Cognitive Systems Engineering Approach to Developing Command and Control Systems

ABSTRACT
Cognitive Systems Engineering (CSE) is a multi-disciplinary human-centred approach to the analysis, design and evaluation of complex socio-technical systems comprising people and technology in real-world domains. This article describes an endeavour to investigate the efficacy of the CSE approach to develop Command and Control (C2) systems. A Virtual Assistant and Persistent Sentinels system was developed as a concept demonstrator for the Tower Air Traffic Control operations. The project team adopted the Decision-Centred Design (DCD) methodology in the development of the concept demonstrator. This article describes how the DCD methodology was used to develop design features to overcome three cognitive challenges. Preliminary evaluation was conducted by obtaining expert feedback through a cognitive wall walk, using cognitive indicators to assess whether system features hindered cognitive performance, and observing the work performance of tower controllers in a proof-of-concept trial.

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INTRODUCTION

The rapid advancement and adoption of IT have radically transformed Command and Control (C2) functions and processes in the modern military command post. C2 functions in the command post are now largely knowledge and network-centric (Yeo, Mui and Leong, 2007). Networked C2 systems have paved the way for pervasive and near real-time access to massive amounts of data from the battlefield and other information sources from the military enterprise. However, this rapid and easy access to information has increased the tempo of military operations and created new challenges to manage and sieve out critical information.

Cognition refers to the way humans think i.e. how we perceive, learn and reason. In the information-rich and dynamic C2 environment, human operators have to focus on multiple tasks simultaneously, and this could result in cognitive overload. Cognitive overload is a well-known bottleneck in human information processing and originates from limitations in human attention (de Greef and Arciszewski, 2008). The modern C2 command post offers opportunities for the design and development of a wide variety of decision aids and automation to augment the cognitive work performance of human operators and command teams.

However, studies and real-life incidents have highlighted several unintended consequences of technology on human work performance. Some of the common problems in human-systems integration include unbalanced workload, reduced situational awareness, decision biases, mistrust, over-reliance and complacency (Parasuraman and Riley, 1997). The pitfalls associated with relying on technology to solve problems in human cognitive performance have sparked growing interest in applications of Cognitive Systems Engineering (CSE) in C2 domains, leveraging our knowledge of human cognitive, perceptual and collaborative skills (Hoffman, Klein and Laughery, 2002) in C2 systems development.

This article describes an endeavour to investigate the efficacy of the CSE approach to develop C2 systems. The development of a C2 system prototype for human tower controllers working in the Airport Traffic Control Tower (ATCT) is used to illustrate the CSE approach.

Cognitive Challenges in Complex Command and Control Operational Environments

The definition of C2 from a human-centred perspective is “a complex, ill-defined dynamic human decision making process that establishes the common intent and transforms that common intent into a co-ordinated action” (Pigeau, 1998). Boyd’s Observe-Orient-Decide-Act (OODA) loop in Figure 1 captures the cyclic suite of cognitive activities in C2. These activities involve the perception of the environment (Observe), assessment of the situation (Orient), decision making over a course of action (Decide) and implementation of the chosen plan (Act). However, in stark contrast to the simple and straightforward OODA loop, the C2 domain is naturalistic, fraught with operational stressors and environmental effects such as ill-structured problems, dynamic situations, diverse operational goals as well as imperfect and voluminous information. All these factors are further compounded by the fast tempo and time-critical nature of C2 operations.

In C2 domains such as tower air traffic control, human cognition is affected significantly by naturalistic challenges as well as the level of human expertise and experience in the tasks performed. Macro cognition is a collective term used frequently to describe cognitive processes and functions in naturalistic work settings (see Figure 2). These macrocognitive processes and functions are influenced by the context of the operational environment (Klein et al., 2003; Cacciabue and Hollnagel, 1995).

CSE is a multi-disciplinary human-centred approach to the analysis, design and evaluation of complex socio-technical systems comprising people and technologies in real-world domains. CSE practitioners combine theories and techniques from cognitive science, human factors, human-computer interaction design and systems engineering. The aim of CSE is to ensure that technological systems are designed adequately to support human performance in naturalistic work environments.

The subsequent sections of this article describe the CSE approach taken by a C2 systems development team from DSTA to develop a C2 system prototype for tower controllers working in the ATCT.

![Figure 1. The OODA loop of C2 activities (Source: Paradis, Breton and Roy, 1999)](image1)

![Figure 2. Macro cognition functions and processes (Source: Adapted from Klein et al., 2003)](image2)
DESIGNING A COGNITIVE COMMAND AND CONTROL SYSTEM FOR TOWER CONTROLLERS

An Overview of Air Traffic Control Tower Operations

The ATCT is a tall windowed structure that is situated prominently in every airport. A team of tower controllers in the ATCT is responsible for managing ground traffic around the runways and airborne traffic in the immediate vicinity of the airport.

The tower controllers’ primary function is to ensure the timely departure and arrival of aircraft on runways under their control. Tower controllers also face the constant challenge of ensuring that the aircraft and passenger safety are not compromised.

To carry out their responsibilities, the tower controllers must scan the runway and track the positions of airborne aircraft in the surrounding air space. The tower controllers have to communicate and coordinate with many parties including team members, pilots, ground vehicle drivers and Terminal Radar Approach controllers on aircraft arrivals and departures. Occasionally, unexpected events may happen during normal airport operations. The tower controllers have to be proactive in detecting these problems early and prevent them from severely affecting tower air traffic control operations. All these activities require tower controllers to be very focused and vigilant.

The Decision-Centred Design Methodology

The team adopted the Decision-Centred Design (DCD) methodology (Crandall, Klein and Hoffman, 2006) in designing the C2 system prototype. This five-phase design methodology (see Figure 3) guides the CSE development process to ensure that design features of the C2 system effectively address macrocognitive challenges faced by tower controllers.

An overview of the tasks carried out at each phase is as follows.

Phase 1: Preparation – Understanding the Context

The Preparation phase involves understanding the domain and nature of the tower controllers’ work, as well as the tasks and functions they perform. The purpose of this phase is to search for high payoff areas where the CSE efforts should focus on.

After a preliminary assessment of the potential cognitive challenges in ATCT operations, the development team believed that the C2 system prototype can be designed with software assistants to help reduce the tower controllers’ workload and facilitate reasonable levels of operational performance even under chaotic situations. These software assistants comprise decision support technologies that are categorised into two functional groups: Virtual Assistant (VA) and Persistent Sentinels (PS).

VA are software-based ‘helpers’ that aid human operators by performing routine tasks such as information retrieval and simple calculations on their behalf. They may also support more complex planning tasks such as impact analysis and resource optimisation. PS are a specific form of software-based ‘helpers’ that play the role of ‘watchdog’ by offloading monitoring tasks that would otherwise require constant human attention. PS allow human operators to divert their attention from low-level monitoring tasks to more complex cognitive tasks that cannot be automated easily. The human operators are alerted by the PS when unusual events happen.

The design goal of a VA and PS system (VAPS) for the ATCT is to augment the tower controllers’ cognitive performance in their work environment by addressing the cognitive challenges in maintaining comprehensive situational awareness and decision making. The VAPS system functions as a virtual team-mate that is context-sensitive and works together with human operators to achieve operational goals.

As tower controllers work in a highly visual environment, the project team decided that the VAPS system should focus on assisting the tower controllers when unexpected situations occur.

Phase 2: Knowledge Elicitation – Uncovering Macrocognitive Challenges

A critical aspect of the DCD methodology is the Knowledge Elicitation phase. Cognitive systems engineers conduct cognitive task analysis (CTA) interviews to elicit cognitive difficulties faced by human operators, potential errors made by novice operators, as well as the knowledge and strategies subject matter experts use at work.

The project team conducted several CTA interviews with tower controllers, air traffic control trainers and tower supervisors. Through this process, the team gathered information on critical incidents that served as the base data for the Analysis and Representation phase. Three scenarios that contain good examples of key cognitive challenges faced by the tower controllers were also identified. These scenarios were used during the Evaluation phase to demonstrate the features of the VAPS system to the tower controllers.

Phase 3: Analysis and Representation – Framing Macrocognitive Requirements

During the Analysis and Representation phase, the project team collated key findings from the Knowledge Elicitation phase in a Macrocognitive Requirements Table (MRT). Macrocognitive challenges are broken down into smaller and distinct challenges, each characterised by critical sensemaking cues and decision anchors.

The critical cues and anchors identified in the MRT were especially important in the Application Design phase, as they eventually evolved to be key design elements in user
**Phase 4: Application Design – Transforming Macrocognitive Requirements into Design Elements**

In this phase, the team designed the features of the VAPS system based on the macrocognitive requirements identified at the Analysis and Representation phase. The following three examples show how macrocognitive challenges have led to the development of design concepts.

**Macrocognitive Challenge 1: Determining Type and Magnitude of an Incident**

A recurrent cognitive challenge for tower controllers is the difficulties in interpreting and understanding incidents as they unfold. The tower controllers’ direct line of sight may sometimes be obstructed by surrounding buildings and foliage. In these cases, they may have to rely on information obtained from ground personnel to determine the type and magnitude of the incident. Difficulties in acquiring sufficient information impeded their ability to perform effective sensemaking.

To overcome this challenge, one of the features of the VAPS system is the control of pan-tilt-zoom cameras that allows the tower controllers to obtain a close-up video of visually obstructed areas.

A straightforward solution would be to provide the tower controllers with manual control of the cameras. However, the project team realized that having to control and monitor the cameras individually would increase the tower controllers’ regular workload. The team also observed that the various locations and directions these cameras were facing affected one’s ability to manually correlate the video to a location – this could further exacerbate the tower controllers’ mental workload.

The team decided that the graphical user interface of the system prototype should include a two-dimensional (2D) schematic plan of the work area with reference lines to help the tower controllers quickly associate the video to corresponding locations of the cameras (see Figure 4). Manual control of each camera may be an additional burden for tower controllers. Thus, the project team developed software agents that will automatically select the most suitable camera to view the corresponding ground location when the tower controllers click on the 2D schematic plan. This click-and-view feature offers an easy and interactive way for tower controllers to monitor incidents. It alleviates their mental workload as they do not have to remember which cameras can be used to view the location of an incident. The agent-based camera system also reduces the tower controllers’ reliance on the ability of ground personnel to report accurate information and lessens the impact of human-to-human miscommunication.

**Macrocognitive Challenge 2: Determining Courses of Action of an Incident**

Once an incident has been identified, the tower controllers have to determine a method to resolve the incident quickly. The standard operating procedures (SOP) for tower controllers contain checklists of actions for many possible events. The VAPS system is designed with a Course of Action (COA) suggestion feature to automatically provide suggestions of relevant key actions according to the SOP checklists (see Figure 5).

<table>
<thead>
<tr>
<th>Macrocognitive Challenge</th>
<th>Macrocognitive Functions/Processes Involved</th>
<th>Why Difficult?</th>
<th>Critical Cornerstones</th>
<th>Potential Errors</th>
<th>Design Ideas</th>
<th>Macrocognitive Functions/Processes Addressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Determining incident happening in parking areas (CTA 1)</td>
<td>Problem detection • Managing uncertainty • Sensemaking</td>
<td>Unable to have a clear visual due to Air Traffic Control's (ATC) distance from the parking areas</td>
<td>Loud sound of two aircraft colliding • Smoke from engines • Landing of foreign aircraft • Trade space between the safety and time (anchoring)</td>
<td>Delay in informing emergency services due to uncertainty about magnitude of situation</td>
<td>Camera to enable the ATC to look at what is happening in areas that are not visible to the naked eye and through binoculars</td>
<td>• Problem detection • Managing uncertainty • Sensemaking</td>
</tr>
<tr>
<td>2. Determining how best to manage incoming air traffic in the event of runway obstruction (CTA 2)</td>
<td>Planning • Coordination • Managing attention</td>
<td>Uncertain about length of time required to resolve the incident’s obstruction</td>
<td>Magnitude of incident (anchoring) • Verbal reporting by pilot of fuel endurance (usually) in terms of number of minutes remaining • Future expected load</td>
<td>Many estimate wrongly the time required for incident to be resolved • May carry out actions that are more conservative or risky than necessary (e.g., direct all aircraft, tell low fuel aircraft to continue circling)</td>
<td>Provide the ATC with a way to easily obtain and keep track of the fuel levels of aircraft • Provide the ATC with a way to monitor the status of incident resolution process</td>
<td>Planning • Coordination • Managing attention</td>
</tr>
</tbody>
</table>

Table 1. Selected information from the MRT for the VAPS system
(Source: Adapted from Klein and Hutton, 2007)
Locations around the control tower are tagged with priority values that reflect their relative importance with respect to air traffic control. The VAPS system prioritises COA suggestions based on the priority value assigned to the locations where the incident occurred. The COA suggestions are also contextualised taking into account other factors such as locations of aircraft on the ground and runway availability.

**Macrocognitive Challenge 3: Determining the Impact of an Incident**

During the CTA interviews, subject matter experts in the tower air traffic control domain described how unfolding incidents affected their ability to guide the take-offs and landings of aircraft during operations. Tower controllers often require substantial effort in coordination, decision making and sensemaking to resolve an incident quickly. The resulting cognitive overload could cause tower controllers to overlook subtle but critical considerations that might impact tower air traffic operations significantly.

Since the tower controllers’ ability to guide the take-offs and landings of aircraft depends heavily on the availability of runways and taxiways, the project team incorporated a Conflict Management module in the VAPS system that informs tower controllers of impending runway usage conflicts. The Conflict Management module incorporates air traffic control heuristics obtained during the CTA interviews. When a runway is unexpectedly occupied by an aircraft or a ground vehicle, the Conflict Management module uses a flight information system to retrieve pre-defined flight plans automatically. The list of aircraft scheduled to arrive or depart in the near future helps tower controllers to anticipate possible delays to the flight plans.

**Phase 5: Evaluation**

After the prototype was created, the project team conducted a Cognitive Wall Walk with tower controllers (Klein and Hutton, 2007) as a means of preliminary evaluation of the system features. The team also used Cognitive Indicators (Long and Cox, 2007) which are specialised heuristics for evaluating how system features in the VAPS system support or hinder cognitive performance.

A proof-of-concept trial was carried out to assess the overall effectiveness of the VAPS system. Within a controlled laboratory environment, the team designed experiments to determine the extent to which the VAPS system enhanced the tower controllers’ reaction time, quality of decision making and quality of awareness. It was found that tower controllers using the prototype performed better under heavy air traffic volume conditions and had increased incident management capacity. The tower controllers also commented that the system prototype helped to improve their situational awareness.

**CONCLUSION**

The development of the VAPS system demonstrated the effectiveness of CSE in designing complex C2 systems to support cognitive work performance. The DCD methodology provided a structured process to elicit cognitive requirements and translate these requirements into system features.

Apart from its use in designing C2 systems for single human operators, the CSE approach can also be applied in other areas such as human-systems integration in unmanned vehicle operations, as well as collaboration and workload management in command teams.

Designers of future military systems can consider adopting a CSE approach to systems development whenever it is necessary to ameliorate cognitive challenges in complex work domains. The CSE approach helps system developers design appropriate decision aids and other forms of automation technologies to improve system effectiveness, as well as enhance safety and work productivity.

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**REFERENCES**


Cognitive Systems Engineering Approach to Developing Command and Control Systems

BIOGRAPHY

Yeoh Lean Weng is Head of the US Defence Technology Office. He is responsible for prospecting technologies and establishing technology collaborations with US government agencies, academic institutions and innovative companies. He facilitates export control and the release of critical technologies to Singapore. Prior to assuming this position in July 2010, Lean Weng was Director (DSTA Masterplanning and Systems Architecting) and led the development of new operational concepts and architectural frameworks. Lean Weng has extensive experience working on large-scale defence engineering systems. As a systems architect, he played a key role in developing the Enterprise System-of-Systems Architecture for defence applications. He also developed the systems architecting methodology for masterplanning and transformation. Lean Weng is an adjunct professor at the National University of Singapore (NUS). He is the President of International Council on Systems Engineering (INCOSE) Singapore Chapter, the INCOSE Region VI Representative to the Member Board and an INCOSE Fellow. He is the Vice President and Chairman of the Industrial Group in the Institution of Engineers, Singapore (IES). He is the President of International Council on Systems Engineering (INCOSE) Singapore Chapter, the INCOSE Region VI Representative to the Member Board and an INCOSE Fellow. He is the President of International Council on Systems Engineering (INCOSE) Singapore Chapter, the INCOSE Region VI Representative to the Member Board and an INCOSE Fellow. He is the President of International Council on Systems Engineering (INCOSE) Singapore Chapter, the INCOSE Region VI Representative to the Member Board and an INCOSE Fellow.

Linus Low Kar Seng was a Senior Engineer (C4I Development). His areas of work involved the design and development of Command and Control systems for sensemaking, decision making and collaboration. He was also a member of the team which spearheaded the development of the Cognitive Systems Engineering technical competency in DSTA. Linus was a member of the Singapore Armed Forces Centre for Military Experimentation Team which won the Defence Technology Prize Team (Engineering) Award in 2005. A recipient of the Defence Technology Training Award (Local), he obtained a Bachelor of Engineering (Electrical Engineering) degree with First Class Honours, and a Minor in Management of Information Technology from NUS in 2003.

Teh Shi-Hua is a Senior Engineer (C4I Development). She is currently managing a project to develop a Tower Air Traffic Command and Control system. She worked on the development of the Virtual Assistants and Persistent Sentinels subsystem as well as a prototype for an information management system. Under the DSTA Undergraduate Scholarship, Shi-Hua graduated with a Bachelor of Engineering (Electrical Engineering and Computer Science) degree from the University of California-Berkeley, US in 2005. She further obtained a Master of Science (Management Science and Engineering) degree from Stanford University, US in 2006.

Oliver Tan Kok Soon is a Principal Engineer (C4I Development) and has many years of experience in developing C4I systems for the Singapore Armed Forces (SAF). His current areas of work include cognitive systems engineering and decision-support systems. Oliver was a member of the Enterprise Command and Control Information System Team which clinched the Defence Technology Prize Team (Engineering) Award in 2003. He obtained his Master of Technology (Knowledge Engineering) degree from NUS in 2001 where he graduated as the top student. A recipient of the DSTA Postgraduate Scholarship, he further obtained a Master of Science (Modelling, Virtual Environments and Simulation) degree from NPS, US in 2005 where he received awards for his outstanding thesis on surface warfare and for graduating at the top of his class. Oliver is currently pursuing a Master of Science (Human Factors Engineering) degree from Nanyang Technological University.