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THE FUTURE OF C2

Comparing OODA & other models as Operational View C2 Architecture

Topic: C4ISR/C2 Architecture

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Abstract

Boyd's Observe-Orient-Decide-Act (OODA) loop is a model of decision-making created from observing jet fighter pilots in combat. Over the course of time, OODA has been adopted by other military services, has influenced the development of grand concepts such as manoeuvre warfare, "shock and awe", and network-centric warfare (NCW), and is widely taught in officer training. In essence, OODA has become an accepted business process model for military Command & Control (C2). This makes it a leading candidate for the operational view of C2 systems architecture.

Boyd was interested in strategy, not C2 systems architecture. Before OODA can be adopted as a guiding paradigm for C2 systems architecture, it is prudent to critically review its suitability. The purpose of this paper is to compare OODA with other candidate C2 business process models and with the needs of NCW, identifying how OODA should be re-engineered.

Introduction

From his study of dogfights during the Korean and Vietnam Wars, Boyd (1976; 1987; 1996) created the Observe-Orient-Decide-Act (OODA) loop as a model of decision-making. Boyd was himself an outstanding US Air Force fighter pilot. However, the OODA loop is restricted neither to jet fighters nor to Air Force operations. Over the course of time, it has been adopted by other services, has influenced the development of grand concepts such as manoeuvre warfare, "shock and awe", and network-centric warfare (NCW), and is widely taught in officer training. In essence, OODA has become an accepted business process model for military Command & Control (C2)[1].

Boyd never published a conventional paper or book on his OODA model, preferring to give two-day, 200-slide briefings to influential politicians, civil servants and military officers. Moreover, the content of his briefings evolved over time. As a result, there is no definitive OODA material available for study that is scientifically

[1] In this paper C2 will be used as the portmanteau term for C2, C3, C4ISR, CCIS, CICS, etc.

tested in the conventional sense. Despite this, we should not abandon the OODA model out of hand. After all, it is a model specific to the domain of military operations that has been subjected to extensive review by Boyd's peers.

As a business process model, OODA could be considered as a leading candidate for (part of) the Operational View (DODAF, 2004) of C2 systems architecture. This would be attractive from the viewpoint of the principle of human-centred design. This principle says that users will better understand and accept a system that employs user terminology, structures its processing according to users' reasoning processes, uses the same domain knowledge as users do, and displays its results in ways familiar to users. If officers use the OODA loop in thinking about C2, then human-centred design suggests that their C2 systems should do so, too.

Straightforward application of the principle of human-centred design would lead to C2 systems that were decomposed into Observe, Orient, Decide, and Act subsystems. Standardisation of these subsystems and their interfaces would enable interoperability to be extended upward from the technical level (e.g. the current practice of interoperability by message passing or database replication) to all three architectural levels. This would open up the future possibility for the competitive development of a category of interchangeable Commercial Off-The-Shelf (COTS) C2 products, analogous to the emergence of Supervisory Control And Data Acquisition (SCADA) systems in industrial process control.

Before OODA can be adopted as the guiding paradigm, it is wise to critically review its suitability. Application to C2 system architecture was very far from Boyd's mind when he proposed OODA (Osinga, 2005). Hence, the purpose of our "Beyond situation awareness: closing the OODA loop" research theme is to verify whether OODA can and should be used in C2 system architectures, e.g. in the context of existing Dutch military systems such as the Integrated Staff Information System (ISIS) and Battlefield Management System (BMS). The research also has potential civil application, e.g. in crisis & emergency management, in computer & network intrusion detection systems, and in dynamic risk management for fraud control.

The purpose of this paper is to document the comparison of OODA with other candidate C2 business process models and with the needs of NCW, identifying how OODA might be re-engineered. There are four chapters. After this introduction, Chapter 2 describes in detail the comparison between OODA and other leading models, identifying a number of shortcomings in OODA. Chapter 3 describes how OODA should be re-engineered in the light of these shortcomings and the needs of NCW. Chapter 4 outlines further work to formalise and test the re-engineered OODA model.

Comparison

OODA

In Boyd's briefings, OODA is a cyclic model of four processes interacting with the environment. By implication, the OODA processes are possessed by an agent that interacts competitively with other agents in the environment. The other agents should be regarded as also operating according to the OODA model.

Three of the four OODA processes are not defined in detail in Boyd's briefings. The exception was Orient, which Boyd (1987, underlining in original) describes as follows: "Orientation, seen as a result, represents images, views, or impressions of the world … Orientation is an interactive process of many-sided implicit cross-referencing projections, empathies, correlations, and rejections that is shaped by and shapes the interplay of genetic heritage, cultural tradition, previous experiences, and unfolding circumstances. … Orientation is the schwerpunkt. It shapes the way … we observe, the way we decide, the way we act".

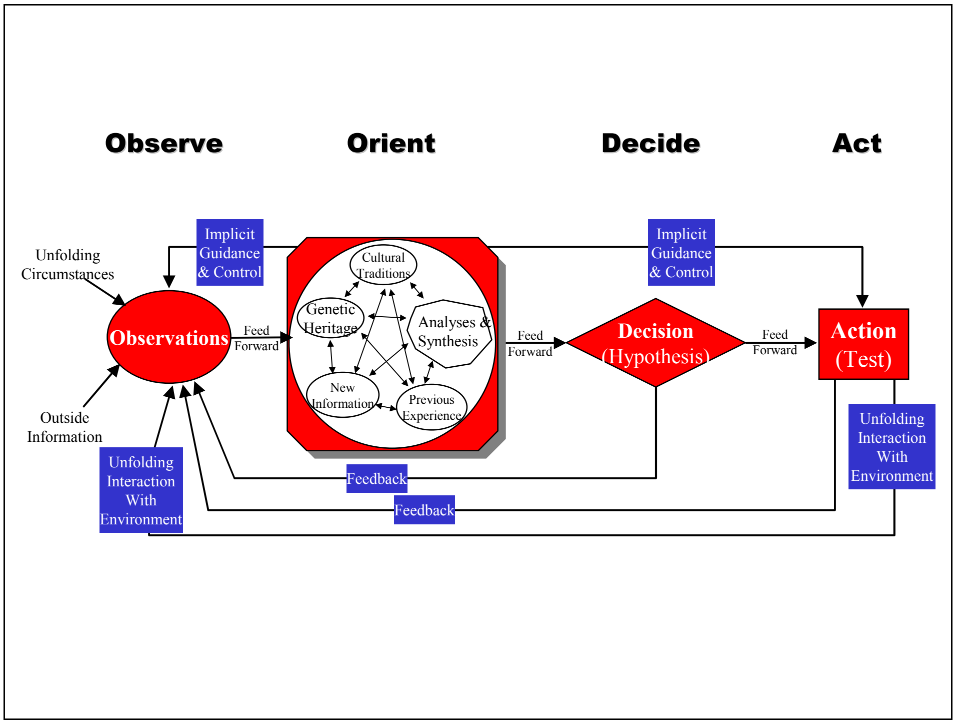

Figure 1. Boyd's (1996) Observe-Orient-Decide-Act model.

The other three processes may be interpreted from Boyd's (1996) depiction of OODA (Figure 1) as follows:

- Observe is the process of acquiring information about the environment by interacting with it, sensing it, or receiving messages about it. Observation also receives internal guidance and control from the Orient process, as well as feedback from the Decide and Act processes.
- Decide is the process of making a choice among hypotheses about the environmental situation and possible responses to it. Decide is guided by internal feed-forward from Orient, and provides internal feedback to Observe.
- Act is the process of testing the chosen hypothesis by interacting with the environment. Act receives internal guidance and control from the Orient process, as well as feed-forward from Decide. It provides internal feedback to Observe.

A unique feature of the OODA model is Boyd's emphasis on *tempo*, i.e. the decision cycle time. Boyd (1987) expressed this as follows: "in order to win, we should operate at a faster tempo or rhythm than our adversaries or, better yet, get inside the adversary's Observation-Orientation-Decision-Action loop".

OODA has a number of shortcomings beyond the absence of a detailed definition of the OODA processes in Boyd's briefings:

- The opponent is not explicitly shown in the OODA model. From Boyd's (1987) statement on tempo we must assume that the opponent's thinking processes can also be modelled as an OODA loop.
- The OODA model was developed from observations of dogfights, i.e. interactions between a small number of agents (typically one-to-one). This does not guarantee that the model can be extrapolated to engagements involving large numbers of participants, i.e. that the model scales up to interactions between many agents. The enthusiastic adoption of OODA by Boyd's peers for large-scale operations is a positive indication – but still no guarantee - that the model does indeed scale up.
- The model is not directly applicable to collaborative decision-making by teams, as in military command staffs. For example, no processes are shown representing negotiation or collaboration between team members. Keus (2002) has extended the OODA model to teams by adding processes for information distribution, the development of shared situation awareness, task re-allocation, confirmation and authorisation of decisions, and team maintenance.

Dehn (2004) has criticised OODA for its lack of psychological validity. In particular, OODA lacks:

- Concepts of attention and memory.
- A cognitive representation of world states and models.

Selection of models

To address these shortcomings of the OODA model, we sought other models in the scientific literature. Like OODA, the models should be process-oriented and at the business / operational level. We preferred models of military decision-making from the psychological literature, but models of decision making in similar real-time, high-risk domains were also relevant.

The following models were used for comparison against OODA:

- Wohl's (1981) Stimulus-Hypothesis-Option-Response (SHOR) model.
- Rasmussen's (1983) model of human thinking in supervisory control.
- Mayk & Rubin's (1988) review of fifteen C2 models.
- Klein's (1998) model of recognition-primed decision-making (RPDM).
- Endsley's (2000) model of situation awareness.
- The Plan-Do-Check-Act model originating from Shewhart (1939) and espoused by Demming (1951).

Wohl's SHOR model

In 1981, Wohl published a scientific paper in the cybernetics literature presenting the Stimulus-Hypothesis-Option-Response (SHOR) model, and placing it in the context of military organisation and operations. Wohl's (1981) paper has been much cited, chiefly because – unlike Boyd's briefings - it is easily accessible in the open scientific literature. Although SHOR is very similar to the OODA loop, there is no sign that Wohl and Boyd were aware of each other's work.

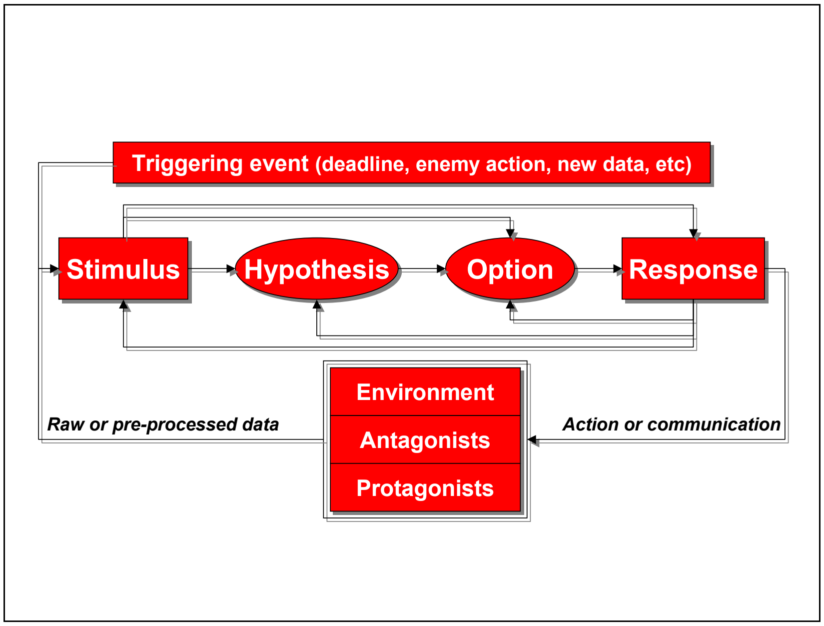

Figure 2. Wohl's (1981) Stimulus-Hypothesis-Option-Response model.

Figure 2 shows the SHOR model. Wohl (1981) decomposes each process in SHOR into sub-processes. We have mapped these sub-processes to OODA as follows:

	Wohl's sub-processes	**Mapping to OODA**
Stimulus (data)	• Gather / detect • Filter / correlate • Aggregate / display • Store / recall	• Observe • Orient • Orient • (Not in OODA)
Hypothesis (perception alternatives)	• Create hypothesis about situation • Evaluate hypothesis • Select hypothesis	• Orient • Orient • Orient
Option (response alternatives)	• Create response options • Evaluate options • Select option	• Decide • Decide • Decide
Response (action)	• Plan • Organize • Execute	• (Not in OODA) • (Not in OODA) • Act

The differences between SHOR and OODA are as follows:

- OODA has no process corresponding to SHOR's store and recall of data. This is equivalent to OODA's lack of a concept of memory and of cognitive representations of world states and models, as noted by Dehn (2004).
- The partitioning of processes differs slightly, in that OODA's Orient process is split over SHOR's Stimulus and Hypothesis processes.
- There are detailed differences in the feedback and feed-forward loops.
- There is no emphasis on tempo in SHOR.

- OODA lacks the equivalent of SHOR's plan and organize sub-processes. In other words, OODA is purely reactive in nature, while SHOR has both deliberative and reactive characteristics. It is noteworthy that, in depicting OODA, some authors add a Plan process.

A key result of Wohl's (1981) paper is his observation that there is a wide divergence between scientific models of decision-making and the reality. Most models assume perfect information about the options available and a rational decision maker whose task is option selection. In reality, military decision-making involves option creation, evaluation and refinement with highly imperfect information. Wohl's observation has been studied in more detail in the naturalistic decision-making (NDM) literature (Klein, 1998).

Rasmussen's model

Rasmussen's (1983) three-level model of human thinking in supervisory control, again published in the cybernetics literature, is even more influential. Rasmussen's key insight is to integrate rule-based decision-making - as in OODA and SHOR - with behavioural stimulus-response ("skill-based") and first-principles ("knowledge-based") reasoning. Figure 3 depicts Rasmussen's model.

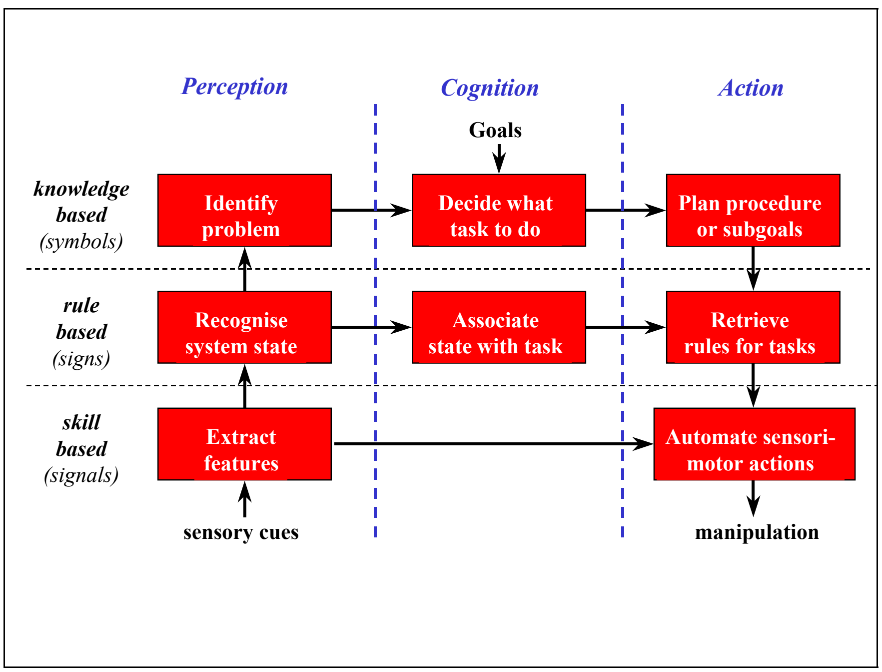

Figure 3. Rasmussen's (1983) three-level model of operator thinking.

According to Rasmussen (1983), decision makers try to minimise cognitive effort, because thinking is such hard work (and takes time). The three levels are applied as follows:

- Decision makers first try to identify signals in the incoming stream of sensory cues that enable them to take action at the lowest, skill-based level of reasoning. This can be done "without thinking", i.e. using stimulus-response behaviour.

- If skill-based reasoning fails, then decision makers apply rule-based reasoning to match the system state to a task that they can execute. As in OODA and SHOR, this involves trying to recognise the situation, to recall a rule linking the situation to a task, and to apply this rule to generate a sequence of sensori-motor actions. This requires some cognitive effort, but is fast. For this reason, rule-based reasoning is common in military constructs such as tactics, doctrine, and standard operating procedures.
- If rule-based reasoning fails (e.g. because the decision maker has no rules for the current situation), then he/she must fall back on knowledge-based reasoning, i.e. on reasoning from first principles. Without decision support, this is very hard work and slow.

Rasmussen's model is particularly fruitful for designing C2 systems. For example, it provides a basis for decision support, for various models of human error, and for designing task analysis methodologies. Sheridan (1988) applies the Rasmussen model to decision support, showing that a system designer can choose to support C2 decision making at the skill-, rule- or knowledge-based levels. Grant (2002) has published a domain-independent software architecture for C2 systems based on the Rasmussen / Sheridan model. The Rasmussen model is the basis for Reason's GEMS model of human error, enabling the development of countermeasures such as design rules for C2 system user interfaces.

The main conclusion to draw from the comparison between OODA and Rasmussen's (1983) model is that OODA needs to be extended from pure rule-based reasoning to all three cognitive levels. Moreover, planning needs to be included in OODA at the knowledge-based level.

Mayk & Rubin's review

Mayk and Rubin (1988) review fifteen C2 models published in the scientific and military literature, including SHOR but not OODA. They observe that one C2 model can be mapped onto another, illustrating their point by providing a "buzz-word generator" that can be used to generate 17576 models. This observation supports the similarities we observed between OODA and SHOR. While it implies that OODA cannot be regarded as unique, it does allow us to re-engineer OODA to include processes or functionality found in other models.

Like Wohl (1981), Mayk and Rubin (1988) point out that published C2 models are decision theoretic in nature. They observe that decision rules are invoked to select an action for a given observation.

Klein's RPDM model

We have seen that Mayk and Rubin (1988) point out that C2 models are decision theoretic. The classic approach to decision making comes from decision theory, itself originally a branch of economic theory. Rational decision-making is seen as a step-by-step process as follows:

- Identify the set of options for responding to the current situation.
- Identify the ways of evaluating these options.

- Weight each evaluation dimension.
- Score each option against each evaluation dimension.
- Select the option with the highest weighted score.

This rational decision-making process depends on the decision maker having the complete set of options and the complete set of ways of evaluating them available to him/her before scoring and selection can take place. When these conditions are met then the selected option is optimal. However, C2 occurs in situations that are invariably uncertain, dynamic and confusing. Rarely do commanders and their staffs have complete information available when they must make a decision. We have seen that Wohl (1981) observes that there is a wide divergence between rational decision-making models and the reality of C2.

About 10 years ago, psychologists started asking themselves whether decision makers used the rational decision-making process in their natural working environment and daily activities (Klein, 1998). The resulting field of research is known as naturalistic decision-making (NDM). NDM researchers noted that decision support systems that enforce the rational decision-making process tend to be rejected by expert users. Moreover, rational decision-making had been found in laboratory experiments, but these experiments usually involved psychology students performing unfamiliar tasks.

Additional experiments showed that people trained in the rational decision-making process did not use it when making decisions in their everyday life outside the classroom. Only when major decisions had to be made like buying a car or a house was the rational decision-making process used. The NDM researchers saw that, for most people, buying a car or a house happened infrequently. In essence, everyone (other than a car salesman or estate agent) is a novice in such situations.

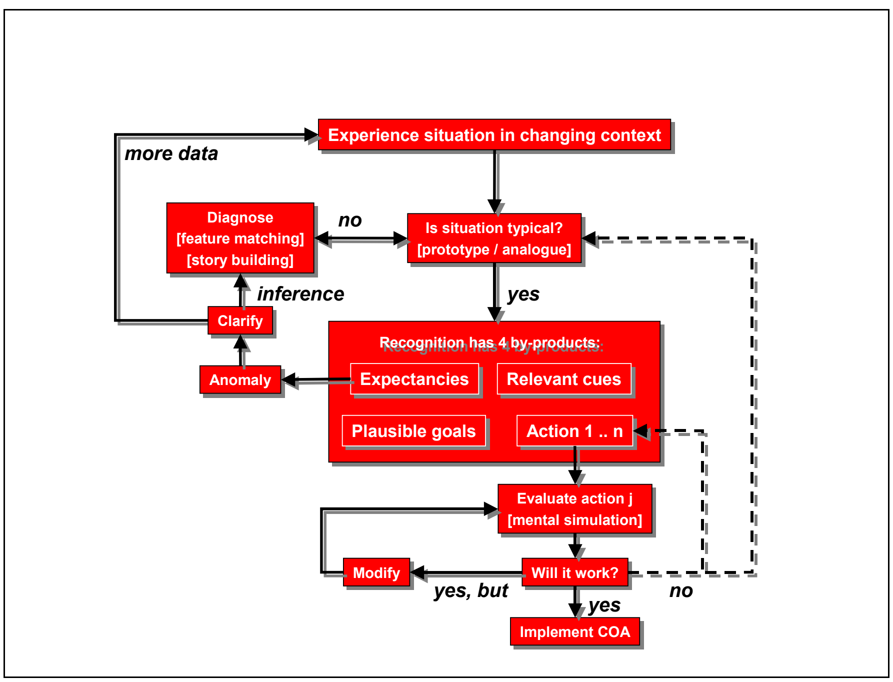

Figure 4. Klein's (1998) Recognition-Primed Decision-Making model.

NDM researchers turned to observing expert decision makers in domains such as fire-fighting, intensive-care nursing, and military C2. Klein (1998) and his co-workers found that experts use a decision making process that has been named the recognition-primed decision model (RPDM); see Figure 4. Experts use their experience of previous incidents to recognise a situation, even a novel one, as an example of a prototype. Since prototypes are associated with a preferred course of action, the experts intuitively know what to do in the situation. As one expert fire-fighter said: “I don’t ever remember when I’ve ever made a decision” (Klein, 1998, p. 11).

Looking at the RPDM with a view to implementing it in a C2 system, we see that it involves processes (Klein, 1998) for:

- Acquiring information about dynamic situation.
- Matching the current situation to a database of prototypes based on relevant cues associated with each prototype. This may not be a direct match, but require making an analogy between the prototypes and the current situation.
- Retrieving the matching prototype, together with its associated preferred COA, plausible goals, and expectancies.
- Identifying anomalies between the prototype’s expectancies and the current situation.
- Clarifying anomalies by obtaining more information about the current situation.
- Diagnosing anomalies to refine the process of matching situations to prototypes.
- Evaluating the preferred COA by simulating it.
- Modifying the COA as necessary based on results of evaluation.
- Initiating implementation of the (modified) COA.
- Initiating retrieval of an alternative COA associated with the matched prototype.
- Initiating search for an alternative prototype matching the current situation.
- Implementing the (modified) COA.
- Generalising particular incidents to become new prototypes, together with their associated relevant cues, preferred COA, plausible goals, and expectancies.

These processes map to the extended OODA model as follows:

OODA	**RPDM**
Observe	• Acquiring information about situation
Orient	• Matching situation to prototypes • Retrieving matching prototype • Identifying anomalies • Diagnosing anomalies to refine matching process
Plan	• Evaluating COA by simulating it • Modifying COA

Decide	• Control of other processes (focus of attention):
	  • Initiating implementation of (modified) COA
	  • Initiating retrieval of alternative COA
	  • Initiating search for alternative prototype

Act	• Clarifying anomalies by obtaining more information • Implementing (modified) COA
OODA lacks learning process	• Generalising incidents to become new prototypes

Comparison with RPDM shows that OODA could benefit from being based on the RPDM sub-processes. Most importantly, OODA lacks a process of learning or adapting to novel situations.

Endsley's SA model

In the cognitive psychology literature, a topic essential to C2 is situation awareness[2]. Situation awareness (SA) is defined as "the perception of elements in an environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 2000).

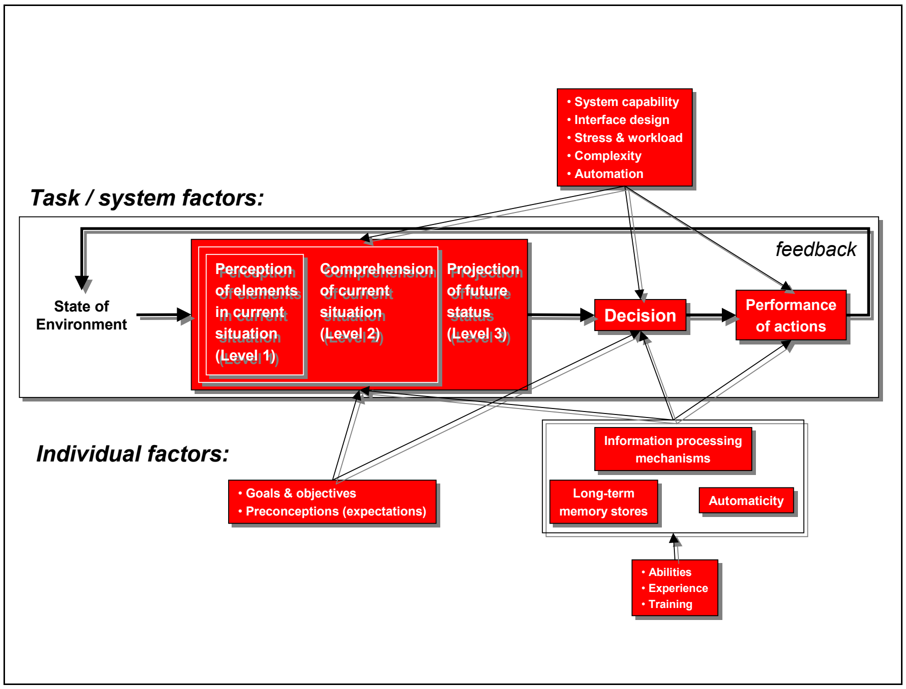

Figure 5. Endsley's (2000) model of Situation Awareness.

When commanders and their staffs have SA, we say that they can see the "big picture" or have a "helicopter view" of the battlefield. If a commander and his/her staff lose SA (or never gain it), then their decisions are almost bound to fail, perhaps spectacularly[3]. The prime function of a C2 system is to provide the information that the commander and his/her staff need to gain and maintain SA.

Comparison of Endsley's model (see Figure 5) with the extended OODA model shows that her three levels of situation awareness (viz. perception, comprehension, and projection) can be mapped to OODA processes as follows:

- Level 1 SA (Perception) is directly equivalent to OODA's Observe process.

[2] In NCW jargon, this is called "battlespace awareness".
[3] Many "pilot error" aircraft crashes are the result of loss of SA. A notorious example is the American Airlines 757 that flew into the Andean mountains surrounding Cali airport because the pilots were too engrossed in discussing their salaries to notice that they had flown beyond their turning point. For military examples see "The Psychology of Military Incompetence".

- Level 2 SA (Understanding) is directly equivalent to OODA's Orient process.
- Level 3 SA (Projection) has no equivalent in OODA. Projection is a process of predicting future behaviour, which is an aspect of planning. This is again an indication that OODA should be extended to include a Plan process.

The mapping of Endsley's (2000) SA model to OODA clarifies the structure and inputs and outputs of the OODA processes. It also tells us in which order the necessary C2 functionality should be implemented: first Perception / Observe, then Comprehension / Orient, and lastly Prediction / Plan.

Plan-Do-Check-Act

Plan-Do-Check-Act (PDCA) model originated in the quality control literature. It originated with Shewhart (1939) as a three-process cyclic model (Specification-Production-Inspection). Demming (1951) added a fourth process, generalised it to PDCA, and promoted it[4]. PDCA has reached the mainstream of management consulting as a model for measuring the performance of commercial and public organisations. It is central to risk management, even finding application in the BSI 17799 standard for information and computer security.

The key message from comparing PDCA and OODA is that the latter lacks a learning process or adapting to novel situations.

Re-engineering OODA

OODA's shortcomings

In summary, the shortcomings that we have identified by comparing OODA with other models include:

- Boyd's OODA definition was rudimentary. Boyd did not specify the scope of the four processes, nor did he decompose any process (apart from Orient) further. He identified inter-process interfaces in terms of feed-forward and -back loops without defining the information feeding over the interfaces. Before implementing any OODA-based C2 system, the processes would have to be decomposed and formalised and the interfaces would have to be defined in terms of information flow.
- Boyd's OODA definition omits the planning process. Several authors include a fifth Plan process when describing OODA, but this is mismatched with planning and scheduling as understood in the Operations Research and Artificial Intelligence literature. There are research issues here (Biundo et al, 2003) that must be resolved before planning can be integrated into OODA. In particular, planning must be both deliberative (as in SHOR) and reactive (as in RPDM).
- OODA exhibits shortcomings in psychological validity (Dehn, 2004), in that it lacks concepts of memory and attention, and cognitive representations of inter alia world states and domain knowledge. This should be rectified by explicitly including a world model in OODA, with world states and models represented appropriately and store/recall functions for updating the world model. In addition,

[4] To the extent that the Japanese call PDCA the "Demming cycle".

OODA needs a mechanism that determines the focus of attention appropriate to the current situation.
- In terms of Rasmussen's (1983) three-level model of thinking processes in human supervisory control, OODA is limited to rule-based reasoning. This is consistent with the decision theoretic nature of C2 models (Mayk & Rubin, 1988). OODA should be extended to incorporate skill- and knowledge-based reasoning. Knowledge-level reasoning capabilities are needed to support processes such as learning and deliberative planning.
- Reflecting its origins, OODA is a single-agent model. Although the process of interaction between agents is unspecified, competition is assumed. Keus (2002) has applied OODA to teams, but this regards the team as an indivisible, cooperative entity. OODA should be extended to multi-agent groups with diverse disciplines and cultures, and generalised to other forms of interaction, such as collaboration and negotiation. The opponent(s) should be explicitly represented.
- Comparison with RPDM and PDCA shows that OODA lacks any learning process. Given NCW's needs for agility, sense making (Weick, 1995) and self-synchronisation, this is a serious shortcoming that must be corrected.
- OODA assumes rational decision-making. Comparison with SHOR and RPDM shows that this is unrealistic. For user acceptance, OODA should be based on naturalistic decision-making and planning.

NCW Needs

The goal of the NCW enterprise (Alberts, Garstka & Stein, 1999) (Alberts & Hayes, 2003) is to transform "industrial-age" military operations to the "information age". The industrial age is characterised by specialisations and bureaucracies, by hierarchical organisations, by functional differentiation and stovepipe systems, by interchangeable resources, and by plan-based control. By contrast, the information age is characterised by networking, by information sharing, by collaborative understanding and development of intent, by sense making (Weick, 1995) and self-synchronisation, and by agile, reactive control. Instead of power being at the centre of the organisation, power is deployed to the edge.

The needs of NCW will affect C2 systems in the following ways:
- Situation awareness is central to information-age C2 systems.
- Instead of having a hierarchical architecture, information-age C2 systems will take the form of a network of peer-to-peer C2 nodes.
- Each C2 node will be agile and support sense making and self-synchronisation.
- Information-age C2 systems will have to be capable of varying from a totally centralised, cyclic approach to a totally decentralised control-free approach.
- Information-age C2 systems will be multi-echelon with a blurring of the boundaries between strategic, tactical and operational levels and of the boundaries between pre-, during and post-operations phases.
- Information-age C2 systems will support collaborative working.

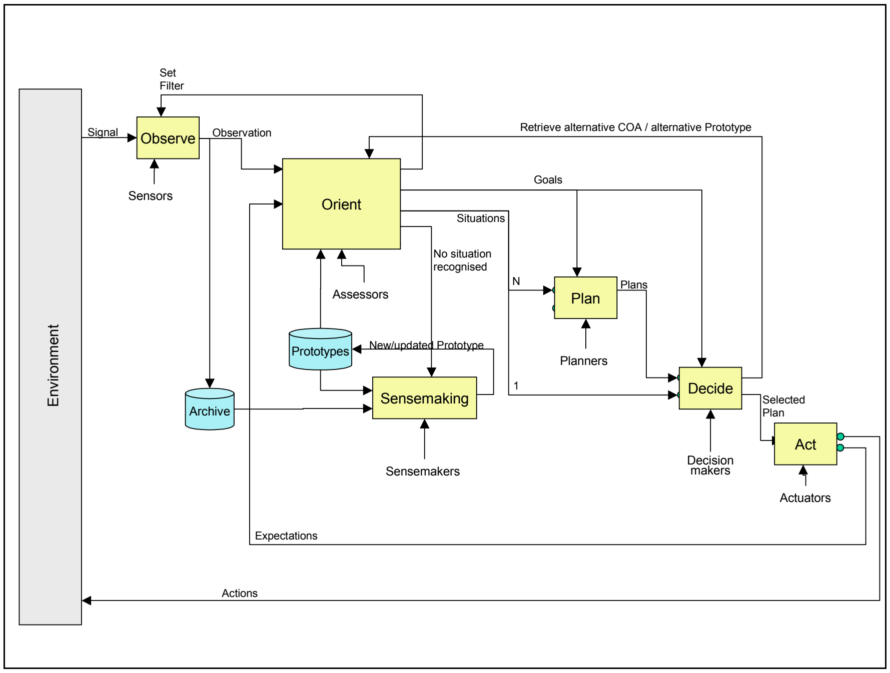

Figure 6. SADT / IDEF0 analysis of OODA requirements.

Further Work

In our "Beyond situation awareness: closing the OODA loop" research theme we are taking a step-by-step approach to verifying whether OODA can and should be used in C2 system architectures. The steps are to:

- Formalise the requirements for OODA in the process-oriented SADT / IDEF0 notation, rectifying the shortcomings identified in this paper and meeting the needs of NCW. The top-level SADT / IDEF0 diagram is shown in Figure 6. This diagram integrates Plan and Sensemaking with Boyd's (1996) four processes.
- Analyse the SADT / IDEF0 diagrams to identify object-classes, relationships, and attributes, formalising this in UML. This started in March 2005.
- Prepare a set of UML sequence diagrams based on top-level scenarios.
- Implement a prototype C2 system compliant with the UML design descriptions.
- Evaluate the implemented prototype under realistic conditions.

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