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AUTOMATING HUMAN SKILLS : PRELIMINARY DEVELOPMENT OF A HUMAN FACTORS METHODOLOGY TO CAPTURE TACIT COGNITIVE SKILLS

Antoinette Caird-Daley
Department of Integrated Systems
Cranfield University
Cranfield
Bedford, MK43 0AL, UK
a.caird-daley@cranfield.ac.uk

Sarah R. Fletcher
Department of Integrated Systems
Cranfield University
Cranfield
Bedford, MK43 0AL, UK
s.fletcher@cranfield.ac.uk

William Baker
Department of Integrated Systems
Cranfield University
Cranfield
Bedford, MK43 0AL
w.baker@cranfield.ac.uk

ABSTRACT

Despite technological advances in intelligent automation, it remains difficult for engineers to discern which manual tasks, or task components, would be most suitable for transfer to automated alternatives. This research aimed to develop an accurate methodology for the measurement of both observable and unobservable physical and cognitive activities used in manual tasks for the capture of tacit skill. Experienced operators were observed and interviewed in detail, following which, hierarchical task analysis and task decomposition methods were used to systematically explore and classify the qualitative data. Results showed that a task analysis / decomposition methodology identified different types of skill (e.g. procedural or declarative) and knowledge (explicit or tacit) indicating this methodology could be used for further human skill capture studies. The benefit of this research will be to provide a methodology to capture human skill so that complex manual tasks can be more efficiently transferred into automated processes.

Keywords: skill acquisition, task analysis, automation.

1 INTRODUCTION

Most modern high-value manufacturing systems continue to rely heavily on manual work processes. Technological advances have increased the possibilities of developing intelligent automation to replace manual tasks which could improve operational efficiency, productivity and working conditions within an organisation. Currently, however, there is insufficient knowledge and understanding of what manual tasks, or task components, would be most suitable for transfer to automated alternatives. Capturing simple and observable physical task activities is relatively straightforward, for example by objective measures of motion. However, more complex manual tasks often involve a significant amount of unobservable cognitive processing that cannot be captured as readily. Thus, if intelligent automation alternatives are to be developed to replace human work, it is necessary to be able to classify the more complex and concealed aspects of human skill – the cognitive processes responsible for the output of physical activity.

1.1 Hierarchical Task Analysis (HTA)

Hierarchical task analysis (HTA) has been recognised as one of the most commonly used and versatile methods for deconstructing and analysing manual activity and has been used to represent a wide range of tasks (Kirwan and Ainsworth 1992), including those with cognitive components. An HTA approach represents a systematic method of describing how work is organised in order to meet the overall task objective. It involves a top-down approach that breaks down a task into a nested hierarchy of goals, sub goals, operations and plans. The operations are the observable actions which need to be performed by an operator (at the lowest level of the HTA). Plans are inserted between the levels of the hierarchy and represent the unobservable decisions of an operator, determining the sequences in which the operations are performed.

There have been concerns over the ability of HTA to fully express cognitive task elements (Stanton, Salmon, Walker, Baber and Jenkins 2005) and subsequent attempts to identify a single analytical method that can adequately assess both types of behaviour, have largely been unsuccessful. Consequently, a number of authors (for example, Phipps, Meakin and Beatty 2011) have proposed extensions to the standard HTA that would incorporate cognitive task components, examples of which will now be discussed.

1.2 Extending HTA: Task Decomposition and Skill Classification

Task Decomposition provides one approach for expanding the HTA method in order to elicit more detailed task information, including the cognitive aspects of task performance. During a Task Decomposition, the lowest levels of an HTA (the operations) are broken down further into a number of categories which are most relevant to the research requirements (Kirwan and Ainsworth 1992). The Task Decomposition technique may be used to apply skill classifications to the HTA and identify task components associated with 'tacit knowledge'.

Tacit knowledge refers to the sort of information that people use readily but find difficult to express because it is not consciously recalled, it is applied instinctively and often resembles intuition (Smith 2001). Unlike explicit or codified knowledge, which can be more readily communicated (verbally or in written formats such as in operating instructions and reference manuals), tacit knowledge is typically experiential, learnt by observation, imitation and practice, or by being socialised into a way of doing things. Consequently, it is difficult to convert tacit knowledge into explicit knowledge as it requires 'finding a way to express the inexpressible' (Smith 2001).

Phipps et al. (2011) investigated the use of the Skill, Rule and Knowledge based (SRK) framework developed by Rasmussen (1983) as a means for expanding HTA to identify tacit cognitive task elements. According to the SRK framework, human performance during a task can be classified using one or more of three 'levels': i) skill based (associated with routine, learned actions); ii) rule based (associated with rule- or heuristic-driven responses to problems) and iii) knowledge based (associated with reasoning about problems for which there is no obvious response). Each of these levels involves progressively more cognitive effort, with the skill based level associated with tacit knowledge and the knowledge based level associated with declarative (explicit) knowledge.

The aim of this research was to trial an appropriate methodology for the capture of tacit skill to enable the measurement of both observable and unobservable physical and cognitive activities associated with manual tasks. In light of the proposed techniques outlined above, the methodology to be trialled would involve HTA and Task Decomposition.

2 METHOD

The study was designed to test a methodology for capturing tacit skills by exploring the cognitive elements involved in the performance of a manual task. For this, a combined HTA and Task Decomposition approach was selected as this would enable progressive exploration of a suitable manual task using subject matter experts (SMEs).

2.1 Task

To test the methodology, a relatively simple manual task involving tacit and explicit skill was required. A tungsten inert gas (TIG) welding task of approximately 5-10 minutes was selected: this was simple enough to minimise unnecessary complexity from the task itself but would still involve a considerable degree of cognitive processing for the co-ordination of continuous and simultaneous physical activities (the use of both hands for the weld and one foot to operate the gas release foot pedal). The task was ideal as it offered a relatively straightforward procedure with the need for tacit skills for continuous information processing and decision-making.

2.2 Participants

Two experienced welders (at least ten years of experience) took part as SMEs for the main data collection which required them to be observed while performing the manual task, describe their actions in recurrent interview sessions, and to instruct two novices. An independent expert welder was also recruited to assess the reliability and validity of the analysis . In addition, a further SME was recruited for informal discussion simply to provide a broader contextual understanding of the task.

2.3 Process

Prior to formal data collection, informal discussions were held with the two SMEs to plan the proposed data collection procedure and build rapport. This provided the researchers with an opportunity to gain a general understanding of the task to help inform subsequent questioning and the selection of task decomposition categories.

Four main data collection sessions lasting between 2.5 to 4.5 hours were conducted, two per SME at their own welding facilities. During the first sessions, the SMEs demonstrated the setting up and laying of several welds, providing detailed explanations of the activities and demonstrations, responding to questioning and providing basic welding theory. During the second sessions, each SME instructed a novice to set up and lay a weld so that the instruction could be observed and notes made on the procedure in order to build the HTA. Both expert welders chose to decompose the welding task into part tasks and then build the part tasks into a full task. Data collection and analysis was progressive and iterative, with emergent data and results being used to refine further data collection and the selection of the task decomposition categories. Observation sessions were run until redundancy was achieved (i.e. until it was evident that no further or new insights were emerging) and full coverage of the task under investigation was achieved.

2.4 Analysis

The progressive re-description of the sub-goal hierarchy could theoretically continue indefinitely and understanding when to stop the analysis can be one of the most difficult aspects of HTA. Stanton et al. (2005) recommended that the analysis should continue until the sub-goals and operations are clear to both the analyst and the subject matter expert(s). This method was used in the current study and the procedure for developing the HTA has been presented in Figure 1.

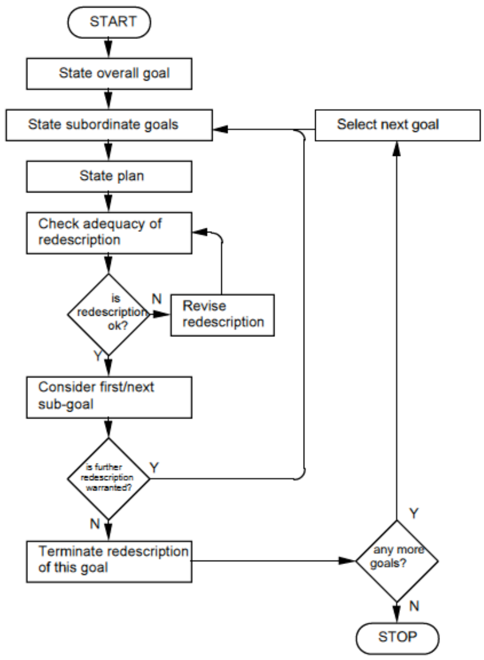

Figure 1: Procedure for developing sub-goal hierarchy (Stanton et al. 2005).

In deciding on the task decomposition categories, reference was made to the categories suggested by Kirwan and Ainsworth (1992) as well as taking into consideration the preceding literature on the nature of human skill, skill acquisition and human error. The HTA and Task Decomposition analysis were reviewed firstly, by one of the welding experts that had taken part in the study and, secondly by an independent subject matter expert.

3 RESULTS AND DISCUSSION

Both the HTA and Task Decomposition analysis were documented in tabular form. The HTA provided a systematic representation of how task processes should be organised in order to successfully complete the assigned task (Table 1). Each level of the HTA was represented in a numerical sequence; for example, the overall goal of 'Lay weld' which was numbered '4' to represent a super-ordinate goal. The immediate sub-goals were then numbered from 4.1 – 4.7, with operations represented in a similar manner (e.g. 4.4.1 – 4.4.2). In this way the HTA fully described the physical task components and provided a template from which further analysis could be performed using a Task Decomposition.

Table 1: Hierarchical Task Analysis for a manual task (a TIG welding example); sub-goals have partially been removed due to space restrictions.

0	**Set up and lay a butt weld.** *Plan 0: 1 - 2 - 3 - 4*		
1	**Set up equipment.** *Plan 1: 1.1 - 1.2 - 1.3*		
	1.1	***Select filler rod***	
	….	**....**	
2	**Simulate laying a weld**. *Plan 2: 2.1 - 2.2 - 2.3 - 2.4 - 2.5 - 2.5 - 2.6 - 2.7*		
	2.1	***Place (right or left) foot on foot pedal, and depress***	
	….	**….**	
3	**Tacking together the welding pieces.** *Plan 3: 3.1 - 3.2*		
	3.1	***Prepare to tack the welding pieces.*** *Plan: 3.1.1 - 3.1.2 - 3.1.3*	
	….	….	
4	**Lay weld.** ***Plan 4: 4.1 - 4.2 - 4.3 then 4.4 - 4.5 - 4.6 in unison throughout the laying of the weld, then 4.7***		
	4.1	***Position torch at the start of the weld***	
	….	**….**	
	4.4	***Manipulate the filler rod.*** ***Plan 4.4: 4.4.1 - 4.4.2 in unison through the laying of the weld***	
		4.4.1	Stroke the filler rod in and out of the weld pool
		4.4.2	Feed the filler rod through the fingers
	4.5 *	***Control the movement of the torch***	
	….	**….**	
5	**Make post weld inspections:** *Plan 5: 5.1 - 5.2 - 5.3 - 5.4*		
	5.1	***Lay down tools, remove mask***	
	….	**….**	

* = sub-goal has been used to illustrate the task decomposition analysis in Table 2

Using an appropriate set of sub-headings / categories, each task process identified in the HTA was described in a series of statements concerning particular aspects of the task. The resulting Task Decomposition analysis has been presented in Table 2 (a partial decomposition of sub-goal 4.5 ‘Control of movement of torch’ is shown for purposes of brevity).

The Task Decomposition showed that the sub-goals and operations described in the HTA could be further broken down according to the different purposes of each task component. The ‘Purpose’ category was therefore used to provide additional background information related to each component in order to improve the comprehension of the HTA and Task Decomposition analysis. Once the context of performance was established, the subsequent categories (‘Cues and expectancies’ and ‘Decision’) identified the system cues that were used by the operators to inform the decision-making process that ultimately lead to a physical ‘Action / response’ in order to achieve the intended purpose.

Within these categories, a range of cues (e.g. visual, tactile or auditory sensory information) were used by the operators to evaluate the characteristics of the system (e.g. 4.5(a): ‘Visual – looking for weld pool to be in the correct plane’) and to make inform decisions. The use of multi-sensory information to perform a single aspect of the task highlights the complexity of human performance.

However, by understanding the cues and decision strategies that initiate human performance, more relevant automation alternatives can be developed.

Table 2: Task Decomposition for a manual TIG welding example (restricted to sub-goal 4.5)

HTA Level	**Task Decomposition Category**									
	Purpose	**Cues and expectancies**	**Decision**	**Action / response**	**Performance level**	**Co-ordination requirements**	**Critical values**	**Likely errors and consequences**	**Potential to correct errors**	**Different welding configurations**
4.5 Control of movement of the torch	(a) For even heat dispersal	**VISUAL:** Looking for the weld pool to be in the correct plane.	Is the weld pool in the wrong plane?	Horizontal movement of torch. Ensure the heat is evenly distributed over the seam line.	***Skill based***	n/a	n/a	The arc is often not uniform. If the weld pool is in the incorrect plane = reduced penetration	n/a	n/a
	(b) To control torch speed	**TACTILE:** Feeling how tacky the weld pool is when the filler rod is dipped into it.	Is the weld pool too viscous?	i) Change speed of the torch. ii) Adjust foot pedal to control the current.	***Skill to Rule based*** (depending on attention).	Co-ordinate weld speed with foot pedal control.	n/a	i) Moving the torch too slowly = heat build-up causing a hole. ii) Moving the torch too fast = reduced penetration	Adjust speed of movement or current.	n/a
	(c) To maintain optimal height above the weld pool	**AUDITORY:** Faint hiss.	Can you hear a faint hiss? Electrode too high from the parent metal.	Move the electrode to the correct height above the parent metal.	***Skill to Rule based*** (depending on attention).	Co-ordinate the filler rod. Ensure tip of filler rod is within the gas envelope.	2 mm above parent metal.	If too high, the heat will reduce.	Move the electrode back towards the parent metal	Variation with different metals, thickness etc.

Additionally, the Task Decomposition enabled the performance of the operators to be classified according to the SRK framework (Rasmussen 1983). This ‘Performance level’ category identified task components in which the action / response of the operator was based on the use of tacit knowledge. The Task Decomposition found that operators predominantly used a Skill to Rule based level of performance which suggested tacit knowledge was mainly used to perform the overall task. None of the task components were classified as Knowledge based, although, this would be expected due to the high level of experience of each operator. In many situations, the distinction between Skill and Rule based performance levels was not clearly defined and task components often involved aspects of both classifications. Generally, the cues and decision-making strategies were found to be Skill based as these relied on subjective evaluations of sensory information obtained by the operators. Rule based aspects of the task components tended to be associated with the selection of appropriate actions / responses from a set of alternatives (e.g. sub-goal 4.5(b)) or where critical values were used to define the intended outcome of the action / response (e.g. sub-goal 4.5(c)).

Skill based task components (relied on tacit knowledge) were more difficult to fully represent than those which were predominantly Rule based and further investigation would be recommended to adequately understand these task components. Nonetheless, the classification of individual task components according to the use of knowledge has provided a useful framework in order to evaluate the suitability of task components for transfer to automation. Although human performance tends to become less error prone with the acquisition of skill and expertise, errors still occur. Automated alternatives may offer improved reliability however, within the context of function allocation between humans and automated systems, it is pertinent to consider the potential for errors and the capacity for a situation to be recovered. Task components associated with a Rule based performance tended to demonstrate an ability to recover errors, which may indicate an improved suitability for transfer to automation. Task components that relied on mainly on Skill based performance however, showed limited potential to resolve errors as there was a greater reliance on tacit knowledge to control performance.

Limitations of this research are related to the small sample size of participants and the specific nature of the task. A larger sample size would enable the influence of individual differences to be assessed. To maximise the reliability and validity of the technique, it should be applied across a range of tasks to assess its applicability in different types of manual work. 'Different welding configurations' were considered within the Task Decomposition to slightly expand the scope of the manual task beyond the particular subject task. It was evident that the operators were not only experienced in a single, particular task but rather across a multiplicity of manual tasks. The Task Decomposition-HTA technique should also be trialled across different experience-level groups so that the effects of training and experiential learning pathway can be better understood.

4 CONCLUSIONS

A Task Decomposition was used to expand traditional Hierarchical Task Analysis to include exploration of tacit knowledge. This method enabled both the observable and unobservable physical and cognitive aspects of a manual task to be identified as well as specific task components that could be suitable for further investigation. Experienced operators were found to mainly use Skill to Rule based performance levels, from which the use of tacit knowledge was inferred. This is likely to be due to their high level of experience and the simplicity of the task. Future investigations should attempt to assess a wider range of experience levels (e.g. novice and apprentice operators) in order to understand the progression associated with training of experiential, acquired knowledge and how this develops instinctive or intuitive activities. Providing instruction to novices was beneficial to the development of the Task Decomposition as, experienced operators had to be more cognisant of what they do in order to verbalise it. This means that observations of training scenarios are likely to provide a head start in further development of the Task Decomposition-HTA technique. Individual differences between operators were observed in situations where they were able to choose between alternative strategies (e.g. sub-goal 4.5(b) in Table 2). These actions would likely be based on 'rules-of-thumb' developed by the operator through experience. The potential impact of individual differences between operators needs to be explored in further research to ensure validity of the Task Decomposition-HTA technique. Finally, as the purpose of developing this methodology is ultimately to evaluate what elements of manual tasks are most suitable for transfer to automation, future work must develop in this direction. When confidence in the reliability and validity of the method has progressed it will then be apt to test suitability for transfer to automation, of varying type and levels. This is the intended direction for this research theme.

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