

Automated CMM inspection planning and knowledge capture formalization

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ABSTRACT

Capturing the strategy followed during a Coordinate Measuring Machine (CMM) inspection planning session has been an extremely challenging issue due to the time-consuming nature of traditional methods, such as interviewing experts and technical documents data mining. This paper presents a methodology demonstrating how a motion capture-based system can facilitate direct and non-intrusive CMM operator logging for capturing planning strategies and representing in knowledge formats. With the use of recorded motion data, embedded knowledge and expertise can be captured automatically and formalized in various formats such as motion trajectory graphs, inspection plans, Integrated DEFinition (IDEF) model diagrams and other representations. Additionally, a part program can be generated for driving a CMM to execute component measurement. The system's outputs can be used to help understand how a CMM inspection strategy is planned, as well as training aids for inexperienced operators and the rapid generation of part programs.

INTRODUCTION

CMMs have been widely used over the last four decades; not only due to their capability for precise testing and product verification but also for providing upstream manufacturing processes with data and feedback enabling a higher level of production process control. However, the programming and operation of a CMM constitutes a time-consuming task slowing down product development and manufacturing and adding further costs to production. Consequently, planning a CMM inspection strategy for a newly developed or modified product can lead to further delays in production.

A solution to this issue comes from the area of Computer Aided Manufacturing (CAM) where a range of Computer Aided Inspection Planning (CAIP) systems were designed to support CMM programmers. However, despite the variety of capabilities provided by CAIP systems, the important part of planning a measurement strategy and decision-making, depends entirely on CMM experts and their experience [1]. Therefore, it is essential that human expertise and knowledge generated during an inspection planning session should be captured and formalized to be reused either directly for process control or in future cases. By achieving this, not only new inspection plans and CMM part programs will be created more quickly but also existing applications can be improved and tailored according to the CMM programmers' needs while a deeper understanding of how a measurement strategy is designed will be gained, leading to further support in this field.

A review of previous work in the area of CAIP [2] has proven that there is no system capable of automatically capturing the strategy generated by a CMM operator or formalizing it for reuse. A major reason for not achieving this is that CMM inspection planning requires high-level expertise and hands-on experience which have traditionally been difficult to capture and formalize [3]. The lack of such a tool inevitably leads to the repetitive regeneration of new inspection plans and strategies for each product being prepared for market. An effort to overcome this was suggested [4] based on a virtual CMM inspection planning environment. By utilizing a MoCap system, the activity of a CMM programmer can be logged with the aid of an inspection stylus analogue during a measurement planning task. In the research reported herein, this work is further enhanced and a range of different representations of the captured strategy are proposed. A significant advancement of this work over previous virtual solutions is the automatic generation of a CMM part program resulting from logging the user and the subsequent formalization of the planned strategy.

REVIEW OF RELATED LITERATURE

Computer Aided Inspection Planning

In the effort to support the time-consuming task of programming a CMM, many researchers attempted to design and build semi- or fully-automated inspection planning systems. Some of these focus only on finding optimal solutions for some aspects of inspection planning, such as the determination of inspection probe accessible directions [5–8], part orientations and setup [9–11], sampling methods for feature probing and reconstruction [12–16] and path generation [17–20], while other works attempt to address and provide complete solutions for the whole measurement strategy. The main approaches used [2] covering the widest range of systems researched are expert systems and virtual reality (VR) based systems.

Expert systems

The main characteristic of an expert system is the utilization of embedded knowledge aiming to solve a complex computational problem by comparing the under-test scenario against past similar cases and retrieving or modifying a suitable solution [21]. In the existing literature, this knowledge is codified in different forms depending on the nature of the system designed, such as a knowledge base and if-then rules, while the system's core may be based on a neural network, a genetic algorithm, a fuzzy logic module or, in some cases, a combination of all of these options [22].

ElMaraghy and Gu [23] developed one of the first expert inspection planning systems integrated with a CAD modelling system. In this work, the feature clustering and sequencing based on datums and geometric information were first introduced. Several sets of rules were presented to support the sub-modules developed. Gu [24] suggested a knowledge-based inspection planner by decomposing the main planning process into sub-tasks: feature accessibility, datums search, path planning, probe selection and developing separate knowledge modules for addressing each step of the plan. Knowledge structured as a list of "if-then" rules is utilized in combination with information from a CAD model. A knowledge based system

proposed by Hwang et al. [25] is capable of generating inspection plans. The tolerance information, as input by the user, is combined with stored knowledge and a set of fuzzy rules to produce optimal measurement strategies. An automated CMM inspection planning system was introduced by Hussien et al. [26] consisting of several rule-based modules for: feature recognition, sampling strategy, accessibility analysis and probe orientation clustering and minimization. The final output generates a Dimensional Measuring Interface Standard (DMIS) code for operating a CMM. Kamrani et al. [27] employed a set of different techniques and algorithms such as neural networks, clustering and graphical methods trying to build a feature-based inspection planning system integrated with CAD. All planning sub-tasks are addressed by the system finally producing a DMIS code file executable by a CMM. An intelligent knowledge based inspection planner was design by Stojadinovic et al. [28]. The rules and algorithms developed deal with the main steps of a planning session: probe accessibility analysis, distribution of measurement points and generation of a collision free path. The output provides an optimal plan in terms of minimizing the time required as well as a measuring protocol.

A common limitation in the papers studied is the lack of an explicit description of the knowledge elicitation techniques used and where the knowledge embedded in the systems comes from.

Virtual Reality based systems

VR inspection planning systems, more commonly called virtual CMMs, were developed primarily for simulating a measurement process focusing on error analysis and uncertainty evaluation [29]. Early work by Stouffer and Horst [30] reports the development of a virtual model of a CMM and an interface for moving it using a real-world controller. A virtual environment for interaction with a CMM was implemented in [31] with the aid of stereoscopic vision devices. A haptics based system was proposed by Chen et al. [32]. The operator uses a hand-held haptic device to input the measurement points and a collision-free inspection path is generated. Based on the previous work, Wang et al. [33] attempted to address the sub-task of probe head accessibility with the aid of a haptic CMM while a capability for calculating associated uncertainties was added by Hu et al. [34]. An “augmented virtuality” integrated CMM was proposed [35] which is operated either by a marker-less gesture recognition algorithm or using two joysticks. The system built contributes to the familiarization and training of novice CMM programmers in such environments by omitting any potential risks and damage that might occur due to inappropriate movements. Zhao and Peng [36] proposed another VR-based CMM for training purposes, allowing users to navigate within the environment and control the virtual machine as in the real world.

From the perspective of knowledge engineering, all the above systems demonstrate the potential for capturing human expertise and knowledge as the virtual environments involve interaction between a human (a possible CMM operator) and a computer enabling the data logging of user activity. Despite this fact, there is no evidence that the authors researched this direction in their studies.

Knowledge capture in CMM inspection planning

In the previous section a variety of expert systems were described involving the utilization of knowledge without describing how this was captured and what were the actual sources. Studying the existing literature for this kind of research, very little work has been reported. Barreiro et al. [3] processed technical documents aiming to identify inspection planning expert knowledge and structure it in an informal model for the preparation of a knowledge base. Their knowledge elicitation method included a data mining software tool for analyzing the documents. The representations produced were in the format of IDEF model diagrams and IDEF integrated ontologies. This work was extended further by Martinez-Pellitero et al. [37] for the purpose of modelling inspection planning knowledge and formulating an ontology. Their method was based on the analysis of text-based knowledge

sources (manual, reports, handbooks) using a data mining software tool. An ontology was designed [38] aiming to support the development of rules for selecting proper resources for CMM inspection planning, for instance when to use a touch trigger or scanning probe and determining the length of stylus and the diameter of the stylus tip. As previously highlighted, knowledge was elicited from technical documentation and rules developed to structure a knowledge base for CMM inspection resources management in [39]. In the context of automated optimal probe orientation and configuration, a knowledge based application was built with knowledge and rules extracted from documents [40].

User logging and engineering knowledge capture

Some past works have used different kinds of human-computer interaction (HCI) systems to capture human knowledge and expertise, e.g. immersive, virtual environments and haptic devices. Ritchie et al. [41,42] presented an early prototype proving that immersive VR as a non-intrusive user logging tool can be used effectively for capturing expert knowledge and the generation of instruction plans or guides in product engineering tasks, i.e. product assembly planning. The proposed system is capable of recording and storing data related to the user's movements, interactions and activities in an automated and non-intrusive manner providing a very rich data source for user activity analysis. The use of a VR cable harness design system [43] was demonstrated via a novel non-intrusive method for knowledge and information capture with user logging. The captured expertise was formalized in multiple representations such as IDEF diagrams, Design Rationale Editor (Dred) graphs, Process Specification Language (PSL), eXtensible Markup Language (XML), annotated movie clips and storyboard representations. Sung et al. [44] 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. A haptic process planning system built by Fletcher et al. [45] can generate time and cost estimated process plans. The user is logged while performing a machining task by moving the haptic stylus to simulate the moves of a machine tool; the operator's expertise is embedded in the generated plan and represents, in form of instructions, each step of the process. A generic framework was proposed by Sivanathan et al. [46] for multimodal data capturing by logging and monitoring various inputs, interactions and biophysical activity with a view to providing meta and chronological performance data for post task analysis of a design session. These studies demonstrate that the wide capabilities of 3D, virtual and digital environments offered for user activity logging can effectively form a framework for developing non-intrusive knowledge capture and formalization tools.

Motion Capture technology

Motion Capture (MoCap) is a well-established method to track humans or objects and record motion data of an activity. The major purpose of using MoCap is to gain a better understanding of human actions and behaviour with a view to modelling and simulating the activity. MoCap or motion tracking technology usually employs sensing devices to calculate the position and orientation of a subject in the tracking space and records these temporally. The logged data are then used to regenerate the motion trajectory enabling many opportunities for study and analysis.

Motion capture techniques and sensors

Depending on the sensing devices and technique employed, MoCap is classified into two categories: optical and non-optical [47]. Optical MoCap can be marker-based or marker-less. The main characteristic of optical motion tracking is the calculation of object's spatial position and orientation using digital images. For this purpose, special markers are attached on an object or participant, representing the position in the space. There can be two kinds of markers: passive and active. A passive marker could be a plastic ball covered with a retro-reflective material capable of reflecting the InfraRed (IR) light back to a camera when emitting it towards the tracking space. Active markers are IR Light Emitting Diodes (IR-LEDs) supplied by a power source. In marker-less motion tracking systems the shape from an object's or subject's silhouette is extracted and monitored by a vision-based algorithm.

Apart from the use of optical means of motion tracking, various other sensors can be used, forming other MoCap methods [48]. Mechanical MoCap employs electromechanical potentiometers for measuring the orientation displacement of a set of joints. Inertia-based MoCap is achieved by monitoring the object's acceleration and angular velocity using accelerometers and gyroscopes. Magnetic MoCap provides subject's position and orientation based on measurements of electromagnetic fields established through precise current pulses in mounted transmitting antennae. In acoustic MoCap, ultrasonic transmitters and microphones are attached to a moving object or human and the position is estimated based on the intensity of acoustic pulses. Since each different approach has its own disadvantages, depending on the case study a combination of the above systems could be used for compensating any errors introduced and improving the level of accuracy as required.

Motion capture applications

MoCap applications can be categorized [49] in three different ways: surveillance, control and analysis. Surveillance applications include cases where several subjects are monitored, for example, vehicle counting and crowd flux or congestion analysis. Control applications are related to the use of MoCap data for creating a control interface for a model or object. This is commonly used in HCI studies. Analysis applications cover the field of analyzing MoCap data for diagnostic or optimization studies such as clinical and orthopedic patients or athletes' performance.

Specifically, in the field of engineering many papers have reported the use of MoCap technology to study and solve various problems in manufacturing and other areas. Ma et al. [50] proposed a framework for tracking, recognizing and analyzing a worker's activity while performing manual handling tasks such as lifting a component. MoCap data are used to emulate human's actions in digital environment enabling the evaluation of a task's efficiency. With a view to prevention of musculoskeletal disorders, a human modelling and simulation system was proposed in [51]. Using motion tracking data from an automobile assembly workstation, digital models were generated and used for the evaluation of manual tasks and improvements in the ergonomics of the associated workplace. Similar research [52] was conducted by the use of MoCap and modeling human performance in the assembly and disassembly of car engine's connecting rod caps. A low-cost stereo-vision system [53] was developed with multiple Wii remote controllers for MoCap and the generation of a simulation of an assembly task. The system can be used for training purposes, improvement and planning of new assembly sequences. A multi-modal tracking system [54] was used for capturing activity data and modelling an assembly process. The set of sensors employed include radio-frequency identification (RFID) tags and reader, inertial measurement units (IMU) and force-sensitive resistors (FSR) producing a robust activity logging system to capture data for the different task steps and the transitions between them. An optical motion tracking setup was employed as the data capture method in a cyber-physical system [55] proposed for the evaluation of a ladder climbing task. This can contribute to training and support workers in the building and construction sector. A novel multi-depth camera approach [56] was suggested for tracking and observing workers' activity within a production environment aiming to optimize processes and

ergonomics of a workplace. As it can be seen from the research reviewed, motion capture and tracking constitutes an effective tool for logging user actions within a manufacturing environment. The captured data can facilitate and contribute to modelling and transferring real-world activity in a digital format, enabling the process of understanding how human experts think and act when solving complex engineering problems.

PROPOSED SYSTEM AND METHODOLOGY

Overview

In this research, a CMM inspection planning environment is proposed, focusing mainly on capturing the strategy followed and knowledge generated by a user during an inspection planning task. The system aims to emulate the activity of an operator while planning a measurement strategy with a CMM and digitizing it so as it can be analyzed more effectively. To achieve this, a physical setup based on optical motion tracking technology was used. The output of the motion tracker includes all the data related to the motion of a hand-held stylus when moved by the user. That is, the user activity is logged with the aid of the stylus which at the same time emulates the inspection probe of a CMM. The log file generated by the tracking system's operating software is post-processed to create multiple representations of the measurement strategy. A schematic diagram of the proposed setup and process is shown in Figure 1.

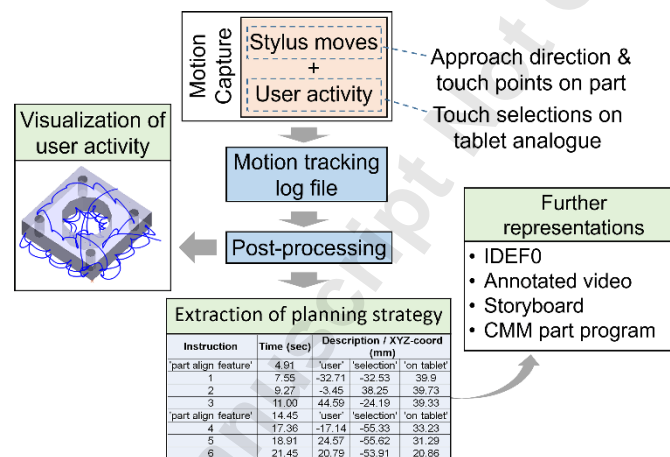


Fig. 1 Schematic diagram of proposed methodology

Apparatus and procedure

The experimental setup for this research consists of a set of twelve infrared (IR) light emitting cameras distributed around the motion tracking space, a hand-held stylus with two passive and one active LED markers attached to it and a tablet analogue used as a user input device for the different inspection planning sub-activities (Figure 2). The optical tracker comes with its own software package for recording, storing and editing the motion data files.

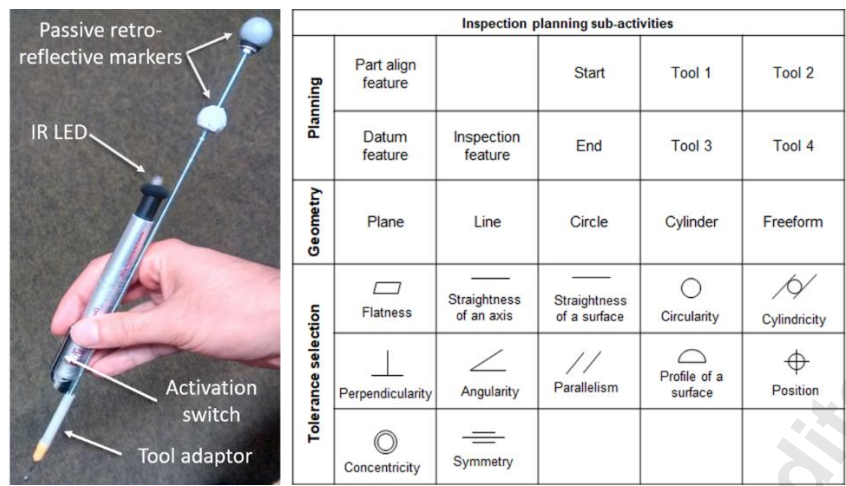


Fig. 2 Inspection stylus and tablet analogue

The two passive markers attached on the stylus are used for tracking its position inside the MoCap volume. Using the markers' spatial coordinates, the position of the stylus' tip is calculated and easily 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 reconstructing a geometrical feature on the part.

To log the user process definition activity throughout the planning session and to create a complete measurement plan when combined with the probed part geometry, a paper printed tablet analogue is used as a key user input device. On the tablet analogue, there are different groups of options that a user may select using the probe depending on the planning session task to be performed; these are: planning sub-activities (part alignment feature, datum feature, inspection feature), inspection stylus selection (tools as defined by the user), shape or geometry options (plane, line, circle, etc.) and tolerance options (flatness, straightness, circularity, cylindricity, etc.).

The tablet analogue must be calibrated beforehand in the MoCap volume prior to the inspection planning session so its relative position is tracked. By tracking tablet's position, each sub-cell of it covers a specific range in x, y and z such that 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 system can detect and record the planner's activity and sequence of the tasks performed in a chronological order. A typical procedure followed during a planning session using the system is illustrated in detail in Figure 3.

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.

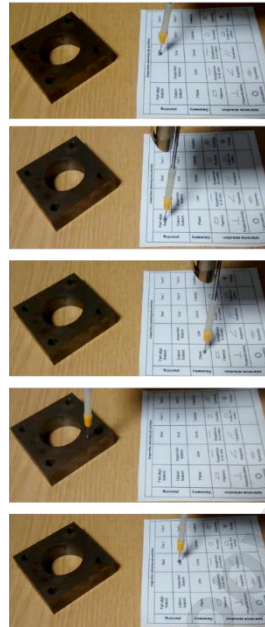


Fig. 3 Procedure to follow in a planning session

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 1.

Table 1. Motion capture log file in CSV format

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

With the use of the two passive markers' recorded positions, a calculation is performed to determine the tool's tip end position. This makes it possible to accurately track and capture stylus' tip position when it is in contact with internal features on a work piece where a marker on the tip would be occluded. In addition, if a marker was attached on the tool's tip then this

would decrease accessibility to small features. Therefore, this tooltip calculation was necessary to overcome these issues.

Strategy capture and data processing

The proposed methodology for this work relies on the hand-held stylus and the tablet analogue combination as the main user input devices for capturing an inspection planning strategy. By using the stylus, a user indicates either probing points on a work piece or an activity on the tablet.

Regarding the probed points, the user must follow a specific procedure: when beginning to approach the component, the LED activation button must be kept pressed until a contact with the workpiece occurs. Then the button is released and the user continues with the rest of the activity. In this way, the path for a probing point is recorded containing the start point, the approach points and the final-end point. With this rule, the user's tactical probing activity can be straightforwardly broken down and recognized within the rich data set. Furthermore, the approach directions and actual touch points are recorded showing how a feature is probed in detail.

Concerning the input from the tablet analogue, before each action the user has to touch the box relative to his or her intended move and press the LED button so that it is recorded in the log file. To involve the tablet in the MoCap, it must be calibrated as explained previously. This occurs prior to the planning session so that its position is logged and recognized later during post-processing. The position of each box on the tablet can then be identified indicating the respective user sub-activity at any specific time.

INSPECTION PLANNING STRATEGY REPRESENTATIONS

As revealed in the literature, inspection planning is a complex task and is made even more difficult with the effort required to capture and represent expertise in meaningful knowledge formats. In this research, a range of different representations are suggested aimed at formalizing this kind of knowledge such as motion trajectory graphs, text instructions, IDEF diagrams, storyboards and annotated video clips. As Sung et al. [43,57] have proven in previous research, these formats can be used to represent engineering knowledge both for analysis and investigation and as advice for novice engineers and training of inexperienced personnel. To demonstrate this, the strategy for aligning a component and measuring the true position of a central hole was captured and formalized using different formats. The test was carried out by only one person with limited experience in metrology and CMM operation. The visual outputs and graphs were produced via a tool developed in C++ using the Visualization Toolkit (VTK) library [58] and MS Visual studio 2015. The outputs are shown and discussed in detail in the next sections.

Inspection plan

According to the National Physical Laboratory [59] a good practice prior to programming a CMM is to write down the intended measurement plan (or inspection plan) so that it can be reviewed and checked for any errors or faults. In this work to fulfil this requirement, the first output of the proposed system is an inspection plan generated using the user-stylus motion log file showing in a chronological order the features probed, the kinds of geometries and shapes inspected, the number of points probed and the inspection tools employed for each step and/or feature (Table 2 & 3). This plan is also associated to, and should be studied in conjunction with, a graph showing the respective features on the work piece and the overall strategic planning sequence of probed features (Figure 4).

Table 2. Part alignment section of generated inspection plan

Instruction	Time (sec)	XYZ coordinates			ID	tool	Points
part alignment feature	22.14	4.51	-84.25	0.92	plane1	tooll	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	tooll	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	tooll	1
touch	38.92	0	34.907	8.5	5		

In the first section of the plan (Table 2) the part alignment steps are shown. In this case three features were probed: a plane, a line and a single point, all with the same tool. As per standard practice, the plane was probed using three points and the line with two. The complete inspection plan (Table 3) generated automatically on completion of the inspection process shows the full strategy for the part that was followed to align the part on the CMM table and measure the true position of a hole.

Table 3. Complete inspection plan

Instruction	Time (sec)	XYZ coordinates			ID	tool	Points
part alignment feature	22.14	4.51	-84.25	0.92	plane1	tooll	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	tooll	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	tooll	1
touch	38.92	0	34.907	8.5	5		
true position	42.00	92.55	-164.78	0.92	tolerance	tooll	
datum feature	43.71	7.08	-104.59	0.97	plane2	tooll	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	tooll	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	tooll	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	tooll	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		

For this activity, several sub-activities were performed and automatically captured such as the definition of three datum features and the actual probing of the hole. All the details related to the part feature geometries, number of points and inspection tools used in each sub-activity are contained in the table. By observing this output, both the strategic and tactical activity of the strategy planned can be recognized. All the actions are listed in chronological order providing the necessary information for repeating the task as required or for training someone with little or no CMM planning experience. An additional piece of information given in the table shows the planning time spent for each step and activity as well as the total time for inspection planning task completion; in the latter case 94.49 seconds. In a practical test to compare this against the time needed to program a CMM in the traditional way using a hand-held joystick, the same trial participant created the strategy and programmed a real computer-driven CMM in 325 seconds. Therefore, early indications show that using the proposed system an inspection planner can generate a component measurement strategy around four times faster, potentially saving a significant amount of time and associated costs.

In Figure 4, which can be studied in isolation from the other outputs, the high level strategic planning sequence is illustrated in the order in which the user performed it. Hence, with a quick visual review, the order of features can be checked along with the geometry and scope within the strategy, e.g. PAF for part alignment feature, DF for datum feature and IF for inspection feature.

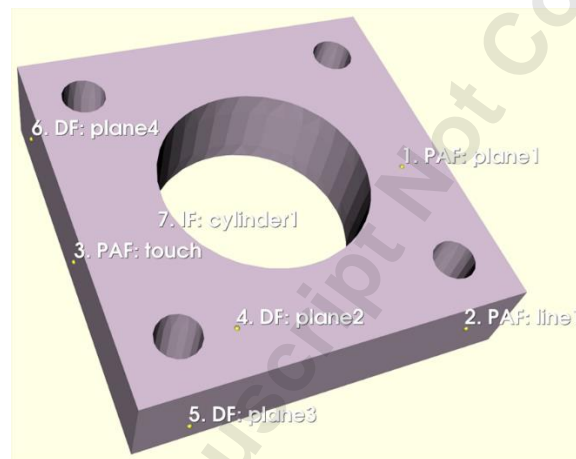


Fig. 4 Strategic activity of planning task

Motion trajectory graphs

Another useful output generated automatically by the system represent parts of the motion trajectory as recorded during the user logging session (Figure 5 & 6) which can be studied in combination.

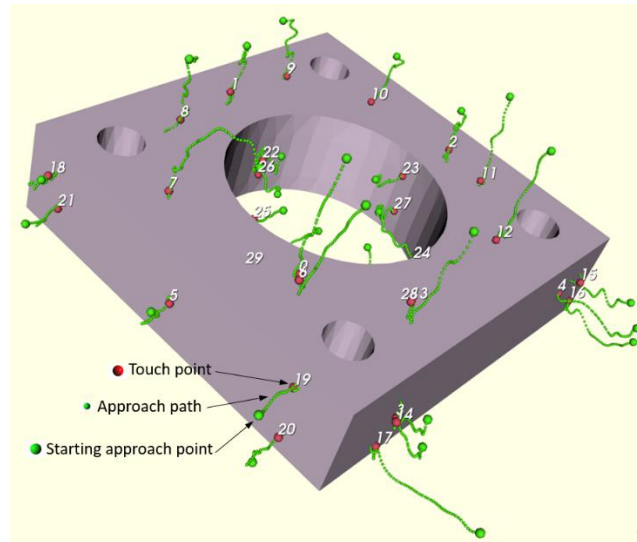


Fig. 5 Trajectory segments of probing points

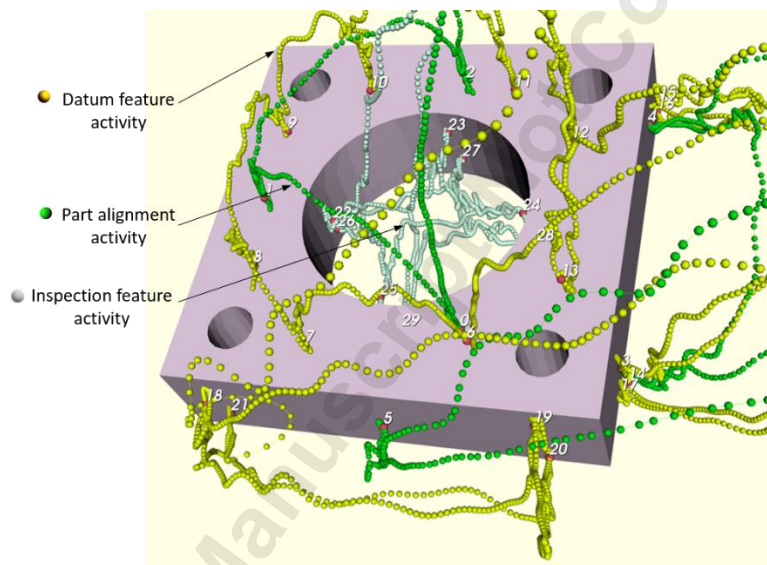


Fig. 6 Strategic activity of different sub-tasks

Figure 5 presents the motion paths for each probing sequence along with the segment points for each feature involved in the inspection strategy. These paths or Chronocyclegraphs, have been used successfully in other knowledge capture applications [60,61] and not only give a visualization of the inspection sequence itself but also provide a unique indication of the inspection planner's behavior whilst generating the inspection plan, e.g. the spacing between the balls indicate faster, more confident movements. Each segment of each path consists of three characteristics: a larger green ball showing its start point, a set of smaller balls indicating the approach path and direction and a red ball for the actual contact points, all numbered accordingly. The color and ball size codification combined with the touch point sequential numbering highlight the tactical component of the inspection process followed by the user at a detailed level. Details for all stages of the plan can be quickly identified; the approach points indicate the off-set implicitly chosen by the user as a safety limit for clear access to the feature relative to other features while the approach paths show the approach direction for accessing each feature and the required number of touch points. Figure 6 also illustrates the strategic activity of the plan highlighting the different sub-actions with different colors. The green colored segments relate to the part alignment activity and features, the yellow segments datum

feature probing and the white segments a feature probing sequence. The sequence numbering is the same in both figures, indicating the respective probing points. Note that the graphs are screenshots from a 3D visual environment which allows the user to explore the trajectories and rotate the viewing angle, focusing on different areas as required. Figure 7 shows different view angles of the same type of view .

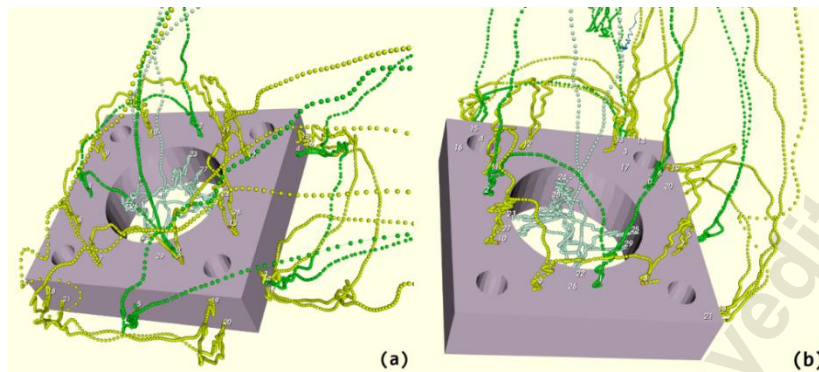


Fig. 7 Different view angles of user strategic activity

Finally, Figure 8 depicts the series of points and lines connecting them together, structuring the inspection path as if it was carried out on a CMM following the finalization of the user defined planning strategy. The system's algorithm uses the captured motion data for generating a collision-free path using a ray-shooting algorithm while adding a retract point for each actual probing point. Each time a collision is detected, the retract point's z coordinate is increased by 5 mm creating a clear, accessible inspection route.

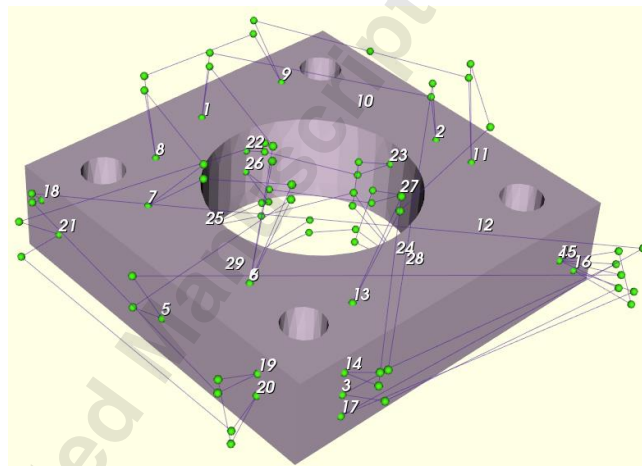


Fig. 8 Collision-free generated inspection path based on captured user strategy

In the future, further studies will be made in relation to the nature of these Chronocyclegraph outputs and what these can tell researchers about the human input to the inspection methodology, process and sequence.

CMM part program

The final output automatically generated by processing the motion log file is a part program which can be used to drive the computer controlled CMM. All the point data are extracted from the structured inspection plan and transformed into the CMM's coordinate system. Additionally, the system creates some midway points for moving the CMM's probing system to safe positions before and after executing the inspection routine for each feature. The program is generated in the CMM's formal programming language DMIS but is adapted to be

executable by the software package Modus [62] provided by Renishaw plc. However, the system's algorithm can easily be adapted to generate any other DMIS code related format. Figure 9 shows a sample of part programming code for driving the CMM to probe the features "plane4" and "cylinder1" in the case study part inspection sequence and define them as datum and inspection features respectively.

```
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,-0.27
GOTO/CART,37.53,50.94,1.53

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

GOTO/CART,38.03,38.32,-9.29
```

Fig. 9 CMM part program automatically generated by the system

IDEF diagram

By parsing the previously generated inspection plan, an additional visualization of the strategy captured is in the form of an IDEF diagram (Figure 10 & 11). The diagram is automatically generated via a VBA macro code embedded in a spreadsheet. This kind of representation provides an easy way of representing the steps followed by the inspection planner and shows the parameters involved at each step such as the geometry and feature probed, the number of points, the tool used and the purpose of probing the feature within the measurement plan. The reader can very quickly identify the strategy and the key decisions made during the task as well as the sequence of sub-activities performed.

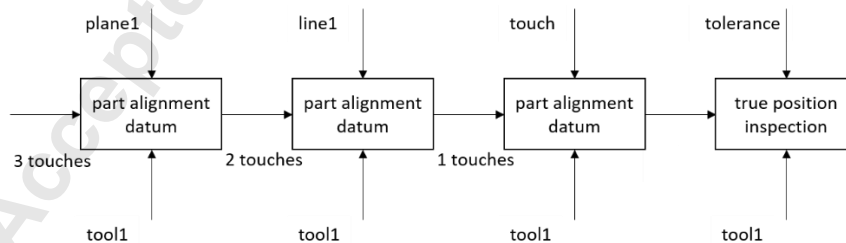


Fig. 10 IDEF diagram of part alignment activity

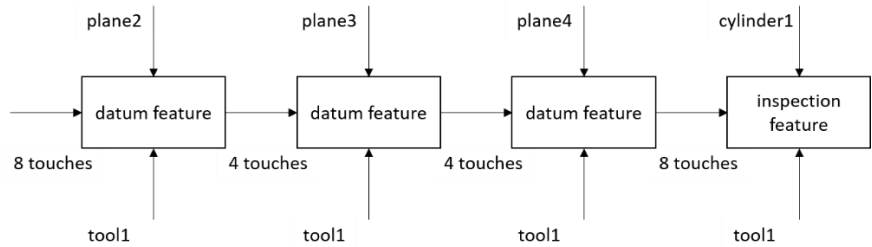


Fig. 11 IDEF diagram of tolerance inspection activity

Text instructions

Another useful format of representing a strategy are the text instructions which provide a brief description of the planning session performed (Figure 12). By generating this format automatically, a set of instructions along with timestamps is provided facilitating a quick review of the planning strategy in chronological order as well as being useful in the training process for inexperienced CMM operators. This format is a summary of the inspection plan generated and complement to this.

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

Fig. 12 Text instructions representation of captured user strategy

Annotated video clip

The last representation, particularly beneficial for training purposes, is an annotated video with subtitles. This shows the expert CMM operator performing a planning strategy session with embedded subtitles, the latter describing the activity taking place at each step. To create these video clips, a video recording device is used during the planning task and the respective inspection plan data file processed to generate a subtitle script file with all the necessary information. Figure 13 below contains screenshots from the video clip captured with embedded subtitles.

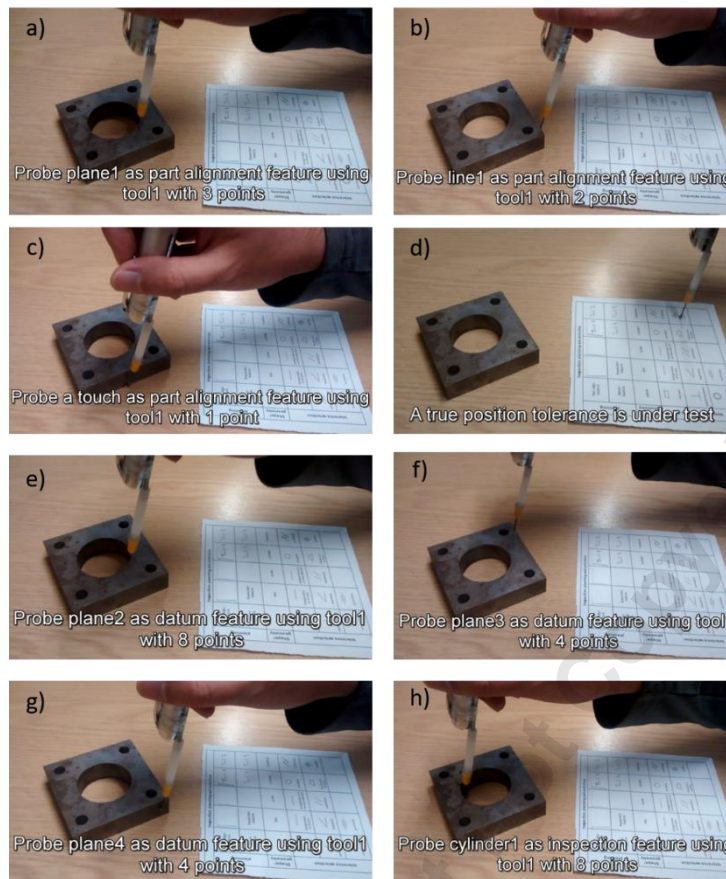


Fig. 13 Screenshots of annotated video clips with subtitles

By way of a brief explanation, in Figure 13, the user first aligns the component using three features a plane, a line and a point (a-c). Then a position tolerance is selected for testing (d) related to the central hole of the part. Three planes are then probed as datum features as part of the position tolerance to check (e-g). Finally, the central hole is inspected using 8 points (h). All the activity is displayed in the video capture along with instructions as subtitles which show details for each step of the inspection plan.

Storyboard

Any combination of the various knowledge representations shown previously can be used. One way of including them all, is to combine them into a single storyboard representation (Figure 14). Sung et al. [43] have proven in past research that this format provides an overview of the captured user activity in chronological order. By studying the storyboard, an engineer can detect all the decisions and sub-actions performed, the tools used and the timing for each step during the planning session either strategically or using the formats of their choice for specific tactical stages of the process.

Due to the breadth and simplicity of its structure, the storyboard can be used by CMM operators with different levels of experience. That is, novice CMM programmers can study this as training material and simply follow it, create a similar strategy altering any element or step they would like to and compare it against the one studied. In the case of experienced users, the storyboard can not only inform the operator regarding the general approach but also how a new and different measurement plan may be possible. The storyboard could also be as reference for generating measurement strategies for different components with similar features or combinations of features. For example, taking the strategy from a component with a pitch circle diameter (PCD) feature and applying it on another part having this similar set of features.

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, -0.995584, -0.0922546, 0.0173746, 84.9917 touch, 24, 39.2461, 16.9877, 13.5, -0.183722, 0.982826, 0.0173207, 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	

Fig. 14 Storyboard representation

CONCLUSION

This paper has demonstrated a real world MoCap-based system for inspection planning capture and formalization using multiple knowledge representations. The automated analysis of MoCap data can be used to capture and extract inspection planning knowledge and represent it in various formats including motion trajectories (Chronocyclegraphs), inspection plans, CMM part programs, text instructions, annotated video clips, IDEF diagrams and storyboards. As shown in previous research, these representations are easily understood while they can be adapted to be stored and embedded in a PLM system.

Although only a single-user test was conducted, this work has proven the practical application of non-intrusive logging of CMM operators and inspection planners in the real world based on motion tracking technology and how it can be used to formalize expertise in multiple formats.

Future work will focus on trials with more participants aiming to identify common patterns of activities during planning a measurement strategy. Moreover, it is intended that the tablet analogue will be further extended as user input device to include more options as well as the evaluation of the system and generated outputs by expert engineers so they can provide feedback for further improvements. The system will also be used to carry out inspection planner behavioral analysis, to provide a deeper understanding of the rationale behind CMM planning.

Finally, this approach also demonstrates an entirely new paradigm for the rapid planning and part programming of CMMs and potentially, other manufacturing processes.

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