Human-Centred Design of an Automatic Train Regulation System

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Abstract

Modern urban light rail systems must deliver a frequent and regular train timetable in order to provide a good service to passengers. This paper describes how a human-centred design approach was taken to the provision of automated functionality that aims to augment human operators in one particular operational practice in the rail domain. Automatic Train Regulation (ATR) is a software tool that automatically modifies train departure times and coasting speed in order to optimise the service against timetable or headway. ATR achieves this by monitoring train movements and issuing control actions based on the detection of actual or predicted service disruptions. It was realised that the way that traffic controllers (signallers) and train drivers understand, interpret, and interact with the ATR system must be carefully designed from the outset. The challenge was to ensure that work practices informed the conceptual design of the automation, not just the visual appearance or interaction design. The paper describes how Human Factors methods were used to address these issues, and in particular how low fidelity prototyping and cognitive walkthroughs were used to explore the task-artefact cycle and raise user requirements during development of the system.

Background

Railways have always been complex, distributed socio-technical systems (Wilson et al 2007) that comprise many human actors such as train drivers, maintainers, and station staff. Within this system there is a need to supervise the rail traffic such that a safe and prompt service is provided to passengers. Historically the traffic controller (also known as the signaller) has provided this function, in conjunction with the rail signalling technology current to the time. From a business perspective, the number of passengers travelling by light rail or metro railway is tending to increase year by year (by 42% between 1995 and 2008 for London Underground (UK Department for Transport (2010a)). This leads to more and more pressure to increase the capacity of metro railway infrastructures, often through the introduction of new technology. Correspondingly, this leads to changes in the role of the traffic controller. Within a modern Communication-based Train Control (CBTC) system, train driving can be fully or partially automated, under control from a timetable (via Automatic Routing Setting (ARS)) and signalling interlocking systems that control the movement of trains. Today, this is the type of system that is supervised by the traffic controller at a remote control centre. The modern CBTC technology has tended to change the role of the traffic controller in much the same ways as automation has affected operators in other high-hazard industries (Bainbridge (1987)): the role of the person tends to changes from an active contributor to more of a 'supervisor' of automated functions (when the system is running to plan).

The high throughput of trains in many metros means that the effect of unplanned system behaviours (perturbations) can have severely disruptive effects, and consequently affect passenger journey time and satisfaction. The traffic controller is increasingly asked to perform a 'strategic' planning function, and to try and fix problems that have occurred, or help the system avoid trouble in the first place. Against this background, an operational practice known as 'regulation' becomes important.

Regulation as an operational practice

Traffic controllers in many British-style railways will perform actions that they will describe as "for regulation purposes" ('regulation' in this sense has more in common with 'to make regular', rather than necessarily to conform to a rule).

The purpose of regulation is to adjust the train traffic so that the pattern of trains conforms to the plan that the traffic controller has for that area of the railway. At the level of goals, regulation is generally in response to an unplanned system perturbation (such as a train cancelation or a late departure from a station). Re-planning the train service in these situations is a necessary and important activity (Kauppi et al (2006)).

At the tactical level, traffic controllers have a range of interventions that they can make for regulation purposes. Delaying a train ahead by preventing a departure route from becoming available is a common regulation tactic when dealing with a late train. If a traffic controller delays a train ahead at a platform, it will pick up more passengers. This makes it possible for a late train behind to catch up, as it need not stop at the station for so long because there will be less passengers waiting to board. It also makes the headway more even hence delivering a better service to passengers, as they wait for shorter periods between trains.

The problem is that small deviations from the timetable tend to propagate through the system and eventually lead to significant service disruptions. With a high throughput railway, even short delays in a train leaving a station can quickly escalate and lead to service degradation and reduced customer service. This is a problem that 'Automatic Train Regulation' (ATR) systems are designed to help solve.

Automatic Train Regulation

ATR systems (implemented within CBTC) monitor and predict the railway service in real-time, checking for actual or predicted service perturbations. If a perturbation is detected or predicted, the ATR system will run a number of 'what if' models, compare them, and come to a conclusion as to the best interventions necessary in order to reduce the impact of the perturbation (Aun and Harris (2005)).

In general ATR systems can control trains automatically by adjusting either the run profile (the time taken by a train to travel between stations) or the dwell time at a station (how long a train stands in a platform, able to receive passengers). Generally run profile adjustments are used to make trains travel faster between stations. Dwell times are changed for a variety of reasons. They can be shortened in order to catch up time for a late train, but can also be lengthened so that more passengers will board a train.

ATR systems generally provide two different strategies for minimising disruptions to the train service; one that attempts to maintain the timetable (schedule adherence) and one that attempts to evenly space the trains on the railway (headway adherence).

The design intent in all these systems is that ATR complements the operational staff. It is intended to make tactical adjustments automatically, allowing operators to concentrate on strategic issues. Realising this design intent is where the Human Factors challenges arise.

Automatic Train Regulation for the Victoria Line Upgrade

Invensys Rail Ltd (IRL) is supplying the Automatic Train Control system for the Victoria Line Upgrade (Heape & Lowe (2009)). The Victoria Line is part of the London Underground metro system, and since the early 2000's the line has been undergoing a significant upgrade that is due to introduce new rolling stock, new signalling, and improve and renew stations and other infrastructure. These upgrades will deliver increased capacity to the line and lead to shorter journey times and more frequent trains for passengers.

As part of this scope, an ATR system is being provided (IRL has previously provided ATR systems for other railways, such as for Singapore North-South and East-West mass rapid transport lines (Aun & Harris (2005)).

Working within IRL, in conjunction with traffic controller subject matter experts at London Underground, we have been applying a human-centred design approach to the provision of the Victoria Line ATR system.

Human Factors is of critical importance to the successful implementation of automation in rail traffic control (Anderssen et al (2009), Balfe et al (2009)), and ATR is no different. The way that operators understand, interpret, and interact with ATR must be carefully designed from the outset. If traffic controllers do not accept ATR or lose confidence in it's functioning, it is unlikely to be used, and the desired benefits will not be achieved.

Not many ATR systems are operational within railway systems, and there are not many users from comparable systems. Based on this situation, we found acknowledgement of the concept of the ‘task-artefact cycle’ (Carroll and Rosson (1991)) valuable from a Human Factors management point of view.

The task-artefact cycle illustrates a difficulty encountered when trying to design novel technology for existing work practices. The cycle shows how new technology (artefacts) introduces new possibilities for behaviour (tasks). In turn, the new behaviour may place new and unexpected demands on the properties of the artefacts designed to support those behaviours, which in turn changes the tasks again, and so on.

The approach taken was to try and iterate through the task-artefact cycle using two main strategies: analysis of the ATR joint system using techniques borrowed from enterprise architecture modelling, and the involvement of representative end-users and the iterative use of low fidelity prototyping techniques within a human-centred design framework.

This has involved conducting system and task analysis, paper prototyping, and low fidelity usability evaluation.

System and Task Analysis

To support the project, a predictive system and task analysis of the capabilities and activities associated with train regulation was constructed. The objective was to understand the underlying work involved in these processes, so that this understanding could be used to inform the design of the joint human-automation system.

The Rail Architecture Framework (TRAK, Department for Transport (2010b)) has been used to produce a set of a system models. TRAK is a set of linked enterprise architecture views that can be used to model different parts of a transport system (such as a railway) and the interactions and dependencies within it. An enterprise architecture is a model of the people, information and technology involved in a system. Using TRAK as a task analysis method allowed the concepts underpinning the joint socio-technical system to be highlighted.

This task analysis (an example is given in Figure 1 below) was based on reviewing previous work on traffic controller cognitive strategies (e.g., Lenior (1993)), and on extensive interviews and observations conducted at a number of rail traffic control centres over a period of time. Due to the fact that traffic controllers of any comparable systems could not be interviewed or observed, the analysis had to focus on the functions associated with the system. To some extent, this was an advantage as it ensured that it was the underlying work, rather than any particular technological implementation, that was represented.

<Figure 1 here>

It was found that the regulation strategies of the traffic controller did involve concepts such as regulation by headway and regulation to the timetable. This indicated that there could be a match (at a high level) between the regulation strategies used by traffic controllers, and those used by the proposed ATR system.

However, a number of relevant issues were highlighted through the task analysis process. For example, it emphasized that the train driver needs to comply with platform departure countdowns at all times, noting that they cannot be sure whether ATR is influencing their train or not.

The task analysis (together with a review of the human-automation interaction literature) was used to describe the provisional system architecture, and the division of functions across system actors (Figure 2). In the proposed allocation of functions, the traffic controller would set the regulation strategy (either regulation to headways or to the timetable) and the ATR subsystem would use it's predictive modelling capabilities to decide how best to intervene, and then to implement those control actions without traffic controller intervention and often explicit knowledge. A similar 'speed adjustment' concept called ERASMUS is currently being evaluated for air traffic control (Averty et al (2007)). Figure 2 also shows how the train driver performs an important role in this system design.

<Figure 2 here>

Based on the division of functions and a review of the background literature, a set of design principles were created in conjunction with traffic controller subject matter experts. These principles stressed our emphasis on joint system performance: our design intent was that ATR would be "an unobtrusive team player" (Christoffersen and Woods (2002)). Therefore our design principles reflected this concern.

Conceptual design storyboards were produced based on the design principles and the provisional allocation of functions. These storyboards and mock-ups were used in the next phase of the project.

Paper Prototyping

The paper prototyping exercises involved subject matter experts (ex-traffic controllers and train drivers) being asked to take the role of traffic controllers and train drivers in a series of group cognitive walkthrough exercises. The purpose of these exercises was to explore the ATR requirements and system behaviour, in relation to the operational practices and possibilities that would be highlighted through operator interaction (with reference to the task-artefact cycle, as described above).

The participants were given situations on the line and asked to talk through and act out how they would use the Automatic Train Control system to respond, with particular reference to the potential ATR system.

<Figure 3 here>

A paper mock-up of the ATR HMI was provided. This was the design that resulted from the system and task analysis process. This HMI was only a starting point in order to understand traffic controller tasks and the design constraints. A system engineer took the role of the 'Computer', and updated the paper HMI and train location snapshots based on the 'actions' of the traffic controllers and how the ATR system would be expected to work. The workshop participants amended the paper HMI with information needs and design ideas as they arose.

It was found that the workshop highlighted behavioural requirements of the ATR system, not just HMI 'look & feel' issues. For example, the workshop reinforced the idea that ATR would need to operate as a 'directable' agent (Klein et al (2004)). The workshop suggested that it should be possible for the human and automatic system components to agree upon a shared regulation strategy (in other words, that the traffic controller would need to tell ATR what the regulation 'goal' was at a particular point in time).

Tasks and information needs associated with communication between ATR, traffic controllers, and the drivers of regulated trains was a reoccurring theme at the workshop. These information needs largely related to the 'observability' (Christoffersen and Woods (2002)) of ATR processes to the human actors. For example, it may be the case that a train driver calls a traffic controller to ask if their train is being regulated, in order to understand why they haven't yet been cleared to depart from a station. There was some agreement that trains that ATR was interacting with should be indicated to the traffic controller, and that the details of the control actions planned by ATR should be available in an associated HMI window. This type of finding was helpful in distinguishing between ATR performance data that was informative to the operator, and data that would potentially be available from ATR but not contribute to situation awareness.

This is an example of how the cognitive walkthrough process was used to explore the requirements and HMI design. On the downside, this is also an example of how the introduction of new automation often introduces new information coordination needs.

By playing through the scenarios it was also concluded that ATR should continue to operate in accordance with traffic controller direction (regulation to headway or by timetable) in emergency situations, taking account of any route holds or manual 'overrides' (e.g. train cancelations, platform skip commands) applied. This also supported the design decision that the ATR system should be 'directed' by the traffic controller. Under this division of functions the general plan should be established by the operator, which should be followed by the automated system components (Klein et al (2004)).

Low-Fidelity Usability Evaluation

Following on from the paper prototyping workshop, a series of low-fidelity interactive HMI prototypes were produced. These prototypes explored different HMI design options, building on the information needs and requirements for human-automation coordination that had been clarified in the workshop.

The prototypes were produced using a number of different tools (e.g., Balsamiq Mockups, Axure RP) at various levels of visual and interactive fidelity.

Initially a very low fidelity mock-up was produced in order to investigate the information that would be displayed in the HMI, and how ATR would provide feedback to the traffic controller (in relation to the 'observability' concept described earlier).

<Figure 4 here>

Over several iterations an increased level of visual (icons, colours) and behavioural (train response) fidelity was introduced into the prototypes.

Usability evaluations following a thinking aloud protocol (Nielsen (1993)) were used to uncover usability and information needs problems with the prototypes. In all cases participants with traffic controller backgrounds were used.

The usability evaluations with the low fidelity prototypes were useful activities in evolving and refining the initial design choices. In particular, findings from these studies showed that the feedback on ATR mode status needed improvement. A range of alternative designs were evaluated before a choice was made.

Following several rounds of low fidelity usability testing, a HMI Specification for the ATR system was produced. This specification captured the HMI visual and interaction design that had been refined through the prototyping phase. The specification was also used to record the operational and Human Factors rationale for design choices. This HMI Specification, and the associated interactive HMI prototype, was found to be a useful communication tool between software engineers and Human Factors specialists. The production ATR system has been built to this specification, and is currently undergoing verification and validation (V&V).

Conclusions

This paper describes how a human-centred design approach was applied to the design and development of an Automatic Train Regulation system.

It was found that an iterative prototyping approach had some merit. Vincente (1999) suggests that this may not be the best approach to take in relation to problems of the task-artefact cycle. However, the design team were able to make progress on the system and HMI design, while at the same time the process revealed cognitive and system behaviour issues that could potentially affect the performance of the joint system. It was also found that this approach made the system modelling 'richer' and added more details regarding the work practice.
The next steps for the project involve further refinement of the system through interactive operability trials, followed by delivery and installation of the product in the near future.

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