.6714,12.7213,-0.976999
GOTO/CART,35.8537,29,3.002

$$<MEAS_PLANE name = "Plane4">
MODE/PROG,MAN
F(Plane4)=FEAT/PLANE,CART,53.4147,25,19.003,0,1,0
MEAS/PLANE,F(Plane4),3
PTMEAS/CART,35.8537,25,-11.998
PTMEAS/CART,58.2927,25,-14
PTMEAS/CART,66.0976,25,-6.993
ENDMES
$$<MEAS_PLANE = Plane4>

GOTO/CART,66.0976,27,3.007
GOTO/CART,29,63.1707,2.001

$$<MEAS_PLANE name = "Plane5">
MODE/PROG,MAN
F(Plane5)=FEAT/PLANE,CART,25,50.813,18.3357,1,0,0
MEAS/PLANE,F(Plane5),3
PTMEAS/CART,25,63.1707,-12.999
PTMEAS/CART,25,54.3902,-7.994
PTMEAS/CART,25,34.878,-14
ENDMES
$$<MEAS_PLANE = Plane5>

GOTO/CART,27,34.878,-14
GOTO/CART,31.9512,71,-7.994

$$<MEAS_PLANE name = "Plane6">
MODE/PROG,MAN
F(Plane6)=FEAT/PLANE,CART,46.5854,75,21.6723,0,-1,0
MEAS/PLANE,F(Plane6),3
PTMEAS/CART,31.9512,75,-7.994
PTMEAS/CART,45.6098,75,-11.998
PTMEAS/CART,62.1951,75,-4.991
ENDMES
$$<MEAS_PLANE = Plane6>

GOTO/CART,62.1951,73,0.00900078
GOTO/CART,50.3701,55.9957,1

$$<MEAS_CYLNDR name = "Cylinder3">
MODE/PROG,MAN
F(Cylinder3)=FEAT/CYLNDR,INNER,CART,49.905,50.4307,13.558,0,0,1,19.9999
MEAS/CYLNDR,F(Cylinder3),11
PTMEAS/CART,50.9227,59.9573,-26.998
PTMEAS/CART,40.1703,51.8375,-27.999
PTMEAS/CART,54.4574,41.0484,-29
PTMEAS/CART,59.9573,50.9227,-24.996
PTMEAS/CART,50,60,-17.989
PTMEAS/CART,40,50,-15.987
PTMEAS/CART,52.7366,40.3817,-13.985
PTMEAS/CART,59.6183,52.7366,-6.978
PTMEAS/CART,43.9737,57.9802,-6.978
PTMEAS/CART,40.3817,47.2634,-4.976
PTMEAS/CART,56.737,42.6099,-4.976
ENDMES
$$<MEAS_CYLNDR = Cylinder3>
```

```
$$<MEAS_CYLNDR name = "CYL002">
MODE/AUTO,PROG,MAN
F(CYL002)=FEAT/CYLNDR,INNER,CART,85,15.011,-14.345,0.002,-0.001,-1,19.983
MEAS/CYLNDR,F(CYL002),7
PTMEAS/CART,85.993,24.938,-22.08,-0.0189,-0.9998,0.0008
PTMEAS/CART,77.461,8.528,-22.08,0.9054,0.4246,0.0015
PTMEAS/CART,93.82,10.509,-22.076,-0.9994,0.034,0.002
PTMEAS/CART,91.42,22.67,-6.613,-0.6413,-0.7673,-0.0004
PTMEAS/CART,77.279,21.035,-6.62,0.9998,-0.0187,0.002
PTMEAS/CART,81.078,5.904,-6.616,0.0199,0.9998,0.0025
PTMEAS/CART,89.917,6.283,-4.763,-0.4556,0.8902,-0.0003
ENDMES
$$<\MEAS_CYLNDR = CYL002>

T(CYL002TruePos)=TOL/POS,2D,0.15,RFS,FA(CYL001),RFS
OUTPUT/FA(CYL002),TA(CYL002TruePos)

GOTO/CART,87.266,11.593,22.404
GOTO/CART,54.675,30.543,13.095

$$<MEAS_PLANE name = "PLN004">
MODE/AUTO,PROG,MAN
F(PLN004)=FEAT/PLANE,CART,51.777,24.982,-8.75,0,1,-0.001
MEAS/PLANE,F(PLN004),3
PTMEAS/CART,38.391,24.981,-10.132,0.0199,0.9998,0.0008
PTMEAS/CART,53.092,24.987,-5.206,0.0199,0.9998,0.0009
PTMEAS/CART,63.851,24.98,-10.917,-0.0408,0.9992,0.0005
ENDMES
$$<\MEAS_PLANE = PLN004>

GOTO/CART,63.675,29.049,18.333
GOTO/CART,28.884,53.018,18.314

$$<MEAS_PLANE name = "PLN005">
MODE/AUTO,PROG,MAN
F(PLN005)=FEAT/PLANE,CART,24.981,48.379,-8.954,1,-0,-0
MEAS/PLANE,F(PLN005),3
PTMEAS/CART,24.987,62.224,-11.436,0.9998,-0.0187,0.0003
PTMEAS/CART,24.981,48.4,-5.395,0.9998,-0.019,0.0016
PTMEAS/CART,24.975,34.569,-10.034,0.9998,-0.019,0.001
ENDMES
$$<\MEAS_PLANE = PLN005>

(PLN005Perpend)=TOL/PERP,0.15,RFS,FA(PLN004),RFS
OUTPUT/FA(PLN005),TA(PLN005Perpend)

GOTO/CART,29.026,34.499,25.918
GOTO/CART,49.685,73.314,17.369

$$<MEAS_PLANE name = "PLN006">
MODE/AUTO,PROG,MAN
F(PLN006)=FEAT/PLANE,CART,48.857,75.003,-5.956,0,-1,0.001
MEAS/PLANE,F(PLN006),3
PTMEAS/CART,33.287,75.002,-3.366,-0.0196,-0.9998,0.0001
PTMEAS/CART,50.846,74.96,-10.762,0.0701,-0.9624,0.2623
PTMEAS/CART,62.409,75.01,-3.995,-0.0189,-0.9998,0.0001
ENDMES
$$<\MEAS_PLANE = PLN006>

T(PLN006Parallel)=TOL/PARLEL,0.2,RFS,FA(PLN004),RFS
OUTPUT/FA(PLN006),TA(PLN006Parallel)

GOTO/CART,62.322,70.961,21.144
GOTO/CART,46.29,49.153,21.143

$$<MEAS_CYLNDR name = "CYL003">
MODE/AUTO,PROG,MAN
F(CYL003)=FEAT/CYLNDR,INNER,CART,49.979,50.011,-20.056,0.001,0,-1,19.988
MEAS/CYLNDR,F(CYL003),11
PTMEAS/CART,50.423,59.99,-23.107,-0.0189,-0.9998,0.0015
PTMEAS/CART,39.991,50.47,-23.108,0.9998,-0.0187,0.0016
PTMEAS/CART,48.905,40.094,-23.102,-0.0304,0.9995,-0.0005
PTMEAS/CART,59.958,49.35,-23.101,-0.9998,0.0193,0.001
PTMEAS/CART,52.789,59.53,-13.961,0.0632,-0.998,0.0015
PTMEAS/CART,40.367,52.637,-13.962,0.9998,-0.0187,0.001
PTMEAS/CART,50.142,40.01,-13.958,0.0192,0.9998,0.0012
PTMEAS/CART,59.277,46.451,-13.344,-0.9998,0.0193,0.001
PTMEAS/CART,45.777,59.074,-5.021,0.4447,-0.8957,0.0016
PTMEAS/CART,43.915,42.116,-5.016,0.3741,0.9274,-0.0004
PTMEAS/CART,59.968,50.791,-5.013,-0.9998,0.019,-0.0003
ENDMES
$$<\MEAS_CYLNDR = CYL003>

T(CYL003TruePos)=TOL/POS,2D,0.15,RFS,FA(PLN004),RFS,FA(PLN005),RFS
OUTPUT/FA(CYL003),TA(CYL003TruePos)

GOTO/CART,53.929,50.91,21.688
```

Figure C2. 1 Part programs – Part 1, Plan 7

Appendix C.4 Part 2 – Part programs (Plan 8)

Part 2 – Plan 8 part programs:

IPaCK output

IPaCK_Plan8_Part_2_CMM_program.txt - Notepad

File Edit Format View Help

```
MODE/PROG,MAN

$$<MEAS_PLANE name = "Plane1">
MODE/PROG,MAN
F(Plane1)=FEAT/PLANE,CART,69.2052,0,16.6823,0,-1,0
MEAS/PLANE,F(Plane1),3
PTMEAS/CART,116.225,0,-17.979
PTMEAS/CART,25.8278,0,-13.975
PTMEAS/CART,65.5629,0,-37.999
ENDMES
$$<MEAS_PLANE = Plane1>

GOTO/CART,65.5629,-2,17.001
GOTO/CART,-4,31.8408,15.029

$$<MEAS_PLANE name = "Plane2">
MODE/PROG,MAN
F(Plane2)=FEAT/PLANE,CART,0,88.2256,12.3447,-1,0,0
MEAS/PLANE,F(Plane2),3
PTMEAS/CART,0,31.8408,-9.971
PTMEAS/CART,0,188.06,-35.997
PTMEAS/CART,0,44.7761,-36.998
ENDMES
$$<MEAS_PLANE = Plane2>

GOTO/CART,-2,44.7761,3.002
GOTO/CART,8.007,13.9303,4

$$<MEAS_PLANE name = "Plane3">
MODE/PROG,MAN
F(Plane3)=FEAT/PLANE,CART,32.3647,101.37,40,0,0,1
MEAS/PLANE,F(Plane3),3
PTMEAS/CART,8.007,13.9303,0
PTMEAS/CART,80.079,100.13,0
PTMEAS/CART,9.008,190.05,0
ENDMES
$$<MEAS_PLANE = Plane3>

GOTO/CART,9.008,190.05,27
GOTO/CART,50.7839,39.0433,27.016

$$<MEAS_CYLNDR name = "Cylinder1">
MODE/PROG,MAN
F(Cylinder1)=FEAT/CYLNDR,INNER,CART,49.7295,45.4182,34.008,0,0,1,20
MEAS/CYLNDR,F(Cylinder1),6
PTMEAS/CART,50.9802,35.0482,2.016
PTMEAS/CART,55.5557,53.3147,-1.988
PTMEAS/CART,40.4306,42.0972,-0.987
PTMEAS/CART,50.9802,54.9518,-12.999
PTMEAS/CART,60,45,-12.999
PTMEAS/CART,40.4306,42.0972,-8.995
ENDMES
$$<MEAS_CYLNDR = Cylinder1>

GOTO/CART,42.3707,42.5831,16.005
GOTO/CART,81.5781,106,16.005
```

CE Johansson CMM – Modus 1.1

Plan_8_Part2_CMM_part_program.txt - Notepad

File Edit Format View Help

```
$$<MEAS_PLANE name = "PLN001">
MODE/AUTO,PROG,MAN
F(PLN001)=FEAT/PLANE,CART,65.399,0.004,-15.592,-0,-1,-0
MEAS/PLANE,F(PLN001),3
PTMEAS/CART,115.964,-0.001,-15.153,-0.0075,-1,0.0005
PTMEAS/CART,20.758,0.003,-6.992,-0.0078,-1,0.0015
PTMEAS/CART,59.498,0.008,-24.636,-0.0071,-1,0.0015
ENDMES
$$<\MEAS_PLANE = PLN001>

GOTO/CART,59.433,-4.054,42.026
GOTO/CART,-20.373,31.902,41.986

$$<MEAS_PLANE name = "PLN002">
MODE/AUTO,PROG,MAN
F(PLN002)=FEAT/PLANE,CART,0.006,67.671,-21.069,-1,-0,0
MEAS/PLANE,F(PLN002),3
PTMEAS/CART,0.017,44.659,-10.683,-1,0.0075,0.0009
PTMEAS/CART,-0.015,138.826,-26.308,-1,0.0075,-0.0004
PTMEAS/CART,-0.003,19.322,-26.214,-0.9809,0.1944,0.0002
ENDMES
$$<\MEAS_PLANE = PLN002>

GOTO/CART,-4.01,20.111,15.235
GOTO/CART,6.101,9.592,15.239

$$<MEAS_PLANE name = "PLN003">
MODE/AUTO,PROG,MAN
F(PLN003)=FEAT/PLANE,CART,30.831,131.998,-0.001,0,-0,1
MEAS/PLANE,F(PLN003),4
PTMEAS/CART,6.963,5.849,-0.004,-0.0005,-0.0003,1
PTMEAS/CART,2.72,194.21,0.004,-0.0002,-0,1
PTMEAS/CART,82.813,195.937,-0.003,-0.0005,-0,1
PTMEAS/CART,73.765,6.152,0.005,0.0002,0.0003,1
ENDMES
$$<\MEAS_PLANE = PLN003>

DATDEF/FA(PLN003), DAT(A)
DATDEF/FA(PLN001), DAT(B)
DATDEF/FA(PLN002), DAT(C)
D(2)=DATSET/DAT(A),ZDIR,ZORIG,DAT(B),-YDIR,YORIG,DAT(C),XORIG

GOTO/CART,73.748,6.151,34.904
GOTO/CART,49.226,47.83,34.893

$$<MEAS_CYLNDR name = "CYL001">
MODE/AUTO,PROG,MAN
F(CYL001)=FEAT/CYLNDR,INNER,CART,50.084,44.958,-4.35,0.001,0,1,19.945
MEAS/CYLNDR,F(CYL001),6
PTMEAS/CART,49.146,35.039,1.076,0.0084,1,0.0014
PTMEAS/CART,59.427,48.355,1.081,-0.8297,-0.5582,0.0012
PTMEAS/CART,43.143,51.995,1.074,0.9234,-0.3839,0.001
PTMEAS/CART,49.366,54.902,-9.78,-0.0075,-1,0.0015
PTMEAS/CART,58.148,39.129,-9.774,-0.6702,0.7422,-0.0005
PTMEAS/CART,41.33,40.237,-9.783,0.9701,0.2428,0.0008
ENDMES
$$<\MEAS_CYLNDR = CYL001>

T(CYL001TruePos)=TOL/POS,2D,0.1,RFS,DAT(B),RFS,DAT(C),RFS
OUTPUT/FA(CYL001),TA(CYL001TruePos)
```

```
GOTO/CART,42.3707,42.5831,16.005
GOTO/CART,81.5781,106,16.005

$$<MEAS_PLANE name = "Plane4">
MODE/PROG,MAN
F(Plane4)=FEAT/PLANE,CART,55.812,110,49.3417,0,-1,0
MEAS/PLANE,F(Plane4),3
PTMEAS/CART,81.5781,110,6.005
PTMEAS/CART,56.4516,110,20.019
PTMEAS/CART,29.4063,110,2.001
ENDMES
$$<MEAS_PLANE = Plane4>

GOTO/CART,29.4063,108,17.001
GOTO/CART,16,133.846,20.019

$$<MEAS_PLANE name = "Plane5">
MODE/PROG,MAN
F(Plane5)=FEAT/PLANE,CART,20,143.615,48.3407,-1,0,0
MEAS/PLANE,F(Plane5),3
PTMEAS/CART,20,133.846,20.019
PTMEAS/CART,20,122.373,3.002
PTMEAS/CART,20,174.627,2.001
ENDMES
$$<MEAS_PLANE = Plane5>

GOTO/CART,18,174.627,27.001
GOTO/CART,56.9071,117.662,30.017

$$<MEAS_CYLNDR name = "Cylinder2">
MODE/PROG,MAN
F(Cylinder2)=FEAT/CYLNDR,INNER,CART,54.4598,119.861,52.8432,0,0,1,14.000
MEAS/CYLNDR,F(Cylinder2),6
PTMEAS/CART,58.9765,114.239,20.017
PTMEAS/CART,55.8438,126.949,18.015
PTMEAS/CART,48.2034,118.325,21.018
PTMEAS/CART,57.4822,113.455,5.002
PTMEAS/CART,58.2531,126.198,5.002
PTMEAS/CART,48,120,8.005
ENDMES
$$<MEAS_CYLNDR = Cylinder2>

GOTO/CART,49.9964,120.121,28.005
GOTO/CART,79.6094,191,28.012

$$<MEAS_PLANE name = "Plane6">
MODE/PROG,MAN
F(Plane6)=FEAT/PLANE,CART,55.3282,187,48.3407,0,1,0
MEAS/PLANE,F(Plane6),3
PTMEAS/CART,79.6094,187,13.012
PTMEAS/CART,29.4063,187,10.009
PTMEAS/CART,56.9688,187,2.001
ENDMES
$$<MEAS_PLANE = Plane6>

GOTO/CART,56.9688,189,27.001
GOTO/CART,55.6022,179.956,30.017


$$<MEAS_CYLNDR name = "Cylinder3">
MODE/PROG,MAN
F(Cylinder3)=FEAT/CYLNDR,INNER,CART,54.1885,176.25,51.3417,0,0,1,14.000
MEAS/CYLNDR,F(Cylinder3),6
PTMEAS/CART,55.8438,183.949,20.017
PTMEAS/CART,48.051,176.156,21.018
PTMEAS/CART,59.6419,171.76,17.014
PTMEAS/CART,61.7966,178.675,4.001
PTMEAS/CART,48.051,176.156,3
PTMEAS/CART,51.7469,170.802,3
ENDMES
$$<MEAS_CYLNDR = Cylinder3>
```

```
GOTO/CART,45.251,41.327,47.199
GOTO/CART,57.179,99.598,47.208

$$<MEAS_PLANE name = "PLN004">
MODE/AUTO,PROG,MAN
F(PLN004)=FEAT/PLANE,CART,55.362,109.966,13.66,-0,-1,0.001
MEAS/PLANE,F(PLN004),3
PTMEAS/CART,79.087,109.96,7.65,-0.0071,-1,0.0012
PTMEAS/CART,55.253,109.976,23.167,-0.0071,-1,0.0009
PTMEAS/CART,31.768,109.964,10.163,-0.0068,-1,0.0005
ENDMES
$$<\MEAS_PLANE = PLN004>

GOTO/CART,31.714,105.883,55.59
GOTO/CART,3.26,149.735,55.576

$$<MEAS_PLANE name = "PLN005">
MODE/AUTO,PROG,MAN
F(PLN005)=FEAT/PLANE,CART,20.094,144.79,11.376,-1,-0,-0
MEAS/PLANE,F(PLN005),3
PTMEAS/CART,20.095,134.26,19.839,-1,0.0082,0.0002
PTMEAS/CART,20.097,119.121,7.903,-1,0.0079,0.0009
PTMEAS/CART,20.083,180.865,6.386,-0.9938,0.111,-0.0011
ENDMES
$$<\MEAS_PLANE = PLN005>

T(PLN005Perpend)=TOL/PERP,0.15,RFS,FA(PLN004),RFS
OUTPUT/FA(PLN005),TA(PLN005Perpend)

GOTO/CART,16.023,181.319,40.355
GOTO/CART,57.15,120.254,39.447

$$<MEAS_CYLNDR name = "CYL002">
MODE/AUTO,PROG,MAN
F(CYL002)=FEAT/CYLNDR,INNER,CART,55.062,119.929,15.924,-0,0,1,13.926
MEAS/CYLNDR,F(CYL002),6
PTMEAS/CART,60.343,115.592,22.448,-0.3989,0.917,0.0009
PTMEAS/CART,58.2,125.835,22.446,0.2116,-0.9774,0.0013
PTMEAS/CART,49.595,115.641,22.442,0.7227,0.6911,0.0014
PTMEAS/CART,56.014,113.027,9.402,-0.0373,0.9993,-0.0002
PTMEAS/CART,59.459,125.332,9.404,-0.575,-0.8181,-0.001
PTMEAS/CART,48.49,122.072,9.397,1,-0.0072,0.0017
ENDMES
$$<\MEAS_CYLNDR = CYL002>

T(CYL002TruePos)=TOL/POS,2D,0.15,RFS,FA(PLN004),RFS,FA(PLN005),RFS
OUTPUT/FA(CYL002),TA(CYL002TruePos)

GOTO/CART,52.541,122.039,45.752
GOTO/CART,54.244,203.421,45.755


$$<MEAS_PLANE name = "PLN006">
MODE/AUTO,PROG,MAN
F(PLN006)=FEAT/PLANE,CART,56.587,186.902,13.269,-0,1,0.001
MEAS/PLANE,F(PLN006),3
PTMEAS/CART,83.642,186.909,9.681,-0.0097,1,0.0008
PTMEAS/CART,26.013,186.899,9.102,0.0084,1,0.0001
PTMEAS/CART,60.098,186.898,21.026,0.0081,1,-0.0005
ENDMES
$$<\MEAS_PLANE = PLN006>

T(PLN006Parallel)=TOL/PARLEL,0.15,RFS,FA(PLN004),RFS
OUTPUT/FA(PLN006),TA(PLN006Parallel)

GOTO/CART,60.12,190.963,41.057
GOTO/CART,55.505,176.27,41.055

$$<MEAS_CYLNDR name = "CYL003">
MODE/AUTO,PROG,MAN
F(CYL003)=FEAT/CYLNDR,INNER,CART,55.062,176.933,16.57,-0,0.001,1,13.911
MEAS/CYLNDR,F(CYL003),6
PTMEAS/CART,55.574,183.874,24.319,-0.0078,-1,-0.0004
PTMEAS/CART,49.313,173.018,24.314,0.848,0.5301,0.0004
PTMEAS/CART,60.787,173.298,24.319,-1,0.0079,0.0009
PTMEAS/CART,60.707,180.985,8.824,-0.7852,-0.6192,0.0006
PTMEAS/CART,49.361,172.959,8.818,0.764,0.6452,0.0014
PTMEAS/CART,58.976,171.215,8.822,-0.7397,0.6729,0.0011
ENDMES
$$<\MEAS_CYLNDR = CYL003>

T(CYL003TruePos)=TOL/POS,2D,0.15,RFS,FA(PLN003),RFS,FA(CYL002),RFS
OUTPUT/FA(CYL003),TA(CYL003TruePos)


GOTO/CART,55.916,173.945,62.045
```

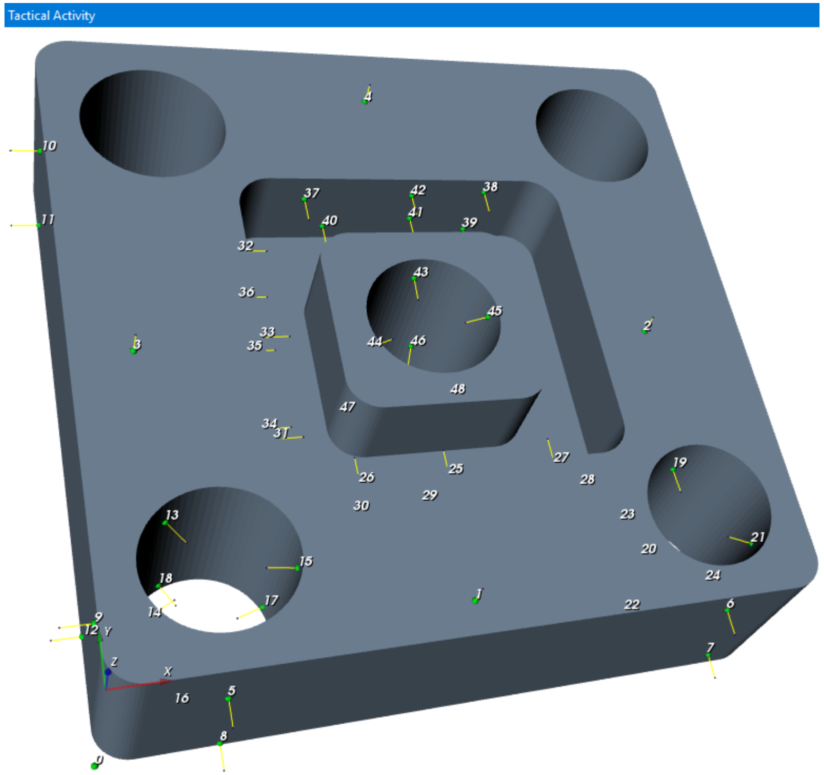
Figure C2. 2 Part programs – Part 2, Plan 8

Appendix D Knowledge representations and questionnaire – Main study

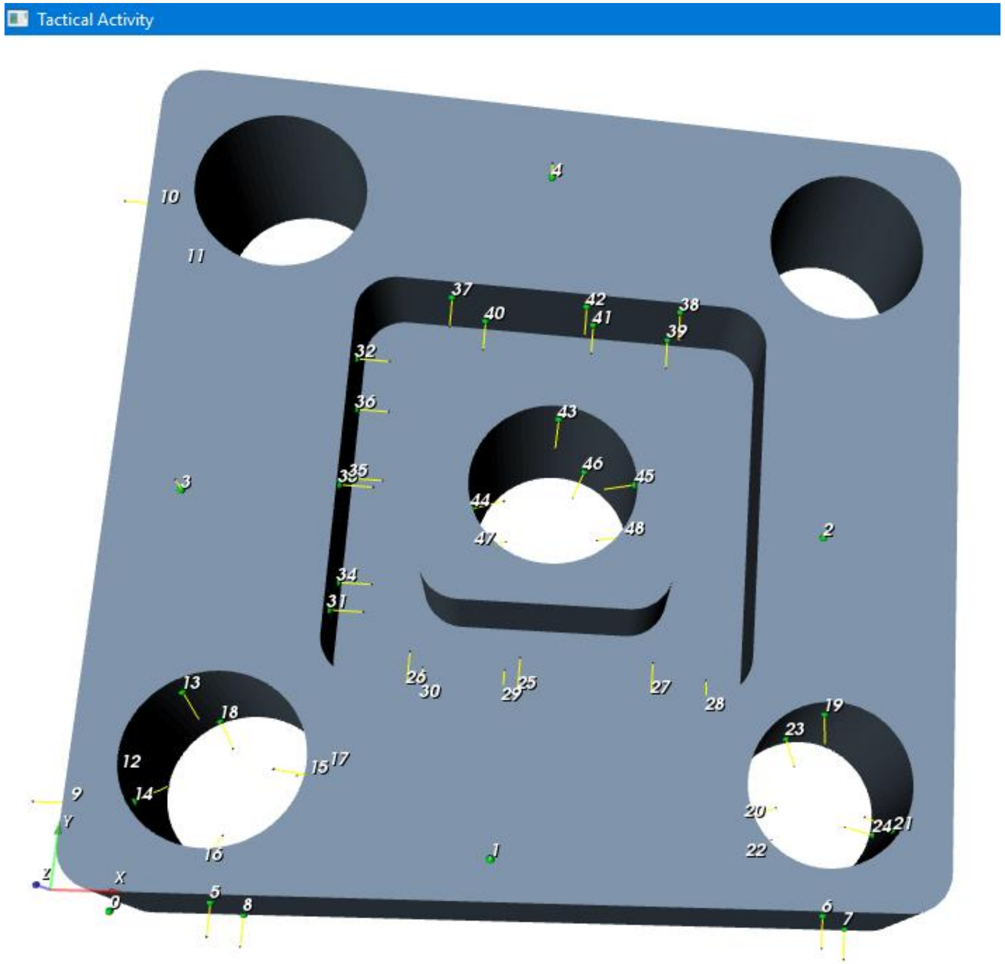
Appendix D.1 Knowledge representations – Part 1

1. Inspection Plan + Tactical Planning Trajectory

Time	Activity	Geo/ID	X	Y	Z	Tool	otal point	I	J	K
37	ZeroZ	Plane1				Stylus1	4			
44	Point	1	46.05	4.808	30			0	0	1
47	Point	2	83.08	45.56	30			0	0	1
50	Point	3	8.007	46.02	30			0	0	1
53	Point	4	47.05	90.38	30			0	0	1
58	ZeroY	Plane2				Stylus1	4			
62	Point	5	14.89	0	20.02			0	-1	0
66	Point	6	85.11	0	25.02			0	-1	0
69	Point	7	91.04	0	4.003			0	-1	0
71	Point	8	15.88	0	1			0	-1	0
78	ZeroX	Plane3				Stylus1	4			
81	Point	9	0	9.945	26.03			-1	0	0
85	Point	10	0	84.12	24.02			-1	0	0
87	Point	11	0	84.12	6.005			-1	0	0
91	Point	12	0	16.87	4.003			-1	0	0
103	Tolerance	Position								
103	Datum	Plane2				Stylus1	4			
108	Datum	Plane3				Stylus1	4			
119	Inspection	Cylinder1				Stylus1	6			
124	Point	13	9.736	23.5	24.02			0.6	-1	0
126	Point	14	6.048	10.54	24.02			0.9	0.5	0
128	Point	15	24.96	14.08	26.03			-1	0.1	0
131	Point	16	10.54	6.048	2.001			0.5	0.9	0
133	Point	17	24.32	18.61	2.001			-0.9	-0	0
135	Point	18	10.54	23.95	2.001			0.5	-1	0
162	Tolerance	Position								
162	Datum	Cylinder1				Stylus1	6			
175	Inspection	Cylinder2				Stylus1	6			
179	Point	19	85	25	22.02			0	-1	0
181	Point	20	75.68	11.39	22.02			0.9	0.4	0
183	Point	21	93.95	10.54	23.02			-0.9	0.4	0
186	Point	22	77.61	8.263	7.006			0.8	0.6	0
189	Point	23	82.26	24.62	5.004			0.3	-1	0
192	Point	24	94.62	12.26	4.003			-1	0.2	0

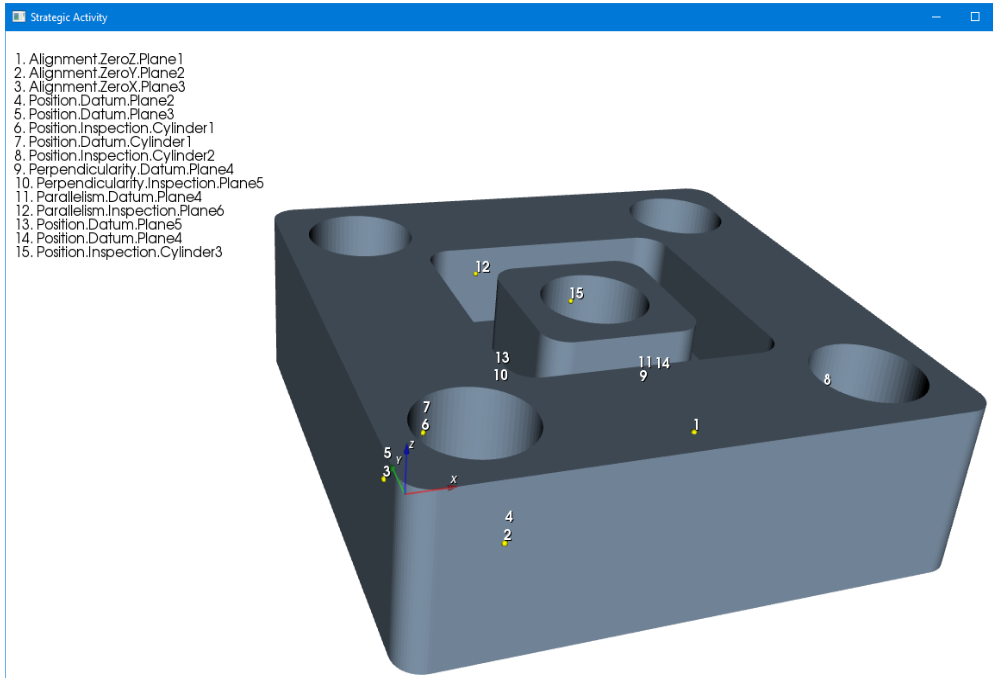


209	Tolerance	Perpendicularity								
227	Datum	Plane4				Stylus1	6			
241	Point	25	47.56	25	27.01			0	1	0
243	Point	26	34.88	25	27.01			0	1	0
245	Point	27	63.17	25	28.01			0	1	0
253	Point	28	70.52	25.03	18.99			-0.1	1	0
256	Point	29	45.61	25	19			0	1	0
259	Point	30	35.85	25	18			0	1	0
297	Inspection	Plane5				Stylus1	6			
301	Point	31	25	33.9	25.01			1	0	0
303	Point	32	25	66.1	24.01			1	0	0
305	Point	33	25	48.54	28.01			1	0	0
307	Point	34	25	38.78	19			1	0	0
309	Point	35	25	52.44	18			1	0	0
311	Point	36	25	61.22	19			1	0	0
358	Tolerance	Parallelism								
358	Datum	Plane4				Stylus1	6			
367	Inspection	Plane6				Stylus1	6			
371	Point	37	35.85	75	25.01			0	-1	0
373	Point	38	64.15	75	27.01			0	-1	0
375	Point	39	63.17	75	17			0	-1	0
378	Point	40	39.76	75	18			0	-1	0
380	Point	41	53.41	75	20			0	-1	0
381	Point	42	52.44	75	26.01			0	-1	0
416	Tolerance	Position								
416	Datum	Plane5				Stylus1	6			
424	Datum	Plane4				Stylus1	6			
437	Inspection	Cylinder3				Stylus1	6			
441	Point	43	50	60	25.02			-0	-1	0
443	Point	44	40.38	47.26	26.03			0.9	0.3	0
445	Point	45	59.83	51.84	26.03			-1	-0	0
447	Point	46	53.61	59.32	6.005			-0.3	-1	0
449	Point	47	40.17	48.16	5.004			1	0.2	0
451	Point	48	59.83	51.84	2.001			-1	-0	0

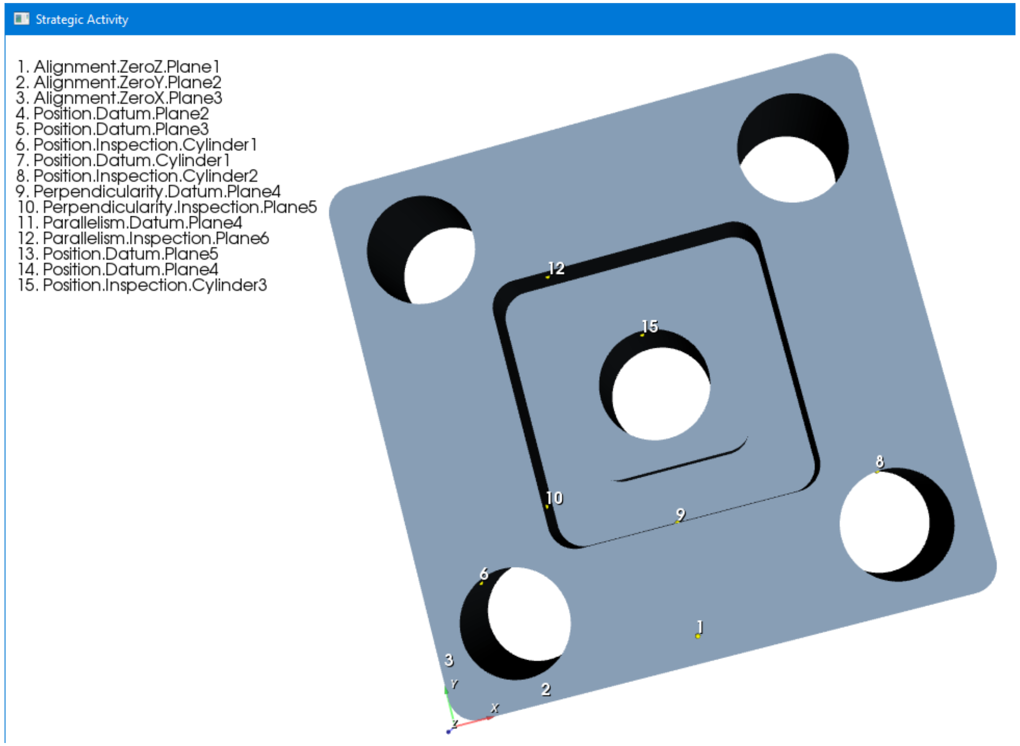


2. Inspection Plan + Strategic Planning Trajectory

Time	Activity	Geo/ID	X	Y	Z	Tool	otal point	I	J	K
37	ZeroZ	Plane1				Stylus1	4			
44	Point	1	46.05	4.808	30			0	0	1
47	Point	2	83.08	45.56	30			0	0	1
50	Point	3	8.007	46.02	30			0	0	1
53	Point	4	47.05	90.38	30			0	0	1
58	ZeroY	Plane2				Stylus1	4			
62	Point	5	14.89	0	20.02			0	-1	0
66	Point	6	85.11	0	25.02			0	-1	0
69	Point	7	91.04	0	4.003			0	-1	0
71	Point	8	15.88	0	1			0	-1	0
78	ZeroX	Plane3				Stylus1	4			
81	Point	9	0	9.945	26.03			-1	0	0
85	Point	10	0	84.12	24.02			-1	0	0
87	Point	11	0	84.12	6.005			-1	0	0
91	Point	12	0	16.87	4.003			-1	0	0
103	Tolerance	Position								
103	Datum	Plane2				Stylus1	4			
108	Datum	Plane3				Stylus1	4			
119	Inspection	Cylinder1				Stylus1	6			
124	Point	13	9.736	23.5	24.02			0.6	-1	0
126	Point	14	6.048	10.54	24.02			0.9	0.5	0
128	Point	15	24.96	14.08	26.03			-1	0.1	0
131	Point	16	10.54	6.048	2.001			0.5	0.9	0
133	Point	17	24.32	18.61	2.001			-0.9	-0	0
135	Point	18	10.54	23.95	2.001			0.5	-1	0
162	Tolerance	Position								
162	Datum	Cylinder1				Stylus1	6			
175	Inspection	Cylinder2				Stylus1	6			
179	Point	19	85	25	22.02			0	-1	0
181	Point	20	75.68	11.39	22.02			0.9	0.4	0
183	Point	21	93.95	10.54	23.02			-0.9	0.4	0
186	Point	22	77.61	8.263	7.006			0.8	0.6	0
189	Point	23	82.26	24.62	5.004			0.3	-1	0
192	Point	24	94.62	12.26	4.003			-1	0.2	0

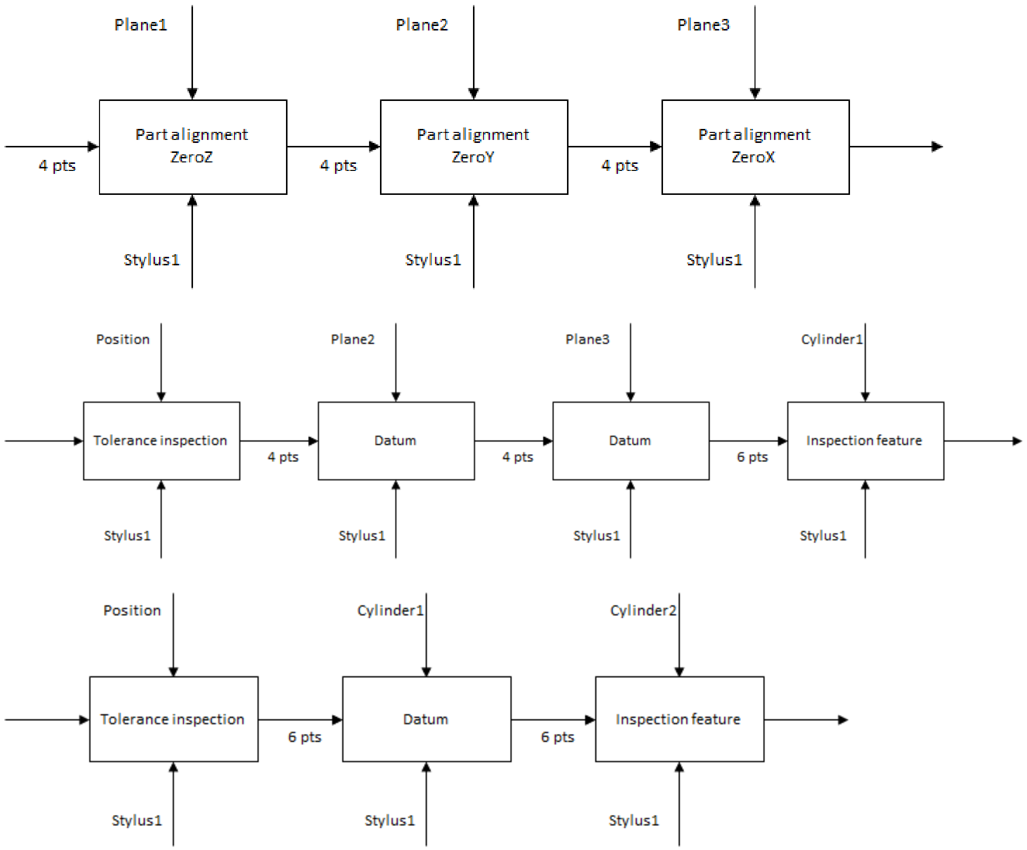


209	Tolerance	Perpendicularity								
227	Datum	Plane4				Stylus1	6			
241	Point	25	47.56	25	27.01			0	1	0
243	Point	26	34.88	25	27.01			0	1	0
245	Point	27	63.17	25	28.01			0	1	0
253	Point	28	70.52	25.03	18.99			-0.1	1	0
256	Point	29	45.61	25	19			0	1	0
259	Point	30	35.85	25	18			0	1	0
297	Inspection	Plane5				Stylus1	6			
301	Point	31	25	33.9	25.01			1	0	0
303	Point	32	25	66.1	24.01			1	0	0
305	Point	33	25	48.54	28.01			1	0	0
307	Point	34	25	38.78	19			1	0	0
309	Point	35	25	52.44	18			1	0	0
311	Point	36	25	61.22	19			1	0	0
358	Tolerance	Parallelism								
358	Datum	Plane4				Stylus1	6			
367	Inspection	Plane6				Stylus1	6			
371	Point	37	35.85	75	25.01			0	-1	0
373	Point	38	64.15	75	27.01			0	-1	0
375	Point	39	63.17	75	17			0	-1	0
378	Point	40	39.76	75	18			0	-1	0
380	Point	41	53.41	75	20			0	-1	0
381	Point	42	52.44	75	26.01			0	-1	0
416	Tolerance	Position								
416	Datum	Plane5				Stylus1	6			
424	Datum	Plane4				Stylus1	6			
437	Inspection	Cylinder3				Stylus1	6			
441	Point	43	50	60	25.02			-0	-1	0
443	Point	44	40.38	47.26	26.03			0.9	0.3	0
445	Point	45	59.83	51.84	26.03			-1	-0	0
447	Point	46	53.61	59.32	6.005			-0.3	-1	0
449	Point	47	40.17	48.16	5.004			1	0.2	0
451	Point	48	59.83	51.84	2.001			-1	-0	0

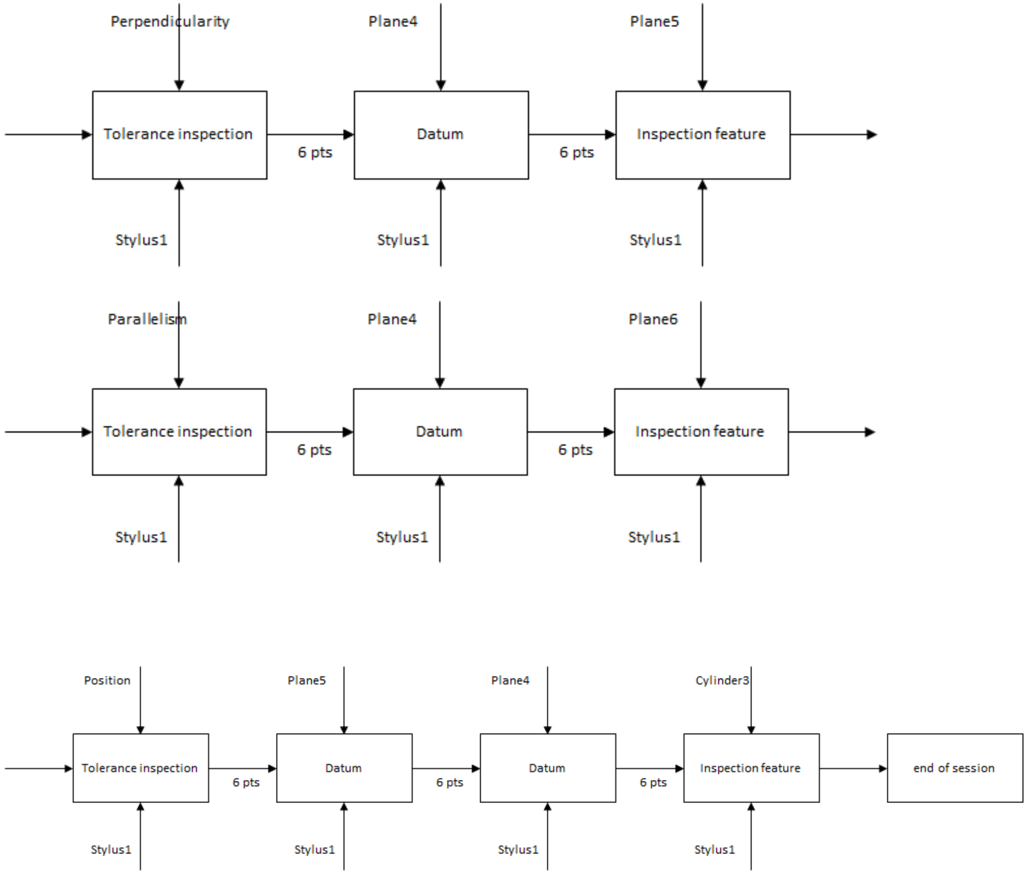


3. Inspection Plan + IDEF0 diagram

Time	Activity	Geo/ID	X	Y	Z	Tool	otal point	I	J	K
37	ZeroZ	Plane1				Stylus1	4			
44	Point	1	46.05	4.808	30			0	0	1
47	Point	2	83.08	45.56	30			0	0	1
50	Point	3	8.007	46.02	30			0	0	1
53	Point	4	47.05	90.38	30			0	0	1
58	ZeroY	Plane2				Stylus1	4			
62	Point	5	14.89	0	20.02			0	-1	0
66	Point	6	85.11	0	25.02			0	-1	0
69	Point	7	91.04	0	4.003			0	-1	0
71	Point	8	15.88	0	1			0	-1	0
78	ZeroX	Plane3				Stylus1	4			
81	Point	9	0	9.945	26.03			-1	0	0
85	Point	10	0	84.12	24.02			-1	0	0
87	Point	11	0	84.12	6.005			-1	0	0
91	Point	12	0	16.87	4.003			-1	0	0
103	Tolerance	Position								
103	Datum	Plane2				Stylus1	4			
108	Datum	Plane3				Stylus1	4			
119	Inspection	Cylinder1				Stylus1	6			
124	Point	13	9.736	23.5	24.02			0.6	-1	0
126	Point	14	6.048	10.54	24.02			0.9	0.5	0
128	Point	15	24.96	14.08	26.03			-1	0.1	0
131	Point	16	10.54	6.048	2.001			0.5	0.9	0
133	Point	17	24.32	18.61	2.001			-0.9	-0	0
135	Point	18	10.54	23.95	2.001			0.5	-1	0
162	Tolerance	Position								
162	Datum	Cylinder1				Stylus1	6			
175	Inspection	Cylinder2				Stylus1	6			
179	Point	19	85	25	22.02			0	-1	0
181	Point	20	75.68	11.39	22.02			0.9	0.4	0
183	Point	21	93.95	10.54	23.02			-0.9	0.4	0
186	Point	22	77.61	8.263	7.006			0.8	0.6	0
189	Point	23	82.26	24.62	5.004			0.3	-1	0
192	Point	24	94.62	12.26	4.003			-1	0.2	0



209	Tolerance	Perpendicularity								
227	Datum	Plane4				Stylus1	6			
241	Point	25	47.56	25	27.01			0	1	0
243	Point	26	34.88	25	27.01			0	1	0
245	Point	27	63.17	25	28.01			0	1	0
253	Point	28	70.52	25.03	18.99			-0.1	1	0
256	Point	29	45.61	25	19			0	1	0
259	Point	30	35.85	25	18			0	1	0
297	Inspection	Plane5				Stylus1	6			
301	Point	31	25	33.9	25.01			1	0	0
303	Point	32	25	66.1	24.01			1	0	0
305	Point	33	25	48.54	28.01			1	0	0
307	Point	34	25	38.78	19			1	0	0
309	Point	35	25	52.44	18			1	0	0
311	Point	36	25	61.22	19			1	0	0
358	Tolerance	Parallelism								
358	Datum	Plane4				Stylus1	6			
367	Inspection	Plane6				Stylus1	6			
371	Point	37	35.85	75	25.01			0	-1	0
373	Point	38	64.15	75	27.01			0	-1	0
375	Point	39	63.17	75	17			0	-1	0
378	Point	40	39.76	75	18			0	-1	0
380	Point	41	53.41	75	20			0	-1	0
381	Point	42	52.44	75	26.01			0	-1	0
416	Tolerance	Position								
416	Datum	Plane5				Stylus1	6			
424	Datum	Plane4				Stylus1	6			
437	Inspection	Cylinder3				Stylus1	6			
441	Point	43	50	60	25.02			-0	-1	0
443	Point	44	40.38	47.26	26.03			0.9	0.3	0
445	Point	45	59.83	51.84	26.03			-1	-0	0
447	Point	46	53.61	59.32	6.005			-0.3	-1	0
449	Point	47	40.17	48.16	5.004			1	0.2	0
451	Point	48	59.83	51.84	2.001			-1	-0	0

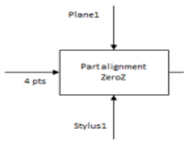
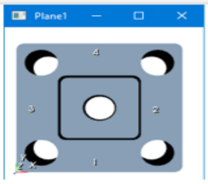
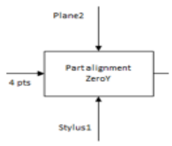
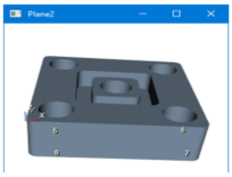
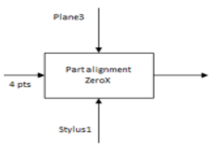
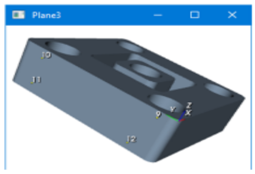
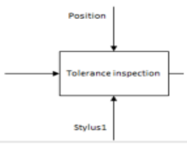
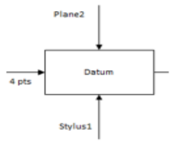
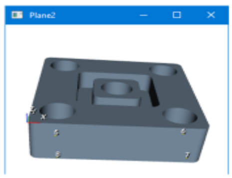
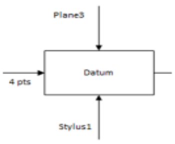
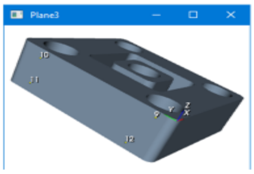
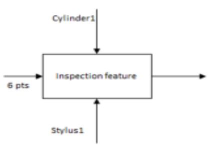
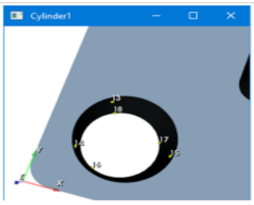


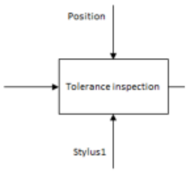
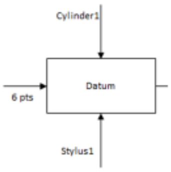
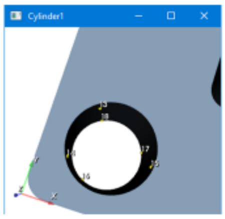
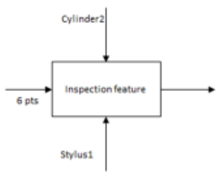
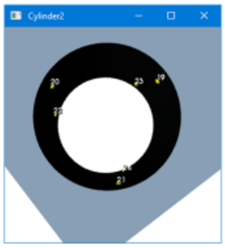
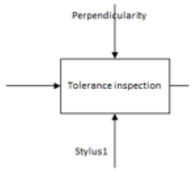
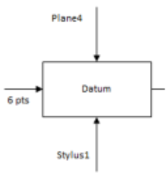
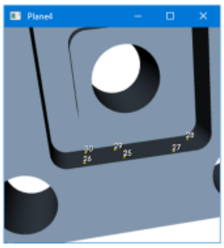
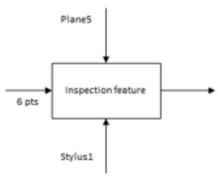
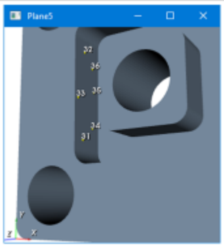
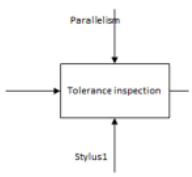
4. Annotated Video-clip

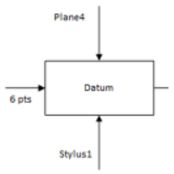
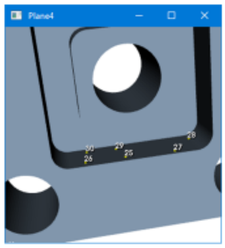
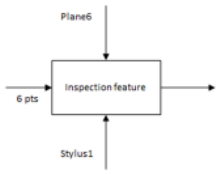
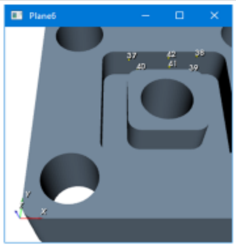
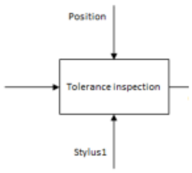
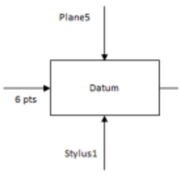
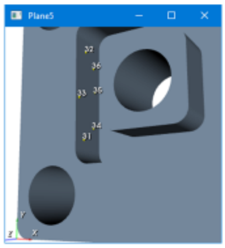
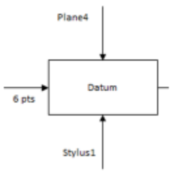
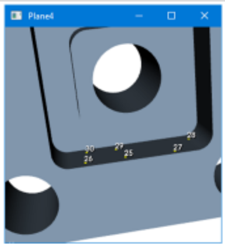
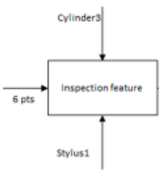
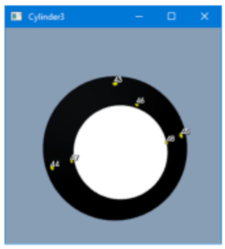
The full video can be found in the link https://youtu.be/4J8dEZUW6f8

Alternatively, it can be found on Youtube.com searching for the video: 'Knowledge format Annotated Video-clip Part 1'.

5. Storyboard

Time (Sec)	IDEF0	Text	Screenshot
37		Probe 4 points on Plane1 with Stylus1. Set as ZeroZ	
58		Probe 4 points on Plane2 with Stylus1. Set as ZeroY	
78		Probe 4 points on Plane3 with Stylus1. Set as ZeroX	
103		Inspection of Position tolerance	
103		Reuse Plane2. Set as Datum	
108		Reuse Plane3. Set as Datum	
119		Probe 6 points on Cylinder1 with Stylus1. Check Position of Cylinder1	

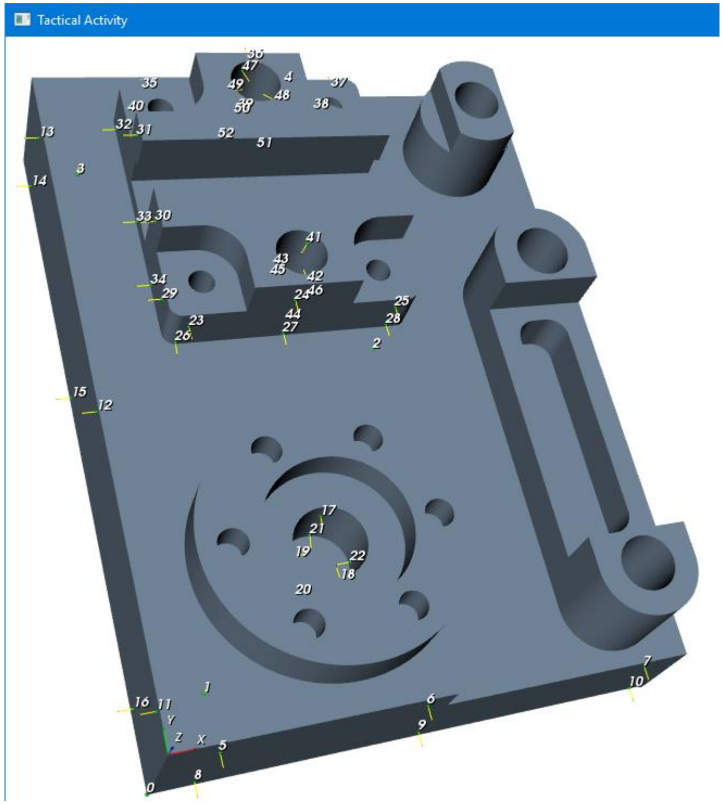
Time (Sec)	IDEF0	Text	Screenshot
162		Inspection of Position tolerance	
162		Reuse Cylinder1. Set as Datum	
175		Probe 6 points on Cylinder2 with Stylus1. Check Position of Cylinder2	
209		Inspection of Perpendicularity tolerance	
227		Probe 6 points on Plane4 with Stylus1. Set as Datum	
297		Probe 6 points on Plane5 with Stylus1. Check Perpendicularity of Plane5	
358		Inspection of Parallelism tolerance	

Time (Sec)	IDEF0	Text	Screenshot
358		Reuse Plane4. Set as Datum	
367		Probe 6 points on Plane6 with Stylus1. Check Parallelism of Plane6	
416		Inspection of Position tolerance	
416		Reuse Plane5. Set as Datum	
424		Reuse Plane4. Set as Datum	
437		Probe 6 points on Cylinder3 with Stylus1. Check Position of Cylinder3	

Appendix D.2 Knowledge representations – Part 2

1. Inspection Plan + Tactical Planning Trajectory

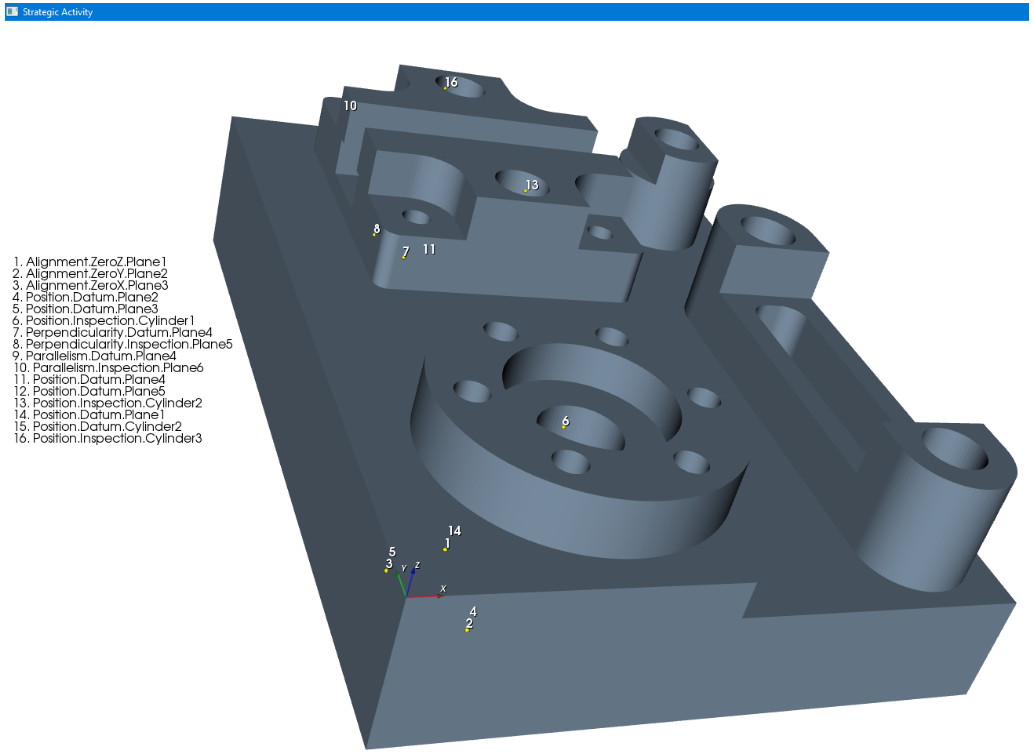
Time	Activity	Geo/ID	X	Y	Z	Tool	otal point	I	J	K
35	ZeroZ	Plane1				Stylus1	4			
40	Point	1	11.01	12.94	40			0	0	1
44	Point	2	78.08	103	40			0	0	1
47	Point	3	7.006	166.2	40			0	0	1
51	Point	4	74.07	198.1	40			0	0	1
69	ZeroY	Plane2				Stylus1	6			
76	Point	5	13.82	0	31.03			0	-1	0
80	Point	6	68.09	0	34.03			0	-1	0
88	Point	7	138.1	0	25.02			0	-1	0
94	Point	8	11.92	0	3.002			0	-1	0
97	Point	9	74.5	0	4.003			0	-1	0
112	Point	10	144	0	1			0	-1	0
117	ZeroX	Plane3				Stylus1	6			
120	Point	11	0	11.94	36.04			-1	0	0
123	Point	12	0	93.53	37.04			-1	0	0
127	Point	13	0	184.1	33.03			-1	0	0
130	Point	14	0	187.1	5.004			-1	0	0
132	Point	15	0	115.4	3.002			-1	0	0
134	Point	16	0	21.89	5.004			-1	0	0
168	Tolerance	Position								
168	Datum	Plane2				Stylus1	6			
172	Datum	Plane3				Stylus1	6			
177	Inspection	Cylinder1				Stylus1	6			
183	Point	17	50.98	54.95	39.01			-0	-1	0
186	Point	18	50.98	35.05	42.02			-0	1	0
188	Point	19	40.19	43.05	43.02			1	0.2	0
194	Point	20	42.93	37.93	27			0.7	0.7	0
199	Point	21	50.98	54.95	26			-0.1	-1	-0
201	Point	22	60	45	27			-1	-0	0



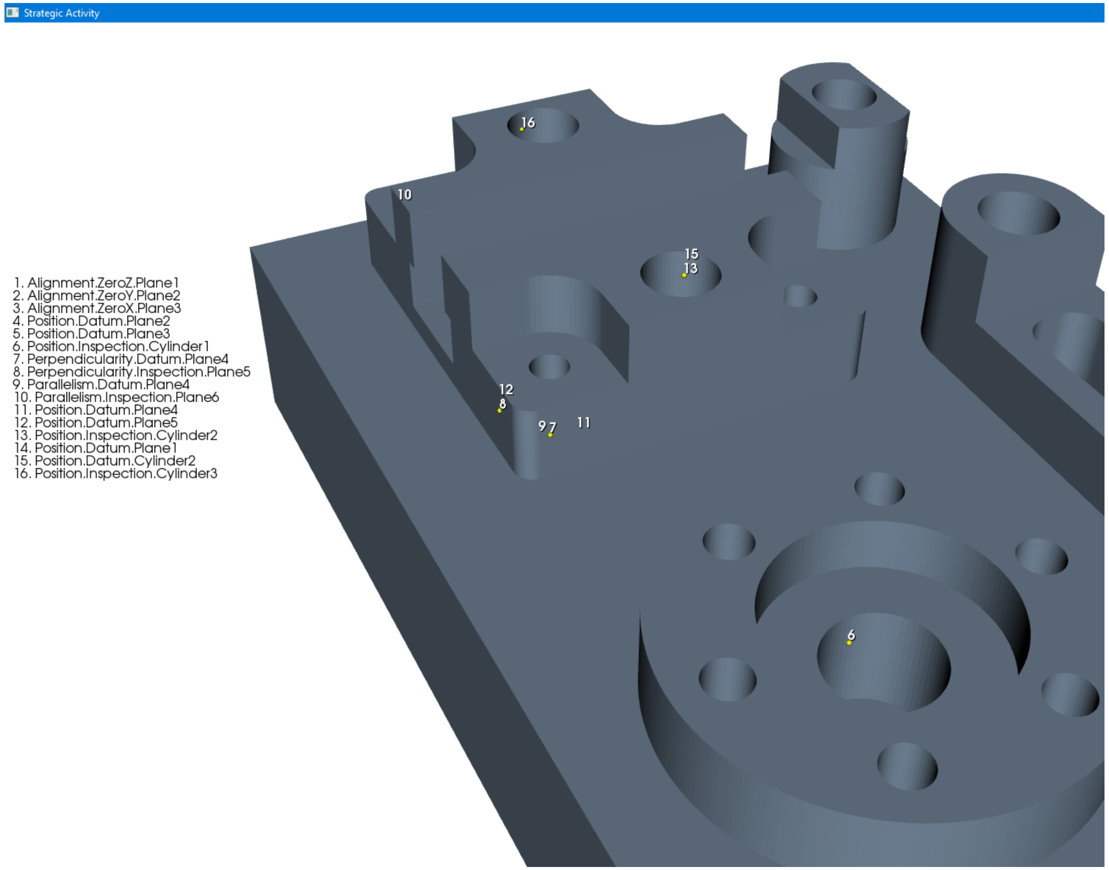
229	Tolerance	Perpendicularity								
265	Datum	Plane4				Stylus1	6			
270	Point	23	25.47	110	49.01			0	-1	0
273	Point	24	52.58	110	59.02			0	-1	0
275	Point	25	83.55	110	51.01			0	-1	0
278	Point	26	23.04	110	41			-0.1	-1	-0
280	Point	27	53.03	110	41			0	-1	0
282	Point	28	83.55	110	41			0	-1	0
292	Inspection	Plane5				Stylus1	6			
297	Point	29	20	118.4	50.01			-1	0	0
302	Point	30	20	135.8	61.02			-1	0	0
305	Point	31	20	162.3	63.02			-1	0	0
314	Point	32	20	180.5	41			-1	0	0
317	Point	33	20	149	41			-1	0	0
319	Point	34	20	128.3	41			-1	0	0
347	Tolerance	Parallelism								
347	Datum	Plane4				Stylus1	6			
353	Inspection	Plane6				Stylus1	6			
359	Point	35	27.44	187	51.01			0	1	0
362	Point	36	55.48	187	64.02			0	1	0
364	Point	37	83.55	187	51.01			0	1	0
366	Point	38	80.59	187	41			0	1	0
368	Point	39	56.97	187	41			0	1	0
373	Point	40	24.48	187	41			0	1	0
408	Tolerance	Position								
408	Datum	Plane4				Stylus1	6			
434	Datum	Plane5				Stylus1	6			
467	Inspection	Cylinder2				Stylus1	6			
472	Point	41	58.98	125.8	62.02			-0.6	-1	0
474	Point	42	55.84	113.1	63.02			-0.1	1	0
476	Point	43	48.05	119.2	63.02			1	0.1	0
478	Point	44	54.16	113.1	43			0.1	1	0
480	Point	45	52.52	126.5	45			0.4	-1	0
482	Point	46	62	120	43			-1	-0	0
516	Tolerance	Position								
516	Datum	Plane1				Stylus1	4			
523	Datum	Cylinder2				Stylus1	6			
531	Inspection	Cylinder3				Stylus1	6			
535	Point	47	53.32	183.8	63.02			0.3	-1	0
537	Point	48	60.24	172.4	64.02			-0.8	0.6	0
538	Point	49	48	177	63.02			1	0.1	0
542	Point	50	55	184	43			0.1	-1	0
545	Point	51	58.98	171.2	43			-0.6	0.8	0
547	Point	52	48.2	175.3	43			1	0.2	-0

2. Inspection Plan + Strategic Planning Trajectory

Time	Activity	Geo/ID	X	Y	Z	Tool	otal point	I	J	K
35	ZeroZ	Plane1				Stylus1	4			
40	Point	1	11.01	12.94	40			0	0	1
44	Point	2	78.08	103	40			0	0	1
47	Point	3	7.006	166.2	40			0	0	1
51	Point	4	74.07	198.1	40			0	0	1
69	ZeroY	Plane2				Stylus1	6			
76	Point	5	13.82	0	31.03			0	-1	0
80	Point	6	68.09	0	34.03			0	-1	0
88	Point	7	138.1	0	25.02			0	-1	0
94	Point	8	11.92	0	3.002			0	-1	0
97	Point	9	74.5	0	4.003			0	-1	0
112	Point	10	144	0	1			0	-1	0
117	ZeroX	Plane3				Stylus1	6			
120	Point	11	0	11.94	36.04			-1	0	0
123	Point	12	0	93.53	37.04			-1	0	0
127	Point	13	0	184.1	33.03			-1	0	0
130	Point	14	0	187.1	5.004			-1	0	0
132	Point	15	0	115.4	3.002			-1	0	0
134	Point	16	0	21.89	5.004			-1	0	0
168	Tolerance	Position								
168	Datum	Plane2				Stylus1	6			
172	Datum	Plane3				Stylus1	6			
177	Inspection	Cylinder1				Stylus1	6			
183	Point	17	50.98	54.95	39.01			-0	-1	0
186	Point	18	50.98	35.05	42.02			-0	1	0
188	Point	19	40.19	43.05	43.02			1	0.2	0
194	Point	20	42.93	37.93	27			0.7	0.7	0
199	Point	21	50.98	54.95	26			-0.1	-1	-0
201	Point	22	60	45	27			-1	-0	0

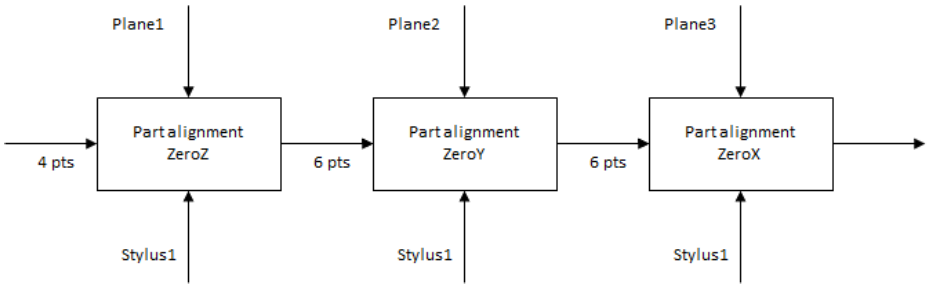


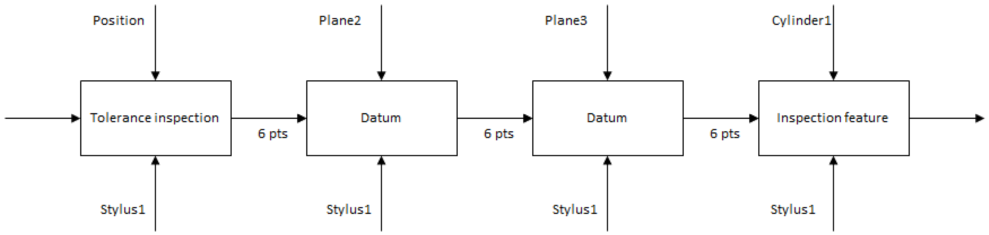
229	Tolerance	Perpendicularity								
265	Datum	Plane4				Stylus1	6			
270	Point	23	25.47	110	49.01			0	-1	0
273	Point	24	52.58	110	59.02			0	-1	0
275	Point	25	83.55	110	51.01			0	-1	0
278	Point	26	23.04	110	41			-0.1	-1	-0
280	Point	27	53.03	110	41			0	-1	0
282	Point	28	83.55	110	41			0	-1	0
292	Inspection	Plane5				Stylus1	6			
297	Point	29	20	118.4	50.01			-1	0	0
302	Point	30	20	135.8	61.02			-1	0	0
305	Point	31	20	162.3	63.02			-1	0	0
314	Point	32	20	180.5	41			-1	0	0
317	Point	33	20	149	41			-1	0	0
319	Point	34	20	128.3	41			-1	0	0
347	Tolerance	Parallelism								
347	Datum	Plane4				Stylus1	6			
353	Inspection	Plane6				Stylus1	6			
359	Point	35	27.44	187	51.01			0	1	0
362	Point	36	55.48	187	64.02			0	1	0
364	Point	37	83.55	187	51.01			0	1	0
366	Point	38	80.59	187	41			0	1	0
368	Point	39	56.97	187	41			0	1	0
373	Point	40	24.48	187	41			0	1	0
408	Tolerance	Position								
408	Datum	Plane4				Stylus1	6			
434	Datum	Plane5				Stylus1	6			
467	Inspection	Cylinder2				Stylus1	6			
472	Point	41	58.98	125.8	62.02			-0.6	-1	0
474	Point	42	55.84	113.1	63.02			-0.1	1	0
476	Point	43	48.05	119.2	63.02			1	0.1	0
478	Point	44	54.16	113.1	43			0.1	1	0
480	Point	45	52.52	126.5	45			0.4	-1	0
482	Point	46	62	120	43			-1	-0	0
516	Tolerance	Position								
516	Datum	Plane1				Stylus1	4			
523	Datum	Cylinder2				Stylus1	6			
531	Inspection	Cylinder3				Stylus1	6			
535	Point	47	53.32	183.8	63.02			0.3	-1	0
537	Point	48	60.24	172.4	64.02			-0.8	0.6	0
538	Point	49	48	177	63.02			1	0.1	0
542	Point	50	55	184	43			0.1	-1	0
545	Point	51	58.98	171.2	43			-0.6	0.8	0
547	Point	52	48.2	175.3	43			1	0.2	-0



3. Inspection Plan + IDEF0 diagram

Time	Activity	Geo/ID	X	Y	Z	Tool	otal point	I	J	K
35	ZeroZ	Plane1				Stylus1	4			
40	Point	1	11.01	12.94	40			0	0	1
44	Point	2	78.08	103	40			0	0	1
47	Point	3	7.006	166.2	40			0	0	1
51	Point	4	74.07	198.1	40			0	0	1
69	ZeroY	Plane2				Stylus1	6			
76	Point	5	13.82	0	31.03			0	-1	0
80	Point	6	68.09	0	34.03			0	-1	0
88	Point	7	138.1	0	25.02			0	-1	0
94	Point	8	11.92	0	3.002			0	-1	0
97	Point	9	74.5	0	4.003			0	-1	0
112	Point	10	144	0	1			0	-1	0
117	ZeroX	Plane3				Stylus1	6			
120	Point	11	0	11.94	36.04			-1	0	0
123	Point	12	0	93.53	37.04			-1	0	0
127	Point	13	0	184.1	33.03			-1	0	0
130	Point	14	0	187.1	5.004			-1	0	0
132	Point	15	0	115.4	3.002			-1	0	0
134	Point	16	0	21.89	5.004			-1	0	0
168	Tolerance	Position								
168	Datum	Plane2				Stylus1	6			
172	Datum	Plane3				Stylus1	6			
177	Inspection	Cylinder1				Stylus1	6			
183	Point	17	50.98	54.95	39.01			-0	-1	0
186	Point	18	50.98	35.05	42.02			-0	1	0
188	Point	19	40.19	43.05	43.02			1	0.2	0
194	Point	20	42.93	37.93	27			0.7	0.7	0
199	Point	21	50.98	54.95	26			-0.1	-1	-0
201	Point	22	60	45	27			-1	-0	0





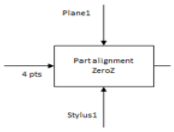
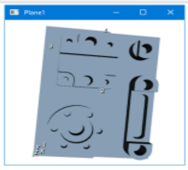
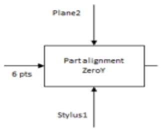
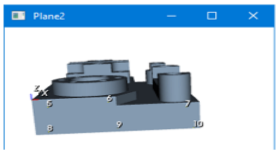
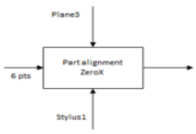
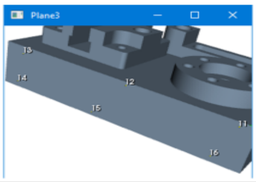
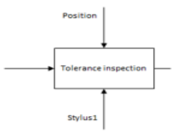
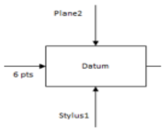
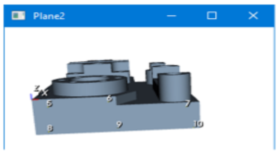
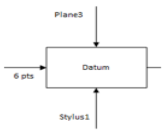
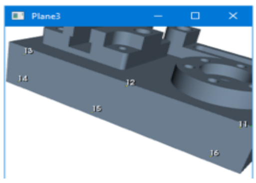
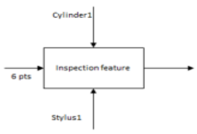
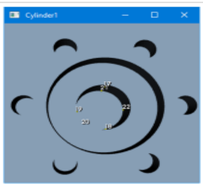
229	Tolerance	Perpendicularity								
265	Datum	Plane4				Stylus1	6			
270	Point	23	25.47	110	49.01			0	-1	0
273	Point	24	52.58	110	59.02			0	-1	0
275	Point	25	83.55	110	51.01			0	-1	0
278	Point	26	23.04	110	41			-0.1	-1	-0
280	Point	27	53.03	110	41			0	-1	0
282	Point	28	83.55	110	41			0	-1	0
292	Inspection	Plane5				Stylus1	6			
297	Point	29	20	118.4	50.01			-1	0	0
302	Point	30	20	135.8	61.02			-1	0	0
305	Point	31	20	162.3	63.02			-1	0	0
314	Point	32	20	180.5	41			-1	0	0
317	Point	33	20	149	41			-1	0	0
319	Point	34	20	128.3	41			-1	0	0
347	Tolerance	Parallelism								
347	Datum	Plane4				Stylus1	6			
353	Inspection	Plane6				Stylus1	6			
359	Point	35	27.44	187	51.01			0	1	0
362	Point	36	55.48	187	64.02			0	1	0
364	Point	37	83.55	187	51.01			0	1	0
366	Point	38	80.59	187	41			0	1	0
368	Point	39	56.97	187	41			0	1	0
373	Point	40	24.48	187	41			0	1	0
408	Tolerance	Position								
408	Datum	Plane4				Stylus1	6			
434	Datum	Plane5				Stylus1	6			
467	Inspection	Cylinder2				Stylus1	6			
472	Point	41	58.98	125.8	62.02			-0.6	-1	0
474	Point	42	55.84	113.1	63.02			-0.1	1	0
476	Point	43	48.05	119.2	63.02			1	0.1	0
478	Point	44	54.16	113.1	43			0.1	1	0
480	Point	45	52.52	126.5	45			0.4	-1	0
482	Point	46	62	120	43			-1	-0	0
516	Tolerance	Position								
516	Datum	Plane1				Stylus1	4			
523	Datum	Cylinder2				Stylus1	6			
531	Inspection	Cylinder3				Stylus1	6			
535	Point	47	53.32	183.8	63.02			0.3	-1	0
537	Point	48	60.24	172.4	64.02			-0.8	0.6	0
538	Point	49	48	177	63.02			1	0.1	0
542	Point	50	55	184	43			0.1	-1	0
545	Point	51	58.98	171.2	43			-0.6	0.8	0
547	Point	52	48.2	175.3	43			1	0.2	-0

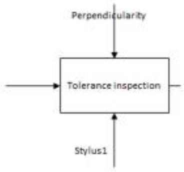
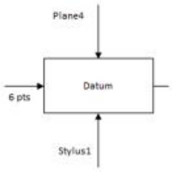
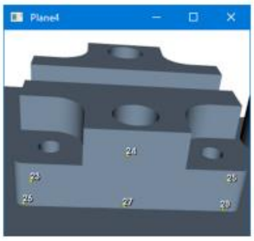
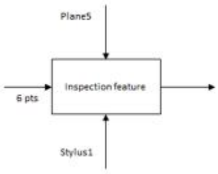
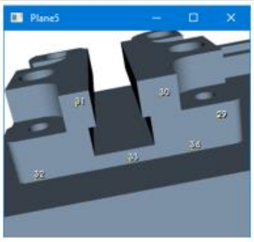
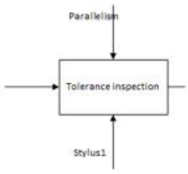
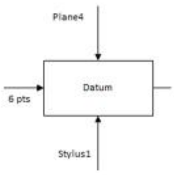
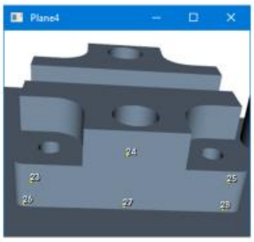
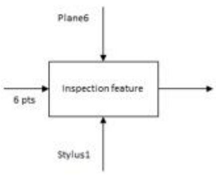
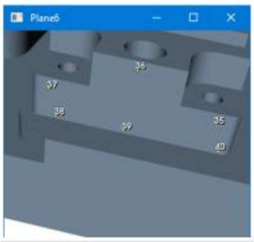
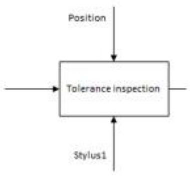
4. Annotated Video-clip

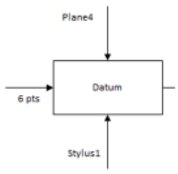
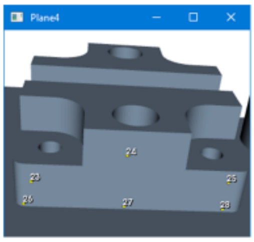
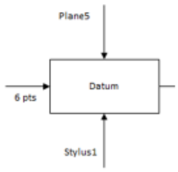
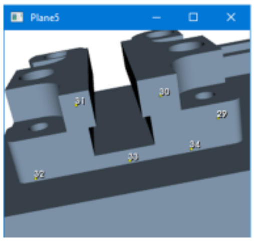
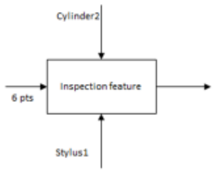
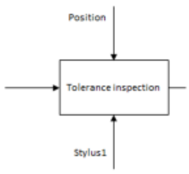
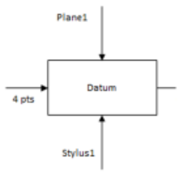
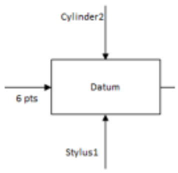
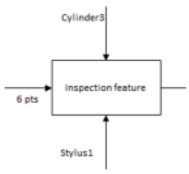
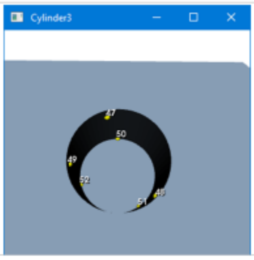
The full video can be found in the link https://youtu.be/eTFzNlb7NEg

Alternatively, it can be found on Youtube.com searching for the video: Knowledge format 'Annotated Video-clip Part 2'.

5. Storyboard

Time (Sec)	IDEF0	Text	Screenshot
35		Probe 4 points on Plane1 with Stylus1. Set as ZeroZ	
40		Probe 6 points on Plane2 with Stylus1. Set as ZeroY	
44		Probe 6 points on Plane3 with Stylus1. Set as ZeroX	
168		Inspection of Position tolerance	
168		Reuse Plane2. Set as Datum	
172		Reuse Plane3. Set as Datum	
177		Probe 6 points on Cylinder1 with Stylus1. Check Position of Cylinder1	

Time (Sec)	IDEF0	Text	Screenshot
229		Inspection of Perpendicularity tolerance	
265		Probe 6 points on Plane4 with Stylus1. Set as Datum	
292		Probe 6 points on Plane5 with Stylus1. Check Perpendicularity of Plane5	
347		Inspection of Parallelism tolerance	
347		Reuse Plane4. Set as Datum	
353		Probe 6 points on Plane6 with Stylus1. Check Parallelism of Plane6	
408		Inspection of Position tolerance	

Time (Sec)	IDEF0	Text	Screenshot
408		Reuse Plane4. Set as Datum	
434		Reuse Plane5. Set as Datum	
467		Probe 6 points on Cylinder2 with Stylus1. Check Position of Cylinder2	
516		Inspection of Position tolerance	
516		Reuse Plane1. Set as Datum	
523		Reuse Cylinder2. Set as Datum	
531		Probe 6 points on Cylinder3 with Stylus1. Check Position of Cylinder3	

Appendix D.3 Knowledge representations – Main experimental study questionnaire

The questionnaire employed in the final experimental study for evaluating the designed knowledge formats and outputs is presented below.

CMM inspection planning knowledge representation survey

This survey constitutes part of a research project about CMM inspection planning and investigation of different formats to represent a strategy for analysis and comparison, future reuse as well as training of novice CMM planners.

In this survey, five different representation formats of a strategy for measuring a component are shown. You will have to score each format in terms of: ease of understanding, usefulness and overall performance. The goal is to evaluate if the formats are readable and interpretable so that the strategy is understood in a way that you could use it either as a guide for measuring the same component, or for generating a measurement plan for a similar component.

*Required

1. **How many years of CMM programming experience do you have? ***
   Mark only one oval.

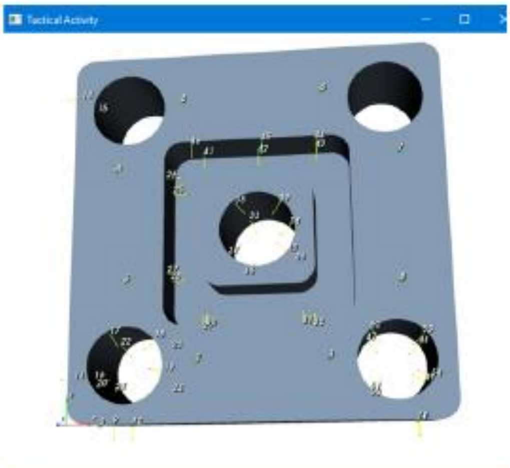
   - 0-2 years
   - 2-5 years
   - 5-10 years
   - over 10 years

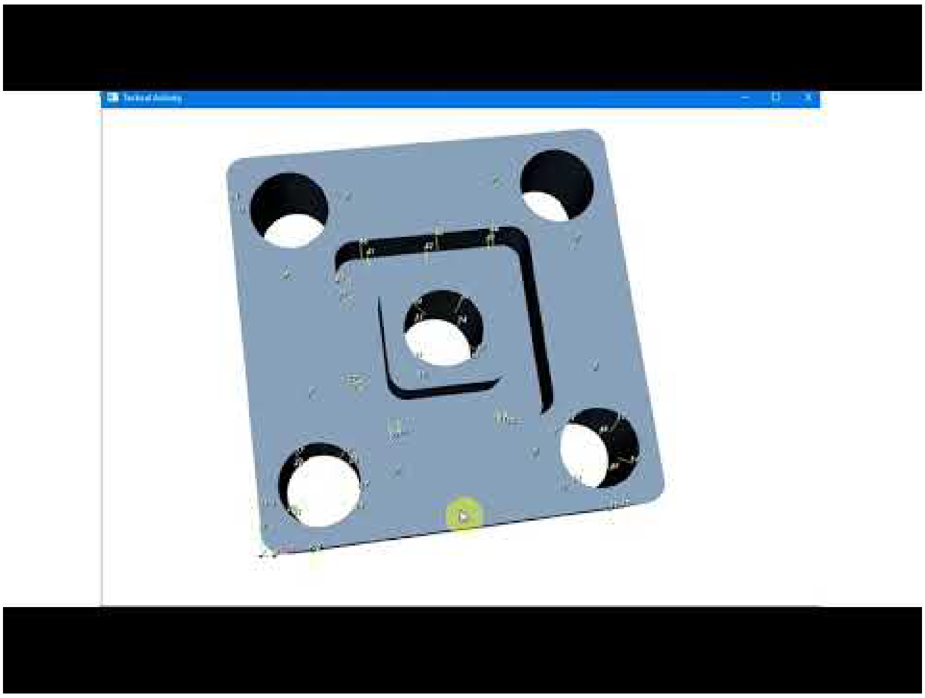
1. Inspection plan - tactical planning trajectory

In this format the followed strategy is displayed as a list of steps (inspection plan) in a chronological order with details on how each tolerance is checked, what geometrical features are used and the number of points with XYZ coordinates and associated normal vectors. The graph on the right shows the points (numbered as in the plan) along with the normal vectors, indicating the distribution of points over each feature.

To see the image in a larger size, please follow the link: https://imgur.com/fkeGHu1

Time	Activity	Geo/ID	X	Y	Z	Tool	Total pts	I	J	K
34	ZeroZ	Plane1				Stylus1	8			
37	Point	1	68.07	15.38	30			0	0	1
39	Point	2	34.03	15.38	30			0	0	1
41	Point	3	15.01	36.76	30			0	0	1
43	Point	4	12.01	67.47	30			0	0	1
45	Point	5	30.01	86.64	30			0	0	1
47	Point	6	68.07	87.5	30			0	0	1
48	Point	7	88.09	69.5	30			0	0	1
51	Point	8	87.09	34.67	30			0	0	1
57	ZeroY	Plane2				Stylus1	4			
61	Point	9	10.93	0	24.02			0	-1	0
64	Point	10	90.05	0	23.02			0	-1	0
66	Point	11	91.04	0	8.007			0	-1	0
68	Point	12	10.93	0	5.004			0	-1	0
80	ZeroX	Plane3				Stylus1	4			
83	Point	13	0	11.92	24.02			-1	0	0
86	Point	14	0	91.04	25.02			-1	0	0
88	Point	15	0	93.02	10.01			-1	0	0
91	Point	16	0	12.91	6.005			-1	0	0
114	Tolerance	Position								
114	Datum	Plane2				Stylus1	4			
118	Datum	Plane3				Stylus1	4			
123	Inspection	Cylinder1				Stylus1	8			
127	Point	17	9.736	23.5	25.02			0.56614	-0.825	0
128	Point	18	21.74	22.39	24.02			-0.7071	-0.70711	0
130	Point	19	24.83	13.16	26.03			-0.9734	0.228951	0
132	Point	20	6.498	9.736	25.02			0.87362	0.486604	0
134	Point	21	6.498	9.736	7.006			0.87362	0.486604	0
136	Point	22	8.263	22.39	8.007			0.63885	-0.76933	0
138	Point	23	22.98	21.03	8.007			-0.7693	-0.63885	0
140	Point	24	22.98	8.974	6.005			-0.825	0.565135	0
152	Tolerance	Position								
160	Datum	Plane4				Stylus1	4			
163	Point	25	25	64.15	17			1	0	0
166	Point	26	25	66.1	26.01			1	0	0
169	Point	27	25	39.76	24.01			1	0	0
170	Point	28	25	38.78	19			1	0	0
175	Datum	Plane5				Stylus1	4			
178	Point	29	33.9	25	19			0	1	0
179	Point	30	35.86	25	26.01			0	1	0
182	Point	31	61.22	25	24.01			0	1	0
183	Point	32	64.15	25	19			0	1	0
189	Inspection	Cylinder2				Stylus1	8			
192	Point	33	45.54	58.96	4.003			0.40392	-0.91479	0
194	Point	34	57.39	56.74	5.004			-0.7693	-0.63885	0
195	Point	35	58.95	45.54	8.007			-0.8736	0.486606	0
197	Point	36	43.97	42.02	7.006			0.63885	0.769335	0
199	Point	37	42.02	43.97	26.03			0.76934	0.638845	0
201	Point	38	43.97	57.98	26.03			0.63885	-0.76934	0
203	Point	39	56.03	57.98	26.03			-0.5651	-0.825	0
204	Point	40	57.98	43.97	27.03			-0.7693	0.638845	0
239	Tolerance	Perpendicularity								
239	Datum	Plane5				Stylus1	4			
255	Inspection	Plane4				Stylus1	4			
284	Tolerance	Parallelism								
284	Datum	Plane5				Stylus1	4			
291	Inspection	Plane6				Stylus1	6			
295	Point	41	33.9	75	18			0	-1	0
297	Point	42	49.51	75	18			0	-1	0
298	Point	43	66.1	75	20			0	-1	0
300	Point	44	66.1	75	27.01			0	-1	0
301	Point	45	61.46	75	28.01			0	-1	0
303	Point	46	31.95	75	27.01			0	-1	0
335	Tolerance	Position								
335	Datum	Cylinder1				Stylus1	8			
345	Inspection	Cylinder3				Stylus1	8			
350	Point	47	78.26	22.39	3.002			0.63885	-0.76933	0
351	Point	48	92.98	21.03	4.003			-0.7693	-0.63885	0
353	Point	49	93.95	10.54	5.004			-0.8736	0.486599	0
354	Point	50	78.97	7.02	3.002			0.63885	0.769334	0
356	Point	51	78.26	7.61	25.02			0.7071	0.707109	0
357	Point	52	78.97	22.98	26.03			0.56514	-0.825	0
359	Point	53	92.39	21.74	25.02			-0.7071	-0.70711	0
361	Point	54	93.96	10.64	26.02			-0.9148	0.403924	0





http://youtube.com/watch?v=WX6dVv6gvSc

In this video, the above digital model is shown in different angles, allowing the participant to have a better view of what is displayed. To watch the video in a larger window please follow the link: https://www.youtube.com/watch?v=WX6dVv6gvSc

2. **On a scale from 1 (lowest) to 5 (highest), please rate the format for each of the following aspects.** *

Mark only one oval per row.

	1	2	3	4	5
Ease of understanding	◯	◯	◯	◯	◯
Usefulness	◯	◯	◯	◯	◯
Overall	◯	◯	◯	◯	◯

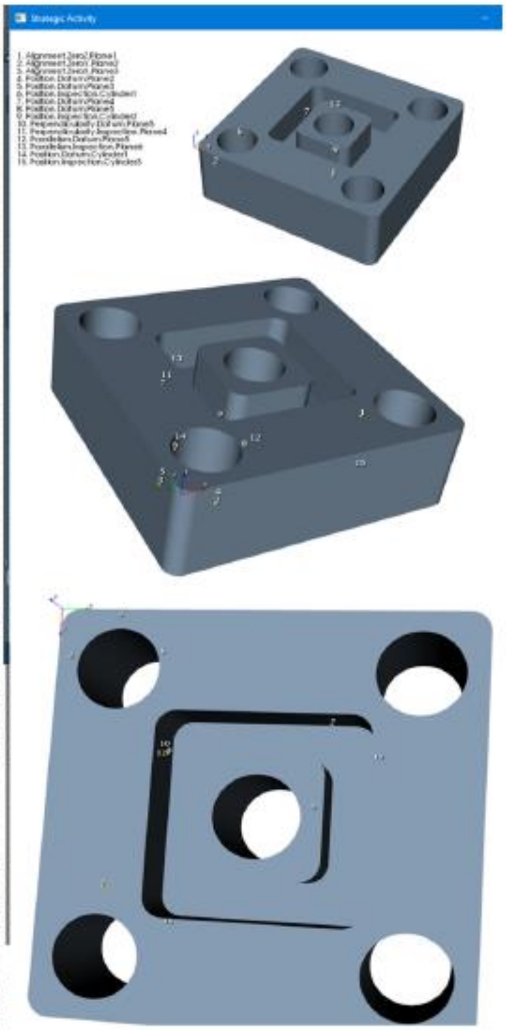
3. **Please leave your comments for this format.** *

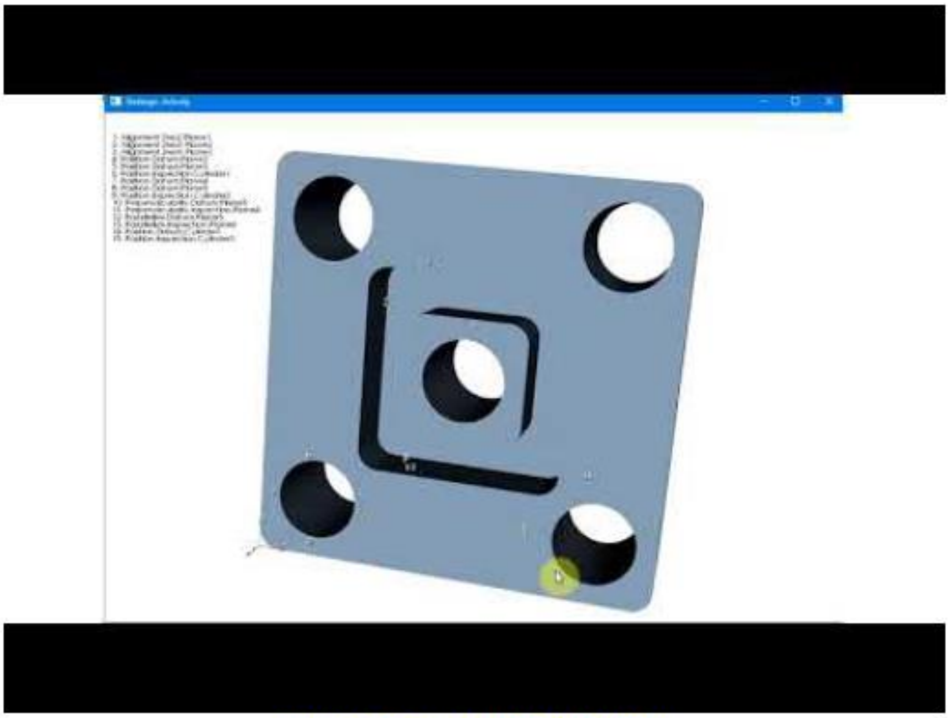
2. Inspection plan - strategic planning trajectory

In the next format, the followed strategy is displayed as a list of steps (inspection plan) in a chronological order as previously. The graph on the right shows the strategy planned in steps, numbered as a list (shown on the top left corner) along with the related features of the component.

To see the image in a larger size, please follow the link: https://imgur.com/Lk5wjtO

Time	Activity	Geo/ID	X	Y	Z	Tool	Total pts	I	J	K
34	ZeroZ	Plane1				Stylus1	8			
37	Point	1	68.07	15.38	30			0	0	1
39	Point	2	34.03	15.38	30			0	0	1
41	Point	3	15.01	36.76	30			0	0	1
43	Point	4	12.01	67.47	30			0	0	1
45	Point	5	30.01	86.54	30			0	0	1
47	Point	6	68.07	87.5	30			0	0	1
48	Point	7	88.09	69.5	30			0	0	1
51	Point	8	87.09	34.67	30			0	0	1
57	ZeroY	Plane2				Stylus1	4			
61	Point	9	10.93	0	24.02			0	-1	0
64	Point	10	90.05	0	23.02			0	-1	0
66	Point	11	91.04	0	8.007			0	-1	0
68	Point	12	10.93	0	5.004			0	-1	0
80	ZeroX	Plane3				Stylus1	4			
83	Point	13	0	11.92	24.02			-1	0	0
86	Point	14	0	91.04	25.02			-1	0	0
88	Point	15	0	93.02	10.01			-1	0	0
91	Point	16	0	12.91	6.005			-1	0	0
114	Tolerance	Position								
114	Datum	Plane2				Stylus1	4			
118	Datum	Plane3				Stylus1	4			
123	Inspection	Cylinder1				Stylus1	8			
127	Point	17	9.736	23.5	25.02			0.56614	-0.825	0
128	Point	18	21.74	22.39	24.02			-0.7071	-0.70711	0
130	Point	19	24.83	13.16	26.03			-0.9734	0.228951	0
132	Point	20	6.498	9.736	25.02			0.87362	0.486604	0
134	Point	21	6.498	9.736	7.006			0.87362	0.486604	0
136	Point	22	8.263	22.39	8.007			0.63885	-0.76933	0
138	Point	23	22.98	21.03	8.007			-0.7693	-0.63885	0
140	Point	24	22.98	8.974	6.005			-0.825	0.565135	0
152	Tolerance	Position								
160	Datum	Plane4				Stylus1	4			
163	Point	25	25	64.15	17			1	0	0
166	Point	26	25	66.1	26.01			1	0	0
169	Point	27	25	39.76	24.01			1	0	0
170	Point	28	25	38.78	19			1	0	0
175	Datum	Plane5				Stylus1	4			
178	Point	29	33.9	25	19			0	1	0
179	Point	30	35.86	25	25.01			0	1	0
182	Point	31	61.22	25	24.01			0	1	0
183	Point	32	64.15	25	19			0	1	0
189	Inspection	Cylinder2				Stylus1	8			
192	Point	33	45.54	68.96	4.003			0.40392	-0.91479	0
194	Point	34	57.39	56.74	5.004			-0.7693	-0.63885	0
195	Point	35	58.95	45.54	8.007			-0.8736	0.486606	0
197	Point	36	43.97	42.02	7.006			0.63885	0.769335	0
199	Point	37	42.02	43.97	26.03			0.76934	0.638845	0
201	Point	38	43.97	57.98	26.03			0.63885	-0.76934	0
203	Point	39	56.03	57.98	26.03			-0.6651	-0.825	0
204	Point	40	57.98	43.97	27.03			-0.7693	0.638845	0
239	Tolerance	Perpendicularity								
239	Datum	Plane5				Stylus1	4			
255	Inspection	Plane4				Stylus1	4			
284	Tolerance	Parallelism								
284	Datum	Plane5				Stylus1	4			
291	Inspection	Plane6				Stylus1	6			
295	Point	41	33.9	75	18			0	-1	0
297	Point	42	49.51	75	18			0	-1	0
298	Point	43	66.1	75	20			0	-1	0
300	Point	44	66.1	75	27.01			0	-1	0
301	Point	45	51.46	75	28.01			0	-1	0
303	Point	46	31.96	75	27.01			0	-1	0
335	Tolerance	Position								
335	Datum	Cylinder1				Stylus1	8			
345	Inspection	Cylinder3				Stylus1	8			
350	Point	47	78.26	22.39	3.002			0.63885	-0.76933	0
351	Point	48	92.98	21.03	4.003			-0.7693	-0.63885	0
353	Point	49	93.95	10.54	5.004			-0.8736	0.486599	0
354	Point	50	78.97	7.02	3.002			0.63885	0.769334	0
356	Point	51	78.26	7.61	25.02			0.7071	0.707109	0
357	Point	52	78.97	22.98	26.03			0.56514	-0.825	0
359	Point	53	92.39	21.74	25.02			-0.7071	-0.70711	0
361	Point	54	93.95	10.54	25.02			-0.9148	0.403924	0





http://youtube.com/watch?v=AcJT97r9e8Y

In this video the above digital format is shown in different angles, allowing the participant to have a better view of what is displayed. To watch the video in a larger window please follow the link: https://www.youtube.com/watch?v=AcJT97r9e8Y

4. **On a scale from 1 (lowest) to 5 (highest), please rate the format for each of the following aspects.** *

Mark only one oval per row.

	1	2	3	4	5
Ease of understanding					
Usefulness					
Overall					

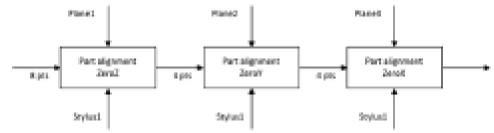
5. **Please leave your comments for this format.** *

3. Inspection plan - IDEF0 diagram

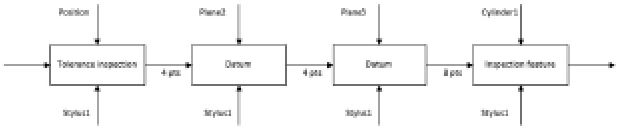
In the following format, the followed strategy is displayed as a list of steps (inspection plan) in a chronological order as before. The graphs on the right represent the steps followed, showing the strategy in a procedural manner. Each tolerance is shown in a separate diagram.

To see the image in larger size, please follow the link: https://imgur.com/vDSLM1h

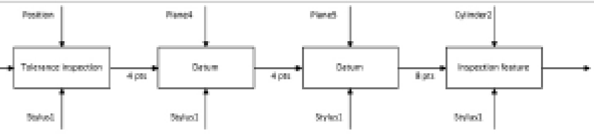
Time	Activity	Geo/ID	X	Y	Z	Tool	Total pts	I	J	K
34	Zero2	Plane1				Stylus1	8			
37	Point	1	68.07	15.38	30			0	0	1
39	Point	2	34.03	15.38	30			0	0	1
41	Point	3	15.01	36.76	30			0	0	1
43	Point	4	12.01	67.47	30			0	0	1
45	Point	5	30.01	86.54	30			0	0	1
47	Point	6	69.07	87.5	30			0	0	1
49	Point	7	88.09	68.5	30			0	0	1
51	Point	8	87.09	34.67	30			0	0	1
57	ZeroY	Plane2				Stylus1	4			
61	Point	9	10.93	0	24.02			0	-1	0
64	Point	10	90.05	0	23.03			0	-1	0
66	Point	11	91.04	0	8.087			0	-1	0
68	Point	12	10.93	0	5.084			0	-1	0
80	ZeroX	Plane3				Stylus1	4			
83	Point	13	0	11.92	24.02			-1	0	0
86	Point	14	0	91.04	25.02			-1	0	0
88	Point	15	0	93.02	10.01			-1	0	0
91	Point	16	0	12.91	6.085			-1	0	0



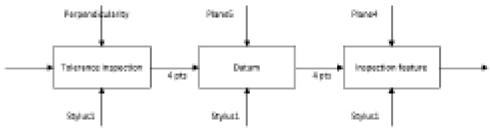
Time	Activity	Geo/ID	X	Y	Z	Tool	Total pts	I	J	K
114	Tolerance	Position								
114	Datum	Plane2				Stylus1	4			
118	Datum	Plane3				Stylus1	4			
123	Inspection	Cylinder1				Stylus1	8			
127	Point	17	8.736	23.5	25.02			0.5651	-0.825	0
128	Point	18	21.74	22.39	24.02			-0.707	-0.70711	0
130	Point	19	24.83	13.16	26.03			-0.973	0.22985	0
132	Point	20	6.496	9.736	25.02			0.8736	0.4866	0
134	Point	21	6.496	9.736	7.086			0.8736	0.4866	0
136	Point	22	8.263	22.39	8.007			0.6388	-0.76933	0
138	Point	23	22.98	21.03	8.007			-0.769	-0.63885	0
140	Point	24	22.98	8.874	6.085			-0.825	0.56514	0



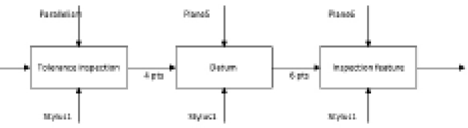
Time	Activity	Geo/ID	X	Y	Z	Tool	Total pts	I	J	K
138	Point	23	22.98	21.03	8.007			-0.769	-0.63885	0
140	Point	24	22.98	8.874	6.085			-0.825	0.56514	0
152	Tolerance	Position								
160	Datum	Plane4				Stylus1	4			
163	Point	25	25	64.15	17			1	0	0
166	Point	26	25	66.1	26.01			1	0	0
169	Point	27	25	38.76	24.01			1	0	0
170	Point	28	25	38.76	19			1	0	0
175	Datum	Plane5				Stylus1	4			
178	Point	29	33.9	25	19			0	1	0
179	Point	30	35.85	25	25.01			0	1	0
182	Point	31	61.22	25	24.01			0	1	0
183	Point	32	64.15	25	19			0	1	0
189	Inspection	Cylinder2				Stylus1	8			
192	Point	33	45.54	58.95	4.083			0.4039	-0.91479	0
194	Point	34	57.39	56.74	5.084			-0.769	-0.63885	0
195	Point	35	58.95	45.54	6.087			-0.874	0.48661	0
197	Point	36	43.97	42.02	7.086			0.6388	0.76934	0
199	Point	37	42.02	43.97	26.03			0.7693	0.63885	0
201	Point	38	43.97	57.98	26.03			0.6388	-0.76934	0
203	Point	39	56.03	57.98	26.03			-0.565	-0.825	0
204	Point	40	57.98	43.97	27.03			-0.769	0.63885	0



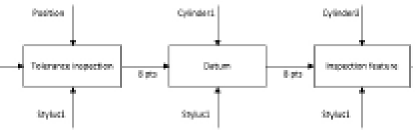
Time	Activity	Geo/ID	X	Y	Z	Tool	Total pts	I	J	K
199	Point	37	42.02	43.97	26.03			0.7693	0.63885	0
201	Point	38	43.97	57.98	26.03			0.6388	-0.76934	0
239	Tolerance	Perpendicularity								
239	Datum	Plane5				Stylus1	4			
255	Inspection	Plane4				Stylus1	4			



Time	Activity	Geo/ID	X	Y	Z	Tool	Total pts	I	J	K
284	Tolerance	Parallelism								
284	Datum	Plane5				Stylus1	4			
291	Inspection	Plane6				Stylus1	6			
295	Point	41	33.9	75	18			0	-1	0
297	Point	42	49.51	75	18			0	-1	0
298	Point	43	66.1	75	20			0	-1	0
300	Point	44	66.1	75	27.01			0	-1	0
301	Point	45	51.46	75	28.01			0	-1	0
303	Point	46	31.95	75	27.01			0	-1	0



Time	Activity	Geo/ID	X	Y	Z	Tool	Total pts	I	J	K
335	Tolerance	Position								
335	Datum	Cylinder1				Stylus1	8			
345	Inspection	Cylinder3				Stylus1	8			
350	Point	47	78.26	22.39	3.002			0.6388	-0.76933	0
351	Point	48	92.88	21.03	4.003			-0.768	-0.63885	0
353	Point	49	93.85	10.54	5.004			-0.874	0.4866	0
354	Point	50	78.87	7.82	3.002			0.6388	0.76933	0
356	Point	51	78.26	7.81	25.02			0.7071	0.70711	0
357	Point	52	78.87	22.98	26.03			0.5651	-0.825	0
359	Point	53	92.39	21.74	25.02			-0.707	-0.70711	0
361	Point	54	93.85	10.54	25.02			-0.915	0.40382	0



6. **On a scale from 1 (lowest) to 5 (highest), please rate the format for each of the following aspects.** *

Mark only one oval per row.

	1	2	3	4	5
Ease of understanding	◯	◯	◯	◯	◯
Usefulness	◯	◯	◯	◯	◯
Overall	◯	◯	◯	◯	◯

7. **Please leave your comments for this format.** *

4. Annotated video clip

In the next format, the video shows the whole strategy followed for measuring the component's tolerances. At each step, captions-annotations along with related details are displayed.

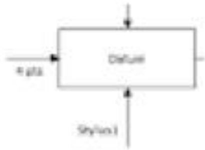
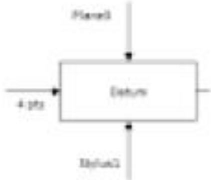
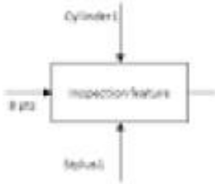
To watch the video in a larger window please follow the link: https://www.youtube.com/watch?v=0A-I2M8mddg

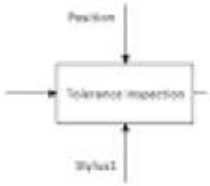
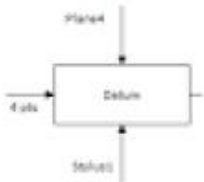
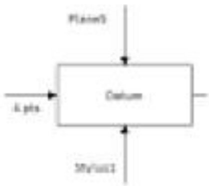
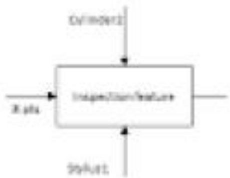
http://youtube.com/watch?v=0A-I2M8mddg

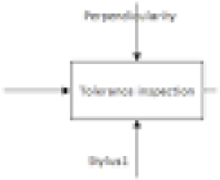
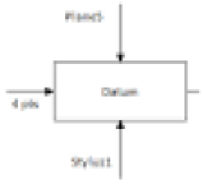
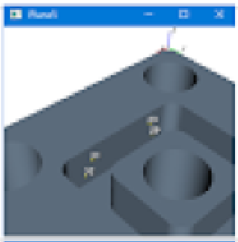
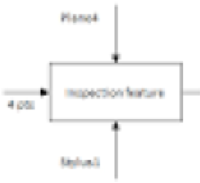
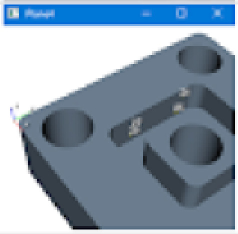
8. **On a scale from 1 (lowest) to 5 (highest), please rate the format for each of the following aspects.** *

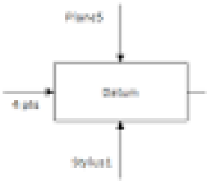
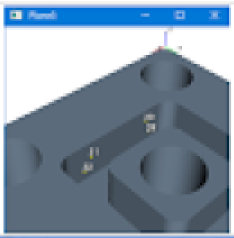
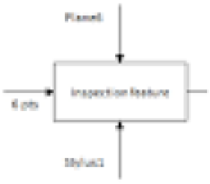
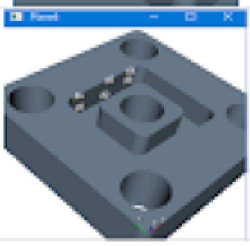
Mark only one oval per row.

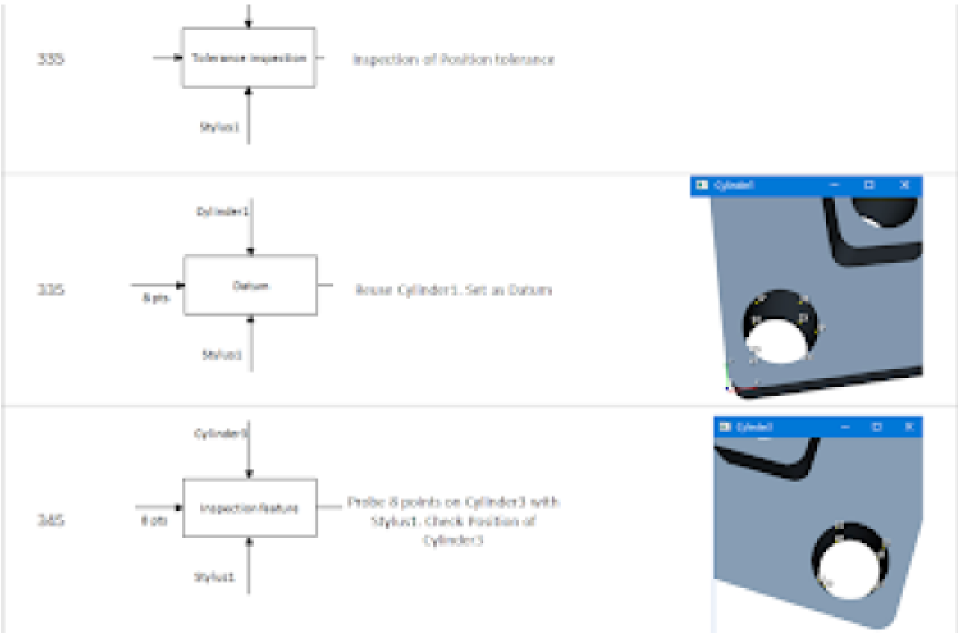
	1	2	3	4	5
Ease of understanding	◯	◯	◯	◯	◯
Usefulness	◯	◯	◯	◯	◯
Overall	◯	◯	◯	◯	◯

114		Reuse Plane2. Set as Datum	
118		Reuse Plane3. Set as Datum	
123		Probe 8 points on Cylinder1 with Stylus1. Check Position of Cylinder1	

Time	IDEF0	Text	Screenshot
152		Inspection of Position tolerance	
160		Probe 4 points on Plane4 with Stylus1. Set as Datum	
175		Probe 4 points on Plane5 with Stylus1. Set as Datum	
189		Probe 8 points on Cylinder2 with Stylus1. Check Position of Cylinder2	

			
239		Inspection of Perpendicularity tolerance	
239		Reuse Plane5. Set as Datum	
255		Reuse Plane4 for inspection. Check Perpendicularity of Plane4	

Time	IDEF0	Text	Screenshot
284		Inspection of Parallelism tolerance	
284		Reuse Plane5. Set as Datum	
291		Probe 6 points on Plane6 with Stylus1. Check Parallelism of Plane6	
			



10. **On a scale from 1 (lowest) to 5 (highest), please rate the format for each of the following aspects.** *

Mark only one oval per row.

	1	2	3	4	5
Ease of understanding					
Usefulness					
Overall					

11. **Please leave your comments for this format.** *

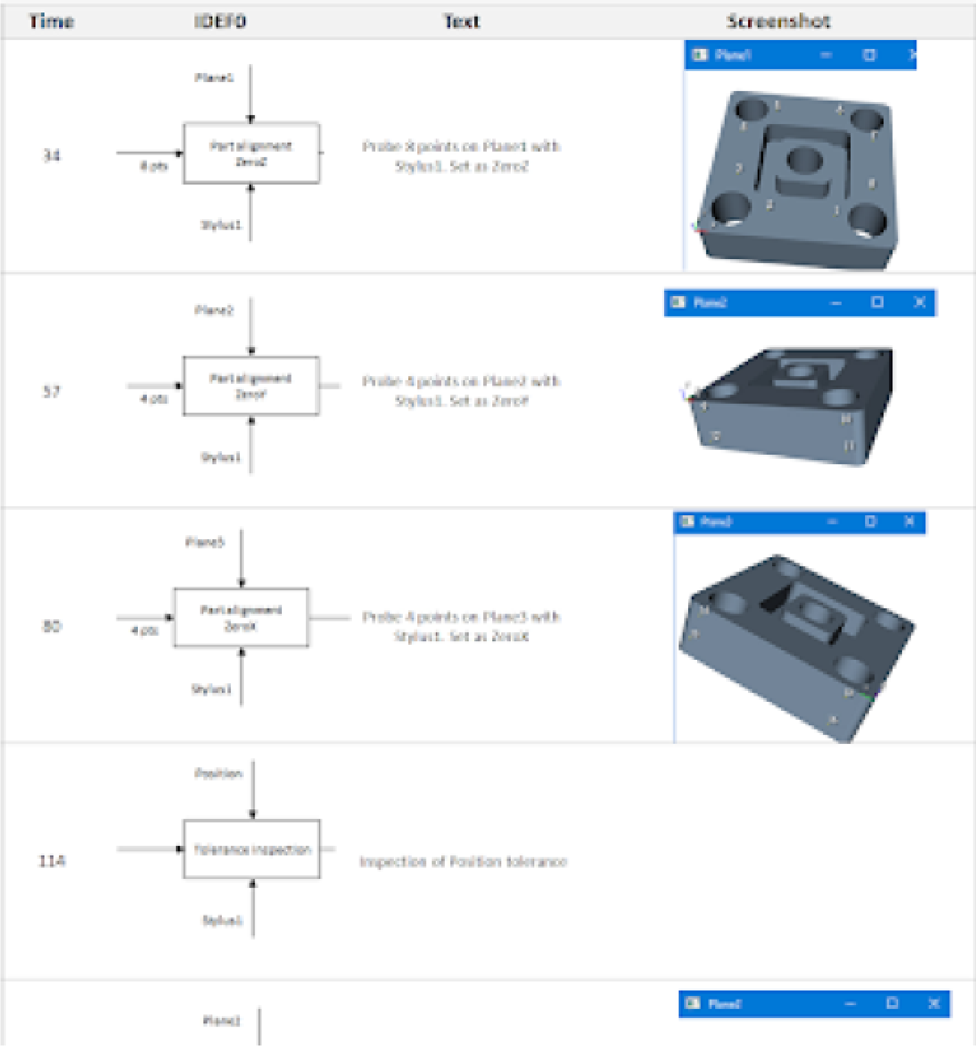
12. **Below you can leave your comments for any aspect of this survey.**

9. Please leave your comments for this format. *

5. Storyboard

The last format shows the measurement strategy in a chronological order as a combination of: IDEF0 diagrams, plain text description and screenshots of the associated features with the numbered points on it.

To see the image in a large size, please follow the link: https://imgur.com/hoMT7k9



Appendix E Raw data

All data related to this research and thesis can be found in the link:

https://heriotwatt-my.sharepoint.com/:x:/g/personal/da178_hw_ac_uk/EVFhN6a29axLpeD5cmdLSzkBHOx4XWIThzAHrVCej1PEmg?e=m7T9kc

Below relevant tables referenced within the thesis are following.

Table E. 1 Raw data for SUS questionnaire – usability study (Trial Novice planners - Set 1)

Experience	Participant	q1	q2	q3	q4	q5	q6	q7	q8	q9	q10	SUS Score
Trial Nov.	p1	4	2	4	3	5	1	4	4	3	2	**70**
Trial Nov.	p2	2	2	4	2	4	1	3	2	4	3	**67.5**
Trial Nov.	p3	4	2	5	1	5	2	5	2	5	1	**90**
Trial Nov.	p4	4	2	3	3	4	2	3	2	4	4	**62.5**
Trial Nov.	p5	3	2	4	1	4	2	5	4	3	1	**72.5**
Trial Nov.	p6	5	1	5	3	5	2	5	1	5	2	**90**
Trial Nov.	p7	3	3	3	1	3	1	3	3	3	1	**65**
Trial Nov.	p8	5	1	4	1	4	1	5	1	5	2	**92.5**
Trial Nov.	p9	4	3	3	2	4	2	4	1	4	2	**72.5**
Trial Nov.	p10	4	4	4	2	5	3	5	2	3	3	**67.5**
										Average		75
										SD		10.78

Table E. 2 Raw data for SUS questionnaire – usability study (Online Experienced planners - Set 1)

Experience	Participant	q1	q2	q3	q4	q5	q6	q7	q8	q9	q10	SUS Score
Online Exp.	p1	5	2	5	1	4	1	5	1	5	1	**95.0**
Online Exp.	p2	5	2	3	1	3	3	1	3	5	1	**67.5**
Online Sen.	p3	2	2	2	1	2	2	3	2	2	1	**57.5**
Online Exp.	p4	3	1	5	1	3	3	5	1	2	1	**77.5**
Online Exp.	p5	5	1	5	1	5	1	5	1	5	1	**100.0**
Online Exp.	p6	3	4	3	1	3	2	3	3	4	1	**62.5**
Online Exp.	p7	3	2	4	2	4	3	4	2	4	2	**70.0**
Online Int.	p8	3	2	4	2	4	2	4	1	5	3	**75.0**
Online Sen.	p9	5	4	5	3	5	1	5	3	5	4	**75.0**
Online Sen.	p10	3	4	2	2	3	4	4	3	4	2	**52.5**
Online Exp.	p11	2	3	4	2	3	3	4	3	3	2	**57.5**
Online Sen.	p12	5	2	5	5	5	2	5	5	5	5	**65.0**
Online Sen.	p13	5	1	5	5	4	3	5	3	1	4	**60.0**
Online Exp.	p14	3	2	4	1	4	2	4	1	3	1	**77.5**
Online Int.	p15	4	2	4	3	3	2	4	3	3	2	**65.0**
Online Exp.	p16	4	2	4	2	4	3	4	2	4	2	**72.5**
Online Int.	p17	4	2	3	3	3	2	4	3	4	4	**60.0**
Online Sen.	p18	1	1	4	2	3	3	3	2	3	3	**57.5**
Online Exp.	p19	3	3	4	2	4	4	4	2	4	2	**65.0**
Online Exp.	p20	4	2	4	2	5	2	4	1	4	1	**82.5**
Online Exp.	p21	3	2	4	2	3	3	4	2	4	2	**67.5**
Online Int.	p22	3	3	5	4	2	4	3	1	3	4	**50.0**
Online Sen.	p23	1	3	2	3	3	3	4	1	3	3	**50.0**
Online Int.	p24	3	2	3	2	2	3	3	3	2	1	**55.0**
Online Int.	p25	2	3	4	2	3	2	4	2	4	2	**65.0**
Online Int.	p26	4	1	5	1	5	3	5	1	5	1	**92.5**
Online Exp.	p27	1	2	4	1	3	3	4	1	4	1	**70.0**
Online Sen.	p28	3	2	4	1	3	3	4	2	4	1	**72.5**
Online Jun.	p29	4	2	5	1	3	3	4	2	4	2	**75.0**
Online Exp.	p30	4	2	3	3	2	4	4	2	4	4	**55.0**
Online Exp.	p31	3	2	4	1	4	2	4	1	5	1	**82.5**
Online Int.	p32	4	3	4	2	3	3	4	2	3	3	**62.5**
Online Int.	p33	3	3	4	1	3	3	4	2	3	2	**65.0**
Online Exp.	p34	2	1	3	3	5	2	4	1	3	2	**70.0**
Online Int.	p35	3	2	3	2	3	2	3	2	3	2	**62.5**
Online Sen.	p36	4	2	4	2	3	2	4	3	3	2	**67.5**
Online Int.	p37	4	2	2	5	5	2	5	2	5	4	**65.0**
Online Jun.	p38	5	1	5	3	3	3	5	2	5	3	**77.5**
Online Int.	p39	3	3	4	2	4	2	4	1	2	2	**67.5**
Online Int.	p40	2	2	3	2	3	5	4	1	5	3	**60.0**
Online Sen.	p41	3	3	4	2	3	3	4	1	3	2	**65.0**
Online Int.	p42	2	4	3	3	3	2	2	3	2	4	**40.0**
Online Jun.	p43	3	2	4	2	4	1	4	1	3	3	**72.5**
Online Jun.	p44	3	2	4	2	4	1	4	1	3	3	**72.5**
Online Jun.	p45	3	1	5	2	4	2	4	1	4	2	**80.0**
Online Int.	p46	5	2	4	2	3	2	3	3	4	2	**70.0**
Online Sen.	p47	4	1	4	2	2	2	4	2	4	2	**72.5**
Online Sen.	p48	3	1	5	1	4	2	5	1	4	1	**87.5**
Online Sen.	p49	3	4	3	1	3	2	3	1	3	1	**65.0**
Online Sen.	p50	4	3	4	3	3	4	4	3	3	2	**57.5**
Online Int.	p51	3	3	3	3	4	3	3	3	3	3	**52.5**
Online Jun.	p52	3	2	3	1	4	1	4	1	5	1	**82.5**
Online Exp.	p53	3	2	4	1	3	3	5	2	4	3	**70.0**
Online Exp.	p54	3	2	4	3	3	3	4	2	4	3	**62.5**
Online Exp.	p55	3	3	4	2	5	2	4	1	4	2	**75.0**
Online Exp.	p56	2	3	3	2	2	3	4	3	2	2	**50.0**
Online Int.	p57	3	2	4	3	4	2	4	1	3	1	**72.5**
Online Jun.	p58	3	3	5	4	3	3	4	3	3	3	**55.0**
Online Jun.	p59	3	3	3	1	4	3	3	3	3	1	**62.5**
Online Exp.	p60	3	1	5	1	4	4	4	1	3	1	**77.5**
Online Exp.	p61	5	2	4	2	3	2	5	1	4	2	**80.0**
Online Exp.	p62	3	2	4	2	3	2	4	2	4	2	**70.0**
Online Int.	p63	2	2	5	1	5	3	4	1	5	3	**77.5**
Online Exp.	p64	5	1	5	2	5	1	5	1	5	2	**95.0**
Online Sen.	p65	1	1	5	1	3	2	5	1	5	1	**82.5**
Online Int.	p66	3	2	4	3	5	2	5	2	4	3	**72.5**
Online Int.	p67	2	1	5	2	4	1	5	1	4	1	**85**
Online Sen.	p68	2	1	4	1	3	3	3	3	2	1	**62.5**
Online Sen.	p69	3	2	4	1	3	3	4	2	4	2	**70**
Online Sen.	p70	3	3	4	3	2	3	4	3	3	3	**52.5**
Online Exp.	p71	4	2	4	2	3	2	5	1	4	2	**77.5**
Online Jun.	p72	2	2	4	1	4	1	5	2	4	2	**77.5**
Online Jun.	p73	2	2	4	2	5	1	3	2	3	1	**72.5**
Online Jun.	p74	4	2	5	2	4	1	5	2	4	2	**82.5**
											Average	69.0
											SD	11.541

Table E. 3 Raw data for SUS questionnaire – usability study (Online junior planners - Set 2)

Experience	Participant	q1	q2	q3	q4	q5	q6	q7	q8	q9	q10	SUS Score
Online Jun.	p29	4	2	5	1	3	3	4	2	4	2	**75.0**
Online Jun.	p38	5	1	5	3	3	3	5	2	5	3	**77.5**
Online Jun.	p43	3	2	4	2	4	1	4	1	3	3	**72.5**
Online Jun.	p44	3	2	4	2	4	1	4	1	3	3	**72.5**
Online Jun.	p45	3	1	5	2	4	2	4	1	4	2	**80.0**
Online Jun.	p52	3	2	3	1	4	1	4	1	5	1	**82.5**
Online Jun.	p58	3	3	5	4	3	3	4	3	3	3	**55.0**
Online Jun.	p59	3	3	3	1	4	3	3	3	3	1	**62.5**
Online Jun.	p72	2	2	4	1	4	1	5	2	4	2	**77.5**
Online Jun.	p73	2	2	4	2	5	1	3	2	3	1	**72.5**
Online Jun.	p74	4	2	5	2	4	1	5	2	4	2	**82.5**
										Average		73.6
										SD		8.00

Table E. 4 Raw data for SUS questionnaire – usability study (Online Intermediate planners - Set 2)

Experience	Participant	q1	q2	q3	q4	q5	q6	q7	q8	q9	q10	SUS Score
Online Int.	p8	3	2	4	2	4	2	4	1	5	3	**75.0**
Online Int.	p15	4	2	4	3	3	2	4	3	3	2	**65.0**
Online Int.	p17	4	2	3	3	3	2	4	3	4	4	**60.0**
Online Int.	p22	3	3	5	4	2	4	3	1	3	4	**50.0**
Online Int.	p24	3	2	3	2	2	3	3	3	2	1	**55.0**
Online Int.	p25	2	3	4	2	3	2	4	2	4	2	**65.0**
Online Int.	p26	4	1	5	1	5	3	5	1	5	1	**92.5**
Online Int.	p32	4	3	4	2	3	3	4	2	3	3	**62.5**
Online Int.	p33	3	3	4	1	3	3	4	2	3	2	**65.0**
Online Int.	p35	3	2	3	2	3	2	3	2	3	2	**62.5**
Online Int.	p37	4	2	2	5	5	2	5	2	5	4	**65.0**
Online Int.	p39	3	3	4	2	4	2	4	1	2	2	**67.5**
Online Int.	p40	2	2	3	2	3	5	4	1	5	3	**60.0**
Online Int.	p42	2	4	3	3	3	2	2	3	2	4	**40.0**
Online Int.	p46	5	2	4	2	3	2	3	3	4	2	**70.0**
Online Int.	p51	3	3	3	3	4	3	3	3	3	3	**52.5**
Online Int.	p57	3	2	4	3	4	2	4	1	3	1	**72.5**
Online Int.	p63	2	2	5	1	5	3	4	1	5	3	**77.5**
Online Int.	p66	3	2	4	3	5	2	5	2	4	3	**72.5**
Online Int.	p67	2	1	5	2	4	1	5	1	4	1	**85**
										Average		65.8
										SD		11.65

Table E. 5 Raw data for SUS questionnaire – usability study (Online Senior planners - Set 2)

Experience	Participant	q1	q2	q3	q4	q5	q6	q7	q8	q9	q10	SUS Score
Online Sen.	p3	2	2	2	1	2	2	3	2	2	1	**57.5**
Online Sen.	p9	5	4	5	3	5	1	5	3	5	4	**75.0**
Online Sen.	p10	3	4	2	2	3	4	4	3	4	2	**52.5**
Online Sen.	p12	5	2	5	5	5	2	5	5	5	5	**65.0**
Online Sen.	p13	5	1	5	5	4	3	5	3	1	4	**60.0**
Online Sen.	p18	1	1	4	2	3	3	3	2	3	3	**57.5**
Online Sen.	p23	1	3	2	3	3	3	4	1	3	3	**50.0**
Online Sen.	p28	3	2	4	1	3	3	4	2	4	1	**72.5**
Online Sen.	p36	4	2	4	2	3	2	4	3	3	2	**67.5**
Online Sen.	p41	3	3	4	2	3	3	4	1	3	2	**65.0**
Online Sen.	p47	4	1	4	2	2	2	4	2	4	2	**72.5**
Online Sen.	p48	3	1	5	1	4	2	5	1	4	1	**87.5**
Online Sen.	p49	3	4	3	1	3	2	3	1	3	1	**65.0**
Online Sen.	p50	4	3	4	3	3	4	4	3	3	2	**57.5**
Online Sen.	p65	1	1	5	1	3	2	5	1	5	1	**82.5**
Online Sen.	p68	2	1	4	1	3	3	3	3	2	1	**62.5**
Online Sen.	p69	3	2	4	1	3	3	4	2	4	2	**70**
Online Sen.	p70	3	3	4	3	2	3	4	3	3	3	**52.5**
											Average	65.1
											SD	9.98

Table E. 6 Raw data for SUS questionnaire – usability study (Online Expert planners - Set 2)

Experience	Participant	q1	q2	q3	q4	q5	q6	q7	q8	q9	q10	SUS Score
Online Exp.	p1	5	2	5	1	4	1	5	1	5	1	**95.0**
Online Exp.	p2	5	2	3	1	3	3	1	3	5	1	**67.5**
Online Exp.	p4	3	1	5	1	3	3	5	1	2	1	**77.5**
Online Exp.	p5	5	1	5	1	5	1	5	1	5	1	**100.0**
Online Exp.	p6	3	4	3	1	3	2	3	3	4	1	**62.5**
Online Exp.	p7	3	2	4	2	4	3	4	2	4	2	**70.0**
Online Exp.	p11	2	3	4	2	3	3	4	3	3	2	**57.5**
Online Exp.	p14	3	2	4	1	4	2	4	1	3	1	**77.5**
Online Exp.	p16	4	2	4	2	4	3	4	2	4	2	**72.5**
Online Exp.	p19	3	3	4	2	4	4	4	2	4	2	**65.0**
Online Exp.	p20	4	2	4	2	5	2	4	1	4	1	**82.5**
Online Exp.	p21	3	2	4	2	3	3	4	2	4	2	**67.5**
Online Exp.	p27	1	2	4	1	3	3	4	1	4	1	**70.0**
Online Exp.	p30	4	2	3	3	2	4	4	2	4	4	**55.0**
Online Exp.	p31	3	2	4	1	4	2	4	1	5	1	**82.5**
Online Exp.	p34	2	1	3	3	5	2	4	1	3	2	**70.0**
Online Exp.	p53	3	2	4	1	3	3	5	2	4	3	**70.0**
Online Exp.	p54	3	2	4	3	3	3	4	2	4	3	**62.5**
Online Exp.	p55	3	3	4	2	5	2	4	1	4	2	**75.0**
Online Exp.	p56	2	3	3	2	2	3	4	3	2	2	**50.0**
Online Exp.	p60	3	1	5	1	4	4	4	1	3	1	**77.5**
Online Exp.	p61	5	2	4	2	3	2	5	1	4	2	**80.0**
Online Exp.	p62	3	2	4	2	3	2	4	2	4	2	**70.0**
Online Exp.	p64	5	1	5	2	5	1	5	1	5	2	**95.0**
Online Exp.	p71	4	2	4	2	3	2	5	1	4	2	**77.5**
											Average	73.2
											SD	11.82

Table E. 7 Raw data for Knowledge representations evaluation – Trial Novice planners - Set 1

	1. Inspection plan + tactical activity			2. Inspection plan + strategic activity			3. Inspection plan + IDEF0		
participant	**Understanding**	**Usefulness**	**Overall score**	**Understanding**	**Usefulness**	**Overall score**	**Understanding**	**Usefulness**	**Overall score**
1	4	5	4	4	4	4	5	5	5
2	2	2	2	5	4	4	5	5	5
3	5	5	5	5	5	5	5	5	5
4	5	5	5	5	5	5	5	2	4
5	4	4	4	4	5	4	4	4	4
6	5	5	5	5	5	5	4	4	4
7	4	2	3	5	4	3	5	4	3
8	2	5	4	5	5	5	3	5	5
9	4	4	4	5	4	4	5	4	3
10	4	3	4	3	4	4	4	4	4
Average	3.9	4	4	4.6	4.5	4.3	4.5	4.2	4.2
SD	1.044	1.183	0.894	0.663	0.500	0.640	0.671	0.872	0.748

	4. Video - annotations			5. Storyboard		
participant	**Understanding**	**Usefulness**	**Overall score**	**Understanding**	**Usefulness**	**Overall score**
1	5	5	5	5	5	5
2	4	5	5	5	5	5
3	5	3	3	5	2	3
4	5	4	4	4	5	4
5	5	5	4	5	5	5
6	5	5	5	5	5	5
7	4	2	3	5	5	5
8	5	5	5	5	5	5
9	5	5	4	4	4	5
10	5	5	5	5	5	5
Average	4.8	4.4	4.3	4.8	4.6	4.7
SD	0.400	1.020	0.781	0.400	0.917	0.640

Table E. 8 Raw data for Knowledge representations evaluation – Online Experienced planners - Set 1

How many	1. Inspection plan + tactical			2. Inspection plan + strategic			3. Inspection plan + IDEF0			4. Video - annotations			5. Storyboard		
years of CMM	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall
over 10 years	2	2	2	2	2	2	2	2	2	3	3	3	4	4	4
over 10 years	5	5	5	5	5	5	4	4	4	5	5	5	5	5	5
5-10 years	2	4	3	4	4	4	2	3	2	5	5	5	2	2	2
2-5 years	2	3	2	3	3	4	1	1	2	5	3	4	5	2	4
2-5 years	3	3	3	3	3	3	1	1	1	4	4	4	5	5	5
2-5 years	2	1	1	2	2	2	1	1	1	4	3	4	4	4	4
5-10 years	2	2	2	2	2	2	3	3	3	3	3	3	2	2	2
over 10 years	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
over 10 years	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
2-5 years	4	4	4	5	5	5	3	5	4	5	5	5	3	3	3
over 10 years	2	2	2	3	3	3	2	2	2	4	4	4	5	5	5
over 10 years	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
5-10 years	2	2	2	3	3	3	3	3	3	3	2	2	3	3	3
over 10 years	2	2	2	3	3	3	1	1	1	2	2	2	2	1	2
over 10 years	4	4	4	4	4	4	4	3	4	4	3	3	4	2	2
2-5 years	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
2-5 years	5	4	4	2	2	3	1	1	1	5	5	5	5	5	5
2-5 years	4	4	4	4	4	4	3	4	4	5	4	5	5	5	5
over 10 years	2	4	3	3	3	3	4	3	3	4	3	3	3	4	3
5-10 years	4	5	4	3	4	3	2	2	2	5	4	4	4	4	4
over 10 years	4	3	3	4	4	4	4	3	3	5	2	3	5	4	4
over 10 years	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
2-5 years	2	4	3	2	3	3	2	2	1	5	2	3	4	4	4
over 10 years	5	3	3	5	3	3	5	3	3	5	3	3	5	3	3
over 10 years	1	1	1	2	2	2	1	1	1	1	1	1	4	4	4
0-2 years	3	4	4	3	3	3	5	4	4	4	3	3	5	5	5
over 10 years	4	5	5	4	4	4	3	3	4	5	5	5	5	5	5
2-5 years	5	5	5	5	5	5	5	4	5	5	5	5	5	5	5
0-2 years	5	3	4	5	5	5	3	3	3	5	4	5	5	4	5

over 10 years	3	2	2	3	2	2	1	1	1	3	3	3	3	1	2
over 10 years	5	2	3	4	2	3	3	1	2	5	1	2	5	4	4
5-10 years	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
over 10 years	3	1	2	3	2	2	3	2	3	3	3	3	3	2	2
over 10 years	4	3	4	4	4	4	5	5	5	5	5	5	5	5	5
5-10 years	5	5	5	5	5	5	2	2	2	5	2	5	5	5	5
over 10 years	5	5	5	1	1	1	4	3	4	5	3	4	4	3	4
2-5 years	4	5	4	4	5	4	3	4	3	4	5	4	5	5	5
over 10 years	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
5-10 years	4	3	3	3	2	2	3	2	2	4	3	3	3	3	3
5-10 years	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
over 10 years	3	3	3	2	2	2	2	2	2	5	4	4	4	4	4
over 10 years	5	5	5	5	5	5	5	2	3	5	3	4	5	3	3
5-10 years	2	2	2	3	2	3	2	2	1	3	3	3	5	3	3
5-10 years	1	3	2	1	3	1	5	4	5	1	4	4	4	3	5
5-10 years	4	4	5	4	4	5	4	4	4	5	5	5	4	4	5
2-5 years	3	4	4	4	4	4	3	5	5	5	5	5	4	4	4
2-5 years	1	2	2	1	2	2	2	2	2	2	3	3	1	1	2
2-5 years	4	2	3	4	3	3	4	3	3	3	2	2	4	3	3
over 10 years	5	4	4	5	4	4	2	2	2	5	5	5	5	5	5
5-10 years	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
5-10 years	3	3	3	3	3	3	4	3	3	5	2	2	4	2	1
over 10 years	4	4	4	3	4	4	4	4	4	4	3	4	4	3	4
5-10 years	3	1	1	4	3	3	3	2	2	4	3	3	3	3	3
2-5 years	4	3	4	3	2	3	2	2	2	4	4	4	3	3	3
2-5 years	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
5-10 years	5	1	1	3	1	1	3	1	1	4	3	3	4	1	1
5-10 years	3	3	3	4	4	4	4	4	4	4	4	4	3	3	3
5-10 years	2	2	2	2	3	2	3	3	2	3	3	3	3	2	2
over 10 years	4	4	4	4	4	4	3	3	3	4	4	4	4	4	4
0-2 years	2	4	3	2	4	3	4	4	4	5	5	5	5	5	5
0-2 years	4	3	4	4	3	3	3	2	3	5	3	4	4	3	4
0-2 years	4	2	2	4	3	3	3	1	1	5	3	3	5	4	4
Average	3.5	3.3	3.3	3.4	3.3	3.3	3.1	2.8	2.9	4.1	3.5	3.7	4	3.5	3.7
SD	1.240	1.247	1.207	1.144	1.133	1.133	1.246	1.260	1.292	1.094	1.132	1.065	1.039	1.227	1.183

Table E. 9 Raw data for Knowledge representations evaluation – Online junior planners - Set 2

Years of CMM programming experience	1. Inspection plan + tactical			2. Inspection plan + strategic			3. Inspection plan + IDEF0			4. Video - annotations			5. Storyboard		
	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall
0-2 years	3	4	4	3	3	3	5	4	4	4	3	3	5	5	5
0-2 years	5	3	4	5	5	5	3	3	3	5	4	5	5	4	5
0-2 years	2	4	3	2	4	3	4	4	4	5	5	5	5	5	5
0-2 years	4	3	4	4	3	3	3	2	3	5	3	4	4	3	4
0-2 years	4	2	2	4	3	3	3	1	1	5	3	3	5	4	4
Average	3.6	3.2	3.4	3.6	3.6	3.4	3.6	2.8	3	4.8	3.6	4	4.8	4.2	4.6
SD	1.020	0.748	0.800	1.020	0.800	0.800	0.800	1.166	1.095	0.400	0.800	0.894	0.400	0.748	0.490

Table E. 10 Raw data for Knowledge representations evaluation – Online intermediate planners - Set 2

Years of CMM programming experience	1. Inspection plan + tactical			2. Inspection plan + strategic			3. Inspection plan + IDEF0			4. Video - annotations			5. Storyboard		
	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall
2-5 years	2	3	2	3	3	4	1	1	2	5	3	4	5	2	4
2-5 years	3	3	3	3	3	3	1	1	1	4	4	4	5	5	5
2-5 years	2	1	1	2	2	2	1	1	1	4	3	4	4	4	4
2-5 years	4	4	4	5	5	5	3	5	4	5	5	5	3	3	3
2-5 years	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
2-5 years	5	4	4	2	2	3	1	1	1	5	5	5	5	5	5
2-5 years	4	4	4	4	4	4	3	4	4	5	4	5	5	5	5
2-5 years	2	4	3	2	3	3	2	2	1	5	2	3	4	4	4
2-5 years	5	5	5	5	5	5	5	4	5	5	5	5	5	5	5
2-5 years	4	5	4	4	5	4	3	4	3	4	5	4	5	5	5
2-5 years	3	4	4	4	4	4	3	5	5	5	5	5	4	4	4
2-5 years	1	2	2	1	2	2	2	2	2	2	3	3	1	1	2
2-5 years	4	2	3	4	3	3	4	3	3	3	2	2	4	3	3
2-5 years	4	3	4	3	2	3	2	2	2	4	4	4	3	3	3
2-5 years	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Average	3.5	3.5	3.5	3.4	3.5	3.6	2.7	2.9	2.9	4.3	3.9	4.1	4.1	3.9	4.1
SD	1.204	1.147	1.087	1.200	1.147	0.952	1.350	1.526	1.500	0.869	1.062	0.884	1.087	1.204	0.929

Table E. 11 Raw data for Knowledge representations evaluation – Online senior planners - Set 2

Years of CMM programming experience	1. Inspection plan + tactical			2. Inspection plan + strategic			3. Inspection plan + IDEF0			4. Video - annotations			5. Storyboard		
	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall
5-10 years	2	4	3	4	4	4	2	3	2	5	5	5	2	2	2
5-10 years	2	2	2	2	2	2	3	3	3	3	3	3	2	2	2
5-10 years	2	2	2	3	3	3	3	3	3	3	2	2	3	3	3
5-10 years	4	5	4	3	4	3	2	2	2	5	4	4	4	4	4
5-10 years	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5-10 years	5	5	5	5	5	5	2	2	2	5	2	5	5	5	5
5-10 years	4	3	3	3	2	2	3	2	2	4	3	3	3	3	3
5-10 years	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
5-10 years	2	2	2	3	2	3	2	2	1	3	3	3	5	3	3
5-10 years	1	3	2	1	3	1	5	4	5	1	4	4	4	3	5
5-10 years	4	4	5	4	4	5	4	4	4	5	5	5	4	4	5
5-10 years	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
5-10 years	3	3	3	3	3	3	4	3	3	5	2	2	4	2	1
5-10 years	3	1	1	4	3	3	3	2	2	4	3	3	3	3	3
5-10 years	5	1	1	3	1	1	3	1	1	4	3	3	4	1	1
5-10 years	3	3	3	4	4	4	4	4	4	4	4	4	3	3	3
5-10 years	2	2	2	2	3	2	3	3	2	3	3	3	3	2	2
Average	3	2.9	2.8	3.1	3.1	2.9	3.1	2.8	2.6	3.7	3.2	3.4	3.4	2.9	3
SD	1.283	1.323	1.307	1.131	1.162	1.305	1.056	1.059	1.234	1.273	1.113	1.141	1.088	1.131	1.372

Table E. 12 Raw data for Knowledge representations evaluation – Online expert planners - Set 2

Years of CMM programming experience	1. Inspection plan + tactical			2. Inspection plan + strategic			3. Inspection plan + IDEF0			4. Video - annotations			5. Storyboard		
	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall	Underst.	Useful.	Overall
over 10 years	2	2	2	2	2	2	2	2	2	3	3	3	4	4	4
over 10 years	5	5	5	5	5	5	4	4	4	5	5	5	5	5	5
over 10 years	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
over 10 years	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
over 10 years	2	2	2	3	3	3	2	2	2	4	4	4	5	5	5
over 10 years	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
over 10 years	2	2	2	3	3	3	1	1	1	2	2	2	2	1	2
over 10 years	4	4	4	4	4	4	4	3	4	4	3	3	4	2	2
over 10 years	2	4	3	3	3	3	4	3	3	4	3	3	3	4	3
over 10 years	4	3	3	4	4	4	4	3	3	5	2	3	5	4	4
over 10 years	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
over 10 years	5	3	3	5	3	3	5	3	3	5	3	3	5	3	3
over 10 years	1	1	1	2	2	2	1	1	1	1	1	1	4	4	4
over 10 years	4	5	5	4	4	4	3	3	4	5	5	5	5	5	5
over 10 years	3	2	2	3	2	2	1	1	1	3	3	3	3	1	2
over 10 years	5	2	3	4	2	3	3	1	2	5	1	2	5	4	4
over 10 years	3	1	2	3	2	2	3	2	3	3	3	3	3	2	2
over 10 years	4	3	4	4	4	4	5	5	5	5	5	5	5	5	5
over 10 years	5	5	5	1	1	1	4	3	4	5	3	4	4	3	4
over 10 years	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
over 10 years	3	3	3	2	2	2	2	2	2	5	4	4	4	4	4
over 10 years	5	5	5	5	5	5	5	2	3	5	3	4	5	3	3
over 10 years	5	4	4	5	4	4	2	2	2	5	5	5	5	5	5
over 10 years	4	4	4	3	4	4	4	4	4	4	3	4	4	3	4
over 10 years	4	4	4	4	4	4	3	3	3	4	4	4	4	4	4
Average	3.7	3.4	3.5	3.6	3.4	3.4	3.3	2.8	3.1	4.1	3.4	3.6	4.2	3.7	3.8
SD	1.184	1.265	1.170	1.095	1.127	1.095	1.287	1.222	1.197	1.070	1.169	1.054	0.849	1.191	1.020

Table E. 13 Raw data for Inspection Plan + Tactical Planning Trajectory evaluation – All subgroups - Set 2

	1. Inspection plan + tactical planning trajectory														
	Ease of understanding					**Usefulness**					**Overall performance**				
	Trial nov	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*	*Trial nov*	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*	*Trial nov*	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*
	4	3	2	2	2	4	4	2	4	2	4	4	2	3	2
	2	5	3	2	5	2	3	3	2	5	2	4	3	2	5
	5	2	2	2	4	5	4	2	2	4	5	3	1	2	4
	5	4	4	4	3	5	3	4	5	3	5	4	4	4	3
	4	4	4	1	2	4	2	4	1	2	4	2	4	1	2
	5		5	5	4	5		5	5	4	5		4	5	4
	4		4	4	2	4		4	3	2	3		4	3	2
	2		2	3	4	2		2	3	4	4		3	3	4
	4		5	2	2	4		5	2	4	4		5	2	3
	4		4	1	4	4		4	3	3	4		4	2	3
			3	4	5			3	4	5			4	5	5
			1	5	5			1	5	3			2	5	3
			4	3	1			4	3	1			3	3	1
			4	3	4			4	1	5			4	1	5
			5	5	3			5	1	2			5	1	2
				3	5				3	2				3	3
				2	3				2	1				2	2
					4					3					4
					5					5					5
					5					5					5
					3					3					3
					5					5					5
					5					4					4
					4					4					4
					4					4					4
Average	3.9	3.6	3.5	3	3.7	3.9	3.2	3.5	2.9	3.4	4	3.4	3.5	2.8	3.5
SD	1.044	1.020	1.204	1.283	1.184	1.044	0.748	1.204	1.323	1.265	0.894	0.800	1.087	1.307	1.170
%	78	72	70	60	74	78	64	70	58	68	80	68	70	56	70

Table E. 14 Raw data for Inspection Plan + Strategic Planning Trajectory evaluation – All subgroups - Set 2

	2. Inspection plan + strategic planning trajectory														
	Ease of understanding					**Usefulness**					**Overall performance**				
	Trial nov	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*	*Trial nov*	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*	*Trial nov*	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*
	4	3	3	4	2	4	3	3	4	2	4	3	4	4	2
	5	5	3	2	5	4	5	3	2	5	4	5	3	2	5
	5	2	2	3	4	5	4	2	3	4	5	3	2	3	4
	5	4	5	3	3	5	3	5	4	3	5	3	5	3	3
	4	4	4	1	3	5	3	4	1	3	4	3	4	1	3
	5		2	5	4	5		2	5	4	5		3	5	4
	5		4	3	3	4		4	2	3	3		4	2	3
	5		2	3	4	5		3	3	4	5		3	3	4
	5		5	3	3	4		5	2	3	4		5	3	3
	3		4	1	4	4		5	3	4	4		4	1	4
			4	4	5			4	4	5			4	5	5
			1	5	5			2	5	3			2	5	3
			4	3	2			3	3	2			3	3	2
			3	4	4			2	3	4			3	3	4
			5	3	3			5	1	2			5	1	2
				4	4				4	2				4	3
				2	3				3	2				2	2
					4					4					4
					1					1					1
					5					5					5
					2					2					2
					5					5					5
					5					4					4
					3					4					4
					4					4					4
Average	4.6	3.6	3.4	3.1	3.6	4.5	3.6	3.5	3.1	3.4	4.3	3.4	3.6	2.9	3.4
SD	0.663	1.020	1.200	1.131	1.095	0.500	0.800	1.147	1.162	1.127	0.640	0.800	0.952	1.305	1.095
%	92	72	68	62	72	90	72	70	62	68	86	68	72	58	68

Table E. 15 Raw data for Inspection Plan + IDEF0 diagram evaluation – All subgroups - Set 2

	3. Inspection plan + IDEF0														
	Ease of understanding					Usefulness					Overall performance				
	Trial nov	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*	*Trial nov*	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*	*Trial nov*	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*
	5	5	1	2	2	5	4	1	3	2	5	4	2	2	2
	5	3	1	3	4	5	3	1	3	4	5	3	1	3	4
	5	4	1	3	4	5	4	1	3	4	5	4	1	3	4
	5	3	3	2	3	2	2	5	2	3	4	3	4	2	3
	4	3	4	1	2	4	1	4	1	2	4	1	4	1	2
	4		1	2	4	4		1	2	4	4		1	2	4
	5		3	3	1	4		4	2	1	3		4	2	1
	3		2	3	4	5		2	3	3	5		1	3	4
	5		5	2	4	4		4	2	3	3		5	1	3
	4		3	5	4	4		4	4	3	4		3	5	3
			3	4	5			5	4	5			5	4	5
			2	5	5			2	5	3			2	5	3
			4	4	1			3	3	1			3	3	1
			2	3	3			2	2	3			2	2	4
			5	3	1			5	1	1			5	1	1
				4	3				4	1				4	2
				3	3				3	2				2	3
					5					5					5
					4					3					4
					5					5					5
					2					2					2
					5					2					3
					2					2					2
					4					4					4
					3					3					3
Average	4.5	3.6	2.7	3.1	3.3	4.2	2.8	2.9	2.8	2.8	4.2	3	2.9	2.6	3.1
SD	0.671	0.800	1.350	1.056	1.287	0.872	1.166	1.526	1.059	1.222	0.748	1.095	1.500	1.234	1.197
%	90	72	54	62	66	84	56	58	56	56	84	60	58	52	62

Table E. 16 Raw data Annotated Video-clip evaluation – All subgroups - Set 2

	4. Anotated video clip														
	Ease of understanding					Usefulness					Overall performance				
	Trial nov	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*	*Trial nov*	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*	*Trial nov*	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*
	5	4	5	5	3	5	3	3	5	3	5	3	4	5	3
	4	5	4	3	5	5	4	4	3	5	5	5	4	3	5
	5	5	4	3	4	3	5	3	2	4	3	5	4	2	4
	5	5	5	5	3	4	3	5	4	3	4	4	5	4	3
	5	5	4	1	4	5	3	4	1	4	4	3	4	1	4
	5		5	5	4	5		5	2	4	5		5	5	4
	4		5	4	2	2		4	3	2	3		5	3	2
	5		5	3	4	5		2	3	3	5		3	3	3
	5		5	3	4	5		5	3	3	4		5	3	3
	5		4	1	5	5		5	4	2	5		4	4	3
			5	5	5			5	5	5			5	5	5
			2	5	5			3	5	3			3	5	3
			3	5	1			2	2	1			2	2	1
			4	4	5			4	3	5			4	3	5
			5	4	3			5	3	3			5	3	3
				4	5				4	1				4	2
				3	3				3	3				3	3
					5					5					5
					5					3					4
					5					5					5
					5					4					4
					5					3					4
					5					5					5
					4					3					4
					4					4					4
Average	4.8	4.8	4.3	3.7	4.1	4.4	3.6	3.9	3.2	3.4	4.3	4	4.1	3.4	3.6
SD	0.400	0.400	0.869	1.273	1.070	1.020	0.800	1.062	1.113	1.169	0.781	0.894	0.884	1.141	1.054
%	96	96	86	74	82	88	72	78	64	68	86	80	82	68	72

Table E. 17 Raw data Storyboard evaluation – All subgroups - Set 2

	5. Storyboard														
	Ease of understanding					Usefulness					Overall performance				
	Trial nov	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*	*Trial nov*	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*	*Trial nov*	*Online Jun*	*Online Int*	*Online Sen*	*Online Exp*
	5	5	5	2	4	5	5	2	2	4	5	5	4	2	4
	5	5	5	2	5	5	4	5	2	5	5	5	5	2	5
	5	5	4	3	4	2	5	4	3	4	3	5	4	3	4
	4	4	3	4	3	5	3	3	4	3	4	4	3	4	3
	5	5	4	1	5	5	4	4	1	5	5	4	4	1	5
	5		5	5	4	5		5	5	4	5		5	5	4
	5		5	3	2	5		5	3	1	5		5	3	2
	5		4	3	4	5		4	3	2	5		4	3	2
	4		5	5	3	4		5	3	4	5		5	3	3
	5		5	4	5	5		5	3	4	5		5	5	4
			4	4	5			4	4	5			4	5	5
			1	5	5			1	5	3			2	5	3
			4	4	4			3	2	4			3	1	4
			3	3	5			3	3	5			3	3	5
			5	4	3			5	1	1			5	1	2
				3	5				3	4				3	4
				3	3				2	2				2	2
					5					5					5
					4					3					4
					5					5					5
					4					4					4
					5					3					3
					5					5					5
					4					3					4
					4					4					4
Average	4.8	4.8	4.1	3.4	4.2	4.6	4.2	3.9	2.9	3.7	4.7	4.6	4.1	3	3.8
SD	0.400	0.400	1.087	1.088	0.849	0.917	0.748	1.204	1.131	1.191	0.640	0.490	0.929	1.372	1.020
%	96	96	82	68	84	92	84	78	58	74	94	92	82	60	76