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Structured, Graphical Analysis of C2 Teams and their Technologies

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Focus & Convergence for Complex Endeavors

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About the Journal

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Structured, Graphical Analysis of C2 Teams and their Technologies

Patrick Hew (Defence Science and Technology Organisation, AUS)

Abstract

This article describes a structured, graphical approach to analyzing C2 teams and their technologies. The analysis can detect qualitative changes in processes and roles, and quantitative changes to system capacity, as afforded by workflow design and technology injection. The key idea is to encapsulate theories of situation awareness, agility and adaptivity into graphical building blocks, and define rules for assembling the blocks. The resultant charts allow human-machine systems to be studied with the same clarity that an electronic engineer gains from a circuit schematic. The approach can be applied to both existing and proposed systems, as illustrated in case studies from engineering Australian Defence Force air-land-sea teams under Network-Centric Warfare.

Introduction

As a small force with large responsibilities, the Australian Defence Force (ADF) looks to gain advantage from integrated air-land-sea operations. Recent operations have built a decade of experience across multiple theatres, in both joint (Army, Navy, Air Force) and coalition (multi-nation) configurations. The epoch has also seen huge advances in technology, notably a synergy in real-time, full-motion remote sensing, high-capacity data links and unmanned/automated systems. The ADF's challenge is to distill this experience into investment decisions, knowing that today's state-of-the-art is tomorrow's legacy.

This article describes methods that have been developed for structured, graphical analysis of C2 teams and their technologies, and reports on how the methods have been used. The key idea is to encapsulate theories of situation awareness, agility and adaptation into graphical building blocks, and define rules for assembling the blocks. The graphics depict where and how situation awareness is being formed, how it translates into battlespace actions, and the command roles that form and adapt the end-to-end workflows. The representation can detect changes to roles and intra-team relationships from introducing technology, and can predict quantitative changes in capacity.

The framework has been applied by the Defence Science and Technology Organisation to generate and develop concepts for the future, network-enabled ADF. The paper is thus organized in three sections. The first section introduces the graphics for analyzing the formation and use of situation awareness in human-machine system, with the case study of Close Air Support. The second section then adds the graphics for structures for applying agility and adaptivity to human-machine systems, with the case study of field artillery. The final section uses the two sets of graphics in concert, on cases in Close Air Support, air defense and airspace management. Overall, we see how the analytic approach helps to conceptualize potential future systems for exploration and predictive analysis, while highlighting a range of issues and opportunities in C2 design.

Background

When an engineer wants to analyze or design an electronic system, he or she constructs a circuit schematic. We seek the same clarity for studying human-machine systems. We draw upon the theory of (artificial) intelligent agents, and use Timed Colored Petri Nets for modeling.

Intelligent Agents

In general usage, an agent is defined as someone or something that acts or has the power to act (Macquarie Dictionary 2009). In Artificial Intelligence research, an intelligent agent is an autonomous entity that observes and acts upon an environment (it is an agent) and directs its activity towards achieving goals (it is rational) (Russell and Norvig 2003). There are no restrictions on an agent's construction (mechanical, electronic, biological, software …), nor whether it is a single unit or a networked assemblage of components, nor whether it is mobile or stationary. Hence, for example, an unmanned aircraft system is best regarded as a collection of agents, each assembled from components (human or artificial) housed by the airframe, on the ground, or elsewhere.

To emphasize, an intelligent agent is characterized by its closing a loop from sensors to effectors. We will be asserting particular models for how agents close their loops, in and around situation awareness and adaptation.

Timed Colored Petri Nets

Timed Colored Petri Nets (Jensen and Kristensen 2009) are an extension of Colored Petri Nets. To summarize, Colored Petri Nets center on networks in which tokens are created, moved, copied, or destroyed (Figure 1). An ellipse denotes a space for holding tokens, up to some capacity (including infinite). Tokens can have properties with values, called *colors* for historical reasons. A rectangle denotes a transition between spaces, from input to output as marked by the arrows. A transition will trigger if it sees tokens of a required number and color in the input spaces. It will collect these tokens from the input, and then deposit a number of tokens into its output spaces, according to some program. A transition can thus be specified to create, copy or destroy tokens. Note that an output space can also be an input space.

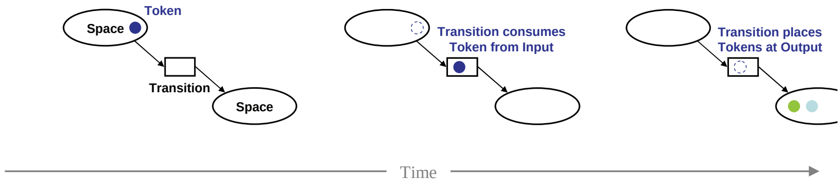


Figure 1. Colored Petri Nets are Networks in which Tokens are Created, Moved, Copied or Destroyed

A Timed Colored Petri Net is a Colored Petri Net that recognizes the temporal dimension. This occurs in two ways: first, a transition can be set to trigger at a specified time, or to trigger periodically over some time interval. Secondly, the transition itself takes some time to complete. Hence, a transition might see the tokens that it needs to trigger, but might nonetheless wait before triggering. Similarly, the duration between collecting and depositing tokens is part of a transition's program.

Petri Nets are just one of many schemes for representing processes and information flows (Byrne 2010). The key advantage of Petri Nets is that they explicitly recognise both storage containers (spaces) and processes (transitions). We will use this to represent information being held or acted on by particular people, or by specific technological systems.

Representing Situation Awareness

Situation awareness (SA) features strongly in ADF thinking on Network-Centric Warfare (NCW). ADF NCW is about linking sensors, decision-makers and weapon systems via modern information technology, aiding people to work together more effectively, to achieve the commander's intent. The ultimate aim is to enable the force to act before the adversary acts, reaching out at the right place and time with the right force for the right effect. The underlying hypothesis is that sharing information enhances collaboration and synchronisation across the force, and that this increases situation awareness (AU Department of Defence 2009).

The *structured graphics for situation awareness* depict the formation and use of SA within a human-machine system. We construct our building block around the Endsley model of SA (Endsley 1995): the perception of the elements in the environment within a volume of space, the comprehension of their meaning and the projection of their status in the near future. We then build on the idea of SA *transactions* as explored by Stanton et al (2006). For this article, we concentrate on the practical application to modeling C2 teams and their technologies, while details on the underlying theory may be found in (Hew, Byrne, and O'Neill In preparation) and (Hew In preparation).

Building Block for Situation Awareness

The building block is a *Data-Tracks-Actions (DTA) agent*, which can have SA, make decisions and take actions. A DTA agent has containers for holding Data, Tracks and Actions, defined as follows:

1. Data Container. For the DTA framework, a *datum* is a measurement of the agent's external universe, as performed by a sensor. Formally, the *data container* holds a collection of *data statements*, each of the form "«*Location*» at «*Time*» was measured as «*Measurements*»." The data records may have meta-statements, for instance «*Error Limits*» or «*Confidence*».

2. Tracks Container. Tracks are the core of a DTA agent's SA; they are the objects over which the agent builds and maintains SA. Formally, an *object* is some subset of the universe, as declared and labeled by the agent. The *tracks container* holds a collection of *track records*, one for each object being tracked by the agent. The track records then hold *track statements* of the form "During «*Time Interval*», «*Object*» has / will have «*Property*» with

«*Value*».” The track statements may have meta-statements, for instance «*Error Limits*» or «*Confidence*». An agent may have an “I” record, containing statements about the agent itself.

A DTA track corresponds to the Endsley model of SA (Figure 2). Level 1 SA (the perception of elements) is the initiation of track records—an agent holds a track record for each element that it has “perceived.” Level 2 SA (the comprehension of meaning) is populating the «*Property*»-«*Value*» pairs within a track, for «*Time Intervals*» in the past. Data is thus accorded “meaning” as properties of tracks. Level 3 SA (projection of status) is about populating track statements for «*Time Intervals*» in the future. This reflects “projection” of status.

3. Actions Container. The agent closes the loop from sensors to effectors by scheduling actions. The *actions container* thus holds a collection of *action statements*, each of the form “[At «*Time*»] [«*Actor Object*»] will «*Act*» [on «*Target Object*»] [using «*Subsystem*»] [directed at «*Location*»]”, where “[]” denotes an optional entry. In general, but not universally, the «*Actor Object*» will be “I”. The action statements may have meta-statements, for instance «*Priority*».

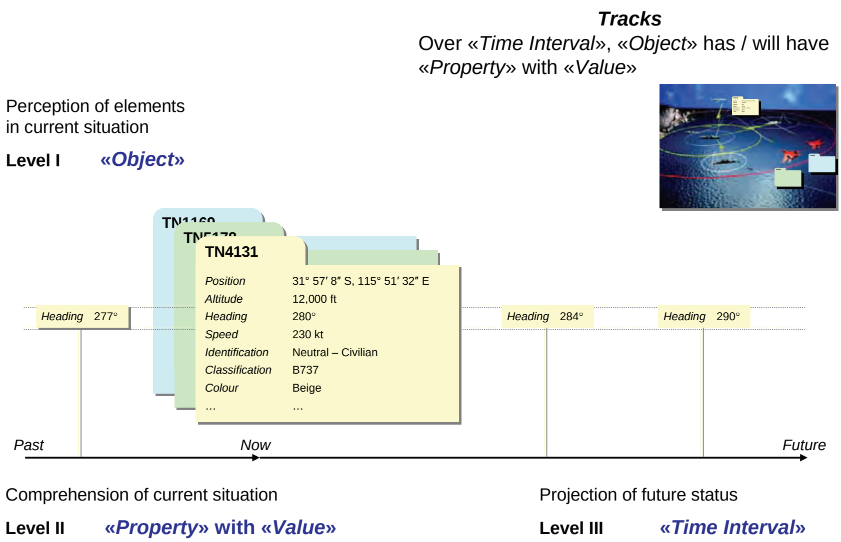


Figure 2. DTA Tracks and Endsley Levels of SA

We then assert the existence of some *DTA processes*, as follows:

1. Collecting Data. The agent uses its sensors to collect data from the environment, storing them as data statements in its data container.

2. Populating Tracks. The agent uses data to initiate and populate track records, as stored in its tracks container.

3. Scheduling Actions. The agent schedules actions for execution at some future time, as action statements in the actions container.

4. Performing Actions. The agent uses its subsystems to interact with the environment, as scheduled.

5. Fusion. The agent takes one or more records from a container, and consolidates them into a composite record. So we can have d*ata fusion*, *track fusion*, or *fusion of actions*.

In terms of Timed Colored Petri Nets, the DTA containers are spaces and the DTA processes are transitions (Figure 3). We also have spaces to represent the external environment, as an infinite source of data tokens, and as an infinite sink of action tokens. At any time, there can be any number of transitions between these spaces, for collecting data, populating tracks, scheduling and performing actions, and fusing tokens.

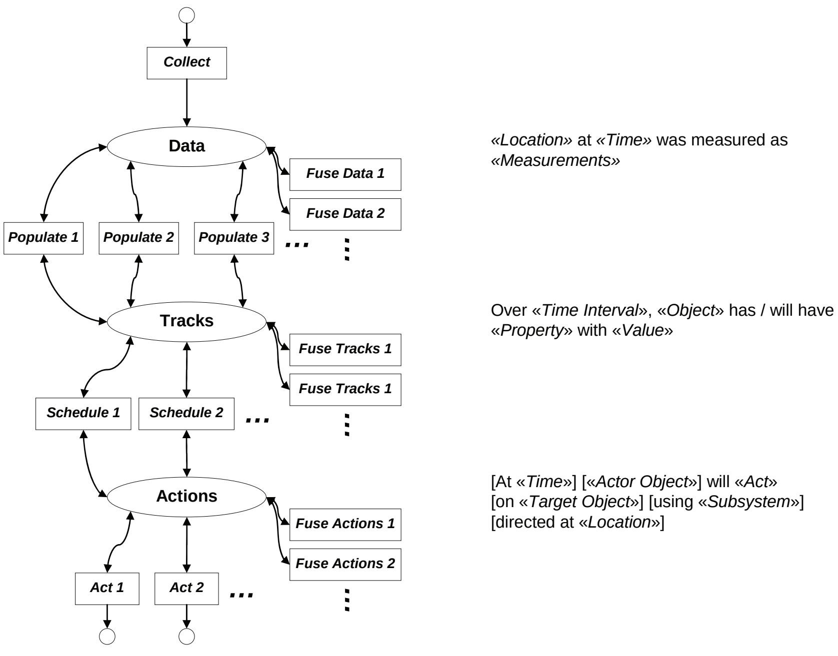


Figure 3. Building block for Situation Awareness, the Data-Tracks-Actions (DTA) Agent

The DTA processes are domain-independent. For any given domain, it is convenient (but not compulsory) to specialize the processes to reflect the real-world happenings. We thus talk about having a DTA template, where agents might implement all or some of the template. For instance, the Sensor-Shooter DTA Template (Figure 4 and Table 1) has broad application in military settings, in covering agents that can sense, shoot and/or manoeuvre. Not all agents will have all capabilities, so networking prompts us to look at the end-to-end combinations (Figure 5).

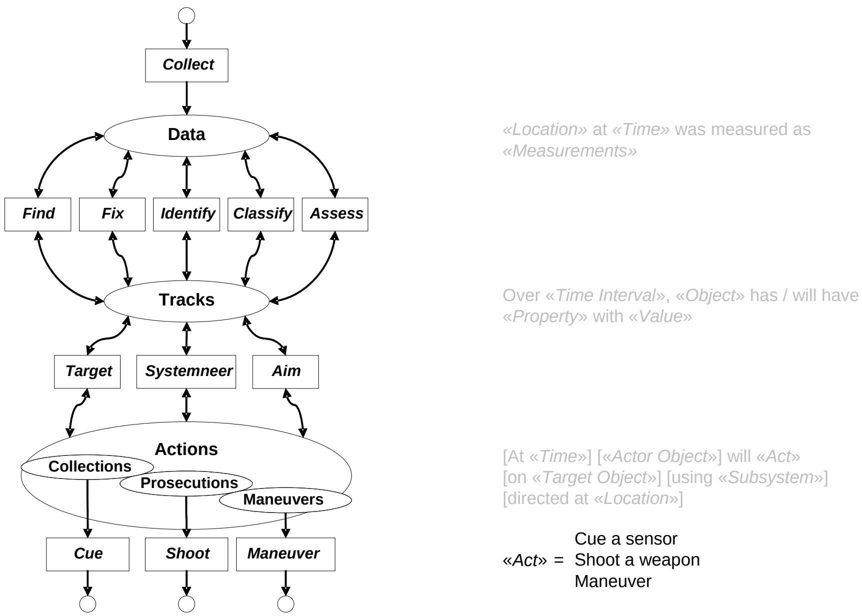
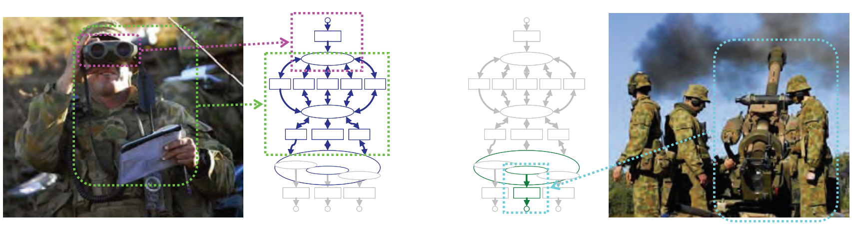


Figure 4. Sensor-Shooter DTA Template

Table 1. Transitions in the Sensor-Shooter DTA Template

Transition	Definition
Collect	Collect data from the environment (using a Sensor). The data is added to the Data container.
Find	Initiates a track record in the Tracks container. This represents detection of an object.
Fix	Populates a track record's «*Location*» property.
Identify	Populates a track record's «*Identity*» property (eg "Hostile" or "Friendly").
Classify	Populates a track record's «*Classification*» property (eg "Airbus A380").
Assess	Populates a track record's «*Alive*» property (eg "Destroyed", "Damaged").
Target	Designate an object for prosecution by a sensor or weapon.
Systemneer	Select a system for use in some action. Generalisation of "weaponeering" to include sensors.
Aim	Select an aimpoint in the environment for prosecution.
Fuse Data	Fuse two or more data records. The operation is hidden unless it is highlighted for study.
Fuse Tracks	Fuse two or more track records. The operation is hidden unless it is highlighted for study.
Fuse Actions	Fuse two or more actions records. The operation is hidden unless it is highlighted for study.



Picture Credits: Commonwealth of Australia, Department of Defence

Figure 5. Agents Implementing Portions of the Sensor-Shooter DTA Template

Rules for Composing Agents

We specify that DTA agents can be composed via publishing data, sharing tracks or directing actions (Figure 6):

1. Publish Data. Agents can *publish data* between their data containers. Formally, there are one or more transitions between the agents' data spaces.

2. Share Tracks. Agents can *share tracks* between their track containers. Formally, there are one or more transitions between the agents' track spaces.

3. Direct Actions. Agents can *direct actions* between their actions containers. Formally, there are one or more transitions between the agents' actions spaces.

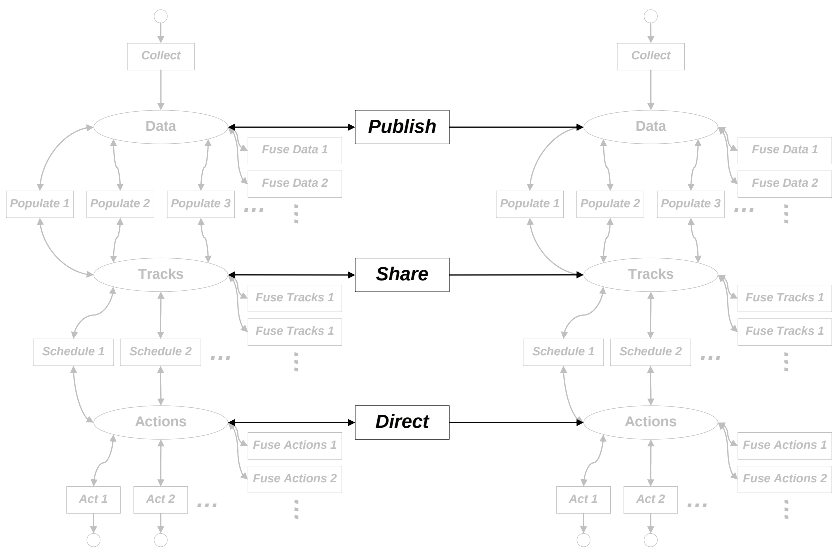


Figure 6. DTA Agents can Publish Data, Share Tracks, or Direct Actions

The rules recognize the affordances from modern and emerging digital communications. Historical systems (both voice and data) have only had the capability to direct actions or share tracks. Advances in technology have led to data links with higher speed and greater capacity, enabling agents to publish data at useful tempos (Table 2). The prototypical example is the streaming of full-motion video, noting that every pixel is a data statement ("«*Location*» at «*Time*» was measured as «*Measurements*»").

Table 2. Modern and Emerging Communication Systems

Technology	Communication Enabled	Tempo
Voice (for comparison)	Direct	One direction every 5-10 seconds.
Voice (for comparison)	Share	One position report every 20-30 seconds
Situation Awareness Data Link	Share	~100 position reports every 5-15 seconds
Cooperative Engagement Capability	Publish	Radar measurements at millisecond rates
Common Data Link	Publish	Video at 24 frames per second

Assembled from (Hew 2009)

Within any C2 team, SA will be formed in and across the people and databases. Our interest is in the architectures under which SA is formed and used. The architectures are represented through *DTA charts*, depicting the following:

1. Numbers of agents in composition. Recall that agents transact information (data, tracks or actions). We add markup to show the number of senders and receivers (Table 3a). The default is to have exactly one agent, but we can have a specified count, or an arbitrary number. The notation follows conventions set by Unified Modeling Language.

2. Speed and tempo. We use line thickness to denote transactions that occur quickly, or that occur frequently (Table 3b). The scale can be qualitative: for instance, *slow time, voice time* and *digital time*.

3. Different data. Icons can depict agents collecting or publishing the same data, versus different data (Table 3c).

4. Different objects or properties. Icons can depict agents holding tracks over the same object, versus different objects. They can also depict tracks from same versus different classes of object (e.g., aircraft versus ships). Horizontal bands depict agents keeping track of the same object properties, versus different properties (Table 3d). So we can have agents tracking different properties of the same object, the same properties across different objects, or any combination.

5. Storage capacity. We need to acknowledge the capacity and persistence of storage. We do so by annotating the charts with the number of tokens that can be held, either in general or for particular kind of token (Table 3e).

Table 3. Notation for Representing Architectures

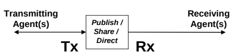
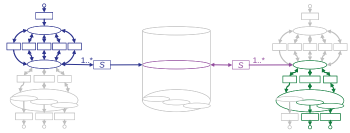
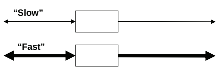
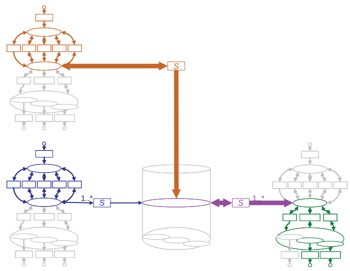
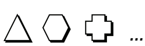
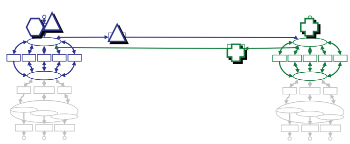
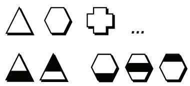
	Notation	Example
a.	**Numbers of agents in composition**  where Tx and Rx represent: 1 Exactly 1 agent (default) 1…# Up to # agents 1…* Arbitrarily many agents and must have Tx =1 or Rx = 1.	 1…* agents shares tracks with 1 storage-only agent, which shares tracks with 1…* agents
b.	**Speed and tempo**  Line thickness denotes transitions that occur quickly (*high speed*) or frequently (*high tempo*).	 1 agent shares tracks at high tempo and 1…* agents shares tracks at slow tempo with 1 storage-only agent, which shares tracks in fast time with 1…* agents
c.	**Different data**  Icons in the data spaces denote different data.	 Agent collects ⬡△, agent collects ✚. △ and ✚ are published, ⬡ is not published.

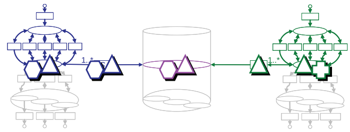
Table 3. (Continued) Notation for Representing Architectures

d.

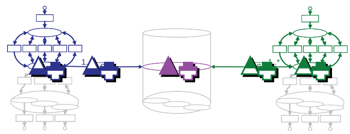
Different objects or properties



Icons in the track spaces denote different objects, or different kinds of objects.



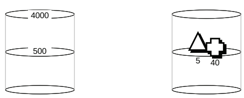
Tracks on ⬡△ are shared, tracks on ✚ are not shared.



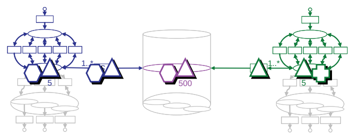
Sharing same property of ✚, sharing different properties on △.

e.

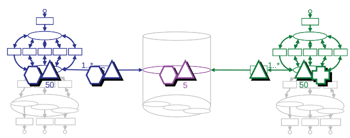
Storage capacity



Annotations denote the number of tokens that can be held, (of a particular type).



Most of △ are stored in the central agent.



Most of △ are stored in the Edge agent.

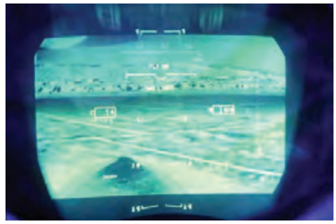
In charting the architecture for a C2 team (proposed or actual), we come to see agents that may not have been initially apparent, but are nonetheless critical for the team's operation. For instance, if the architecture requires each of the team members to be on the same computer network, then the computer network can be modeled as an agent that relays information amongst the members. The same might be said if the members have to be on the same voice radio circuit, or within earshot of each other. This cues us to opportunities for introducing digital technology for improvements in speed, capacity and persistence.

Case Study - Close Air Support

Close Air Support (CAS) is air action by fixed- or rotary-winged aircraft against hostile targets that are in close proximity to friendly forces, and which requires detailed integration of each air mission with fire and movement of these forces (US Department of Defense 2009). This definition sounds simple, but there is considerable debate within the ADF on philosophy, concepts and implementation. The differences have much to do with where and how SA is formed and used, as revealed by DTA charts.

CAS has also seen rapid evolution in technologies post-2001, prompted by deployments in Iraq and Afghanistan. The technology ranges from voice-over-radio in a manner that World War II soldiers would recognize (Brown et al. 2006), through to advanced digital systems including laser rangefinding and designation, global positioning systems (GPS) and full-motion video streamed from aircraft targeting pods (Figure 7). The aspiration is to increase speed and precision, and reduce casualties amongst friendly forces and non-combatants. The following questions then arise: Which technology options are structurally equivalent? Is one workflow the same as another, only faster? Or does the technology enable activities that are qualitatively different?

Ground-Air radio for voice communications.



Infrared Image via LANTIRN pod.

Laser Designator / Rangefinder.

ROVER terminal for receiving video.

Figure 7. Examples of Systems Used in Close Air Support[1]

To address the questions, we consider the system formed from a soldier on the ground and the aircrew in the CAS aircraft. In the ADF context, the ground soldier is a Joint Terminal Attack Controller (JTAC). We use DTA charts to compare a baseline system with a number of possibilities.

In the baseline system (Figure 8), the JTAC collect data to build their SA, and targets an object in the battlespace. They then tell the aircrew the target that they are to prosecute, where it is located, and how to find it. The aircrew build their SA, search for the specified target and complete the prosecution. All of this occurs in voice

1. Picture credits: Northrop Grumman Corp, U.S. Air Force.

LANTIRN	Low Altitude Navigation & Targeting Infrared for Night.
ROVER	Remote Optical Video Enhanced Receiver.

time, with potential for error and missed opportunities as the JTAC share their SA with the aircrew through verbal means. The DTA chart thus depicts communication between the JTAC and aircrew, for sharing SA and directing the prosecution and maneuvers. It also shows that both agents are collecting data to build their SA. Finally, we see that the aircrew shoots at the target, while the JTAC does not shoot.

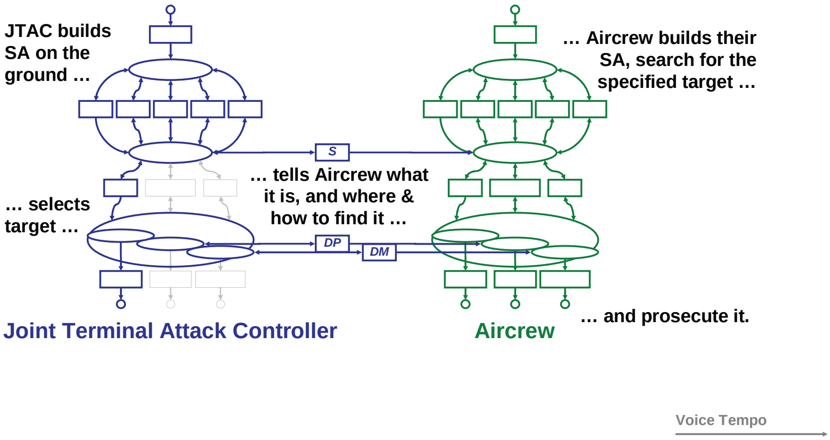


Figure 8. Close Air Support - Baseline

One of the proposals was for so-called *Digital Smoke* (Figure 9). The JTAC would use laser rangefinding, GPS and other systems to select and specify an aimpoint for the attack. The Aircrew would shoot the munitions at that point. This is a *JTAC-centric* concept: the aircrew do not acquire SA of the target, but are launching purely on coordinates supplied by the JTAC. The DTA chart depicts communication between the JTAC and aircrew solely for directing the prosecution and maneuvers; there is no sharing of SA. It also shows that this communication occurs at a digitally-aided tempo.

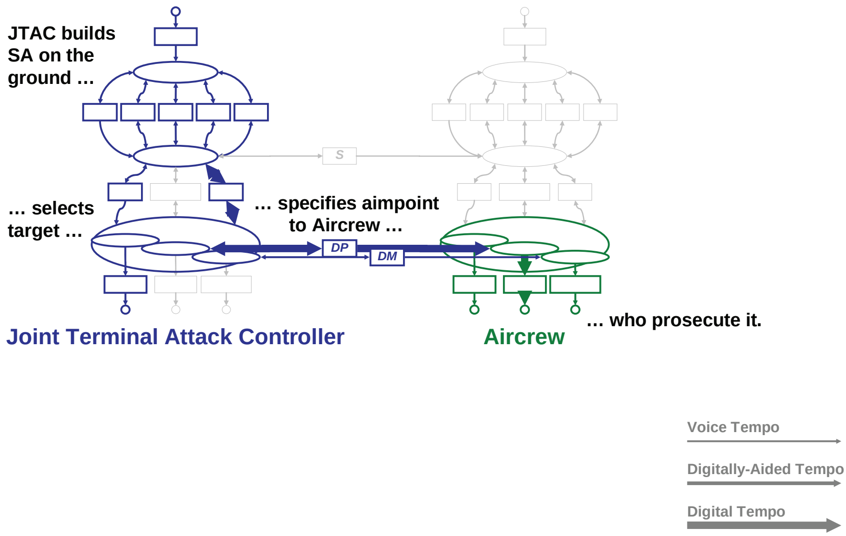


Figure 9. Close Air Support - "Digital Smoke"

In contrast, concepts can be *Aircraft-centric*, such as those using technologies like Situation Awareness Data Link (Figure 10). The Aircrew tie into the ground force SA through the datalink. The JTAC can select a target, and the Aircrew prosecutes it on their behalf. So the DTA chart depicts the JTAC and aircrew each collecting data to build their SA, and SA being shared from JTAC to aircrew at digital tempos.

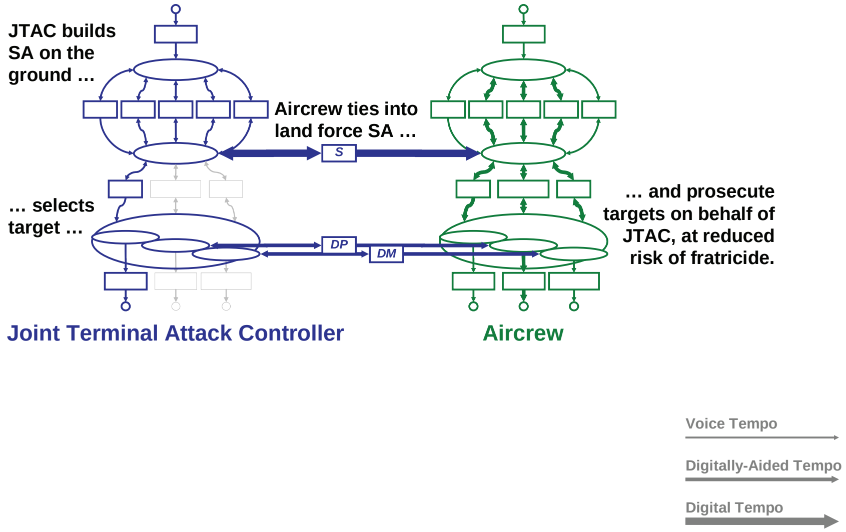


Figure 10. Close Air Support - Situation Awareness Data Link

Meanwhile, recent operations have seen explosive growth in the use of full-motion video (Figure 11). If the JTAC is equipped with a ROVER terminal, and the aircraft has the right communications equipment, then the JTAC can downlink the video picture as published from the aircraft's sensors. The JTAC can mark the video up to highlight objects of interest, and specify a target or aimpoint. The DTA chart thus depicts the aircrew publishing data to the JTAC. The JTAC uses this data, together with data collected by their own sensors, to build their SA and select a target.

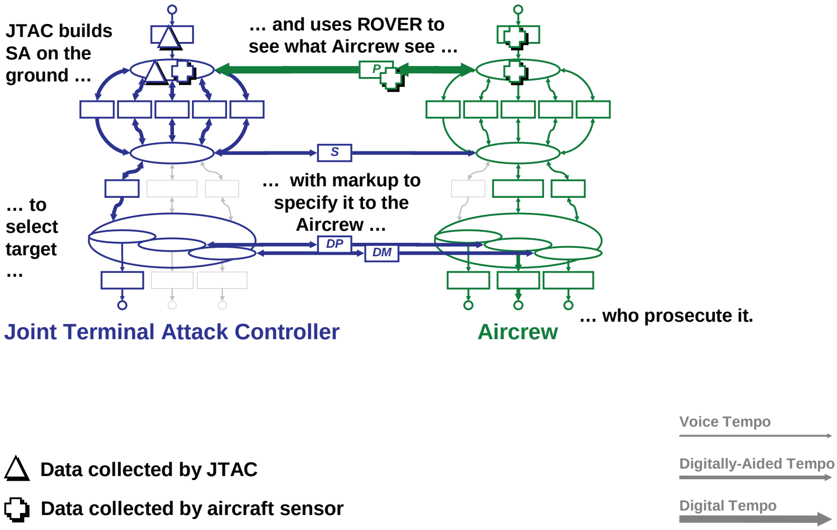


Figure 11. Close Air Support - ROVER and Aircraft Targeting Pods

The DTA charts allow us to compare the ADF CAS configurations side-by-side. The key insight was thus about the impact of digital-tempo technology on roles and relationships. Within the end-to-end workflow of acquiring and prosecuting targets, we can see where individuals are forming SA, and how this sits in the context of the system.

The surprising aspect, revealed by the DTA charts, was how activities could be reassigned to JTAC and/or aircrew. Technology did not just speed up the existing workflow—it opened the way to workflows that were inaccessible without certain technologies (e.g., full-motion video). The charts are thus helping to inform decisions on the equipment to be acquired for CAS, for both current and future operations.

Representing Agility and Adaptivity

The ADF has roughly 55,000 personnel across all ranks and trades —roughly three personnel for every 2 km of Australia's coastline. It simply cannot be continuously strong everywhere and in every way, and looks to advantages from agility and adaptivity. For the ADF, agility is about managing the balance and weight of effort across all lines of operation in time and space (AU Department of Defence 2009). As the enemy is also trying to be agile, the ADF seeks to be better at adapting to new circumstances, through learning and learning-to-learn (AU Department of Defence 2009). The challenge has been in translating this vision into systems and technologies, supporting the C2 teams that manage where and how ADF forces are deployed.

The *structured graphics for adaptation* depict the structures for applying agility and adaptivity to human-machine systems. The key idea is to capture the activities and information flows for forming and adapting C2 teams, as circumstances change. As before, we focus on the practical application to modeling C2 teams and their technologies, and details on the underlying theory may be found in (Hew et al. 2010) and (Hew In preparation).

Building Block for Adaptivity

We construct our building block around *supervisory control*: the intermittent programming of an intelligent agent by a *supervisor* (Sheridan 1992) (Hew et al. 2010). The "programming" can be specific or broad, from small changes in an agent's program through to total reconstruction of the agent.

Supervisory control is otherwise known as "on"-the-loop control. The supervisor is said to be "on" the loop, to distinguish from agents that are "in" the loop, under supervision. Indeed, we observe that Sensor-Shooter DTA agents close a loop from sensors to weapons, and that we want a model for agents that are "on" this loop.

Table 4. Transitions in the Sensor-Shooter DTA Template

Transition	Definition
Collect	Collect data from the environment (using a Sensor). The data is added to the Data container.
Find	Initiates a track record in the Tracks container. This represents detection of an object.
Fix	Populates a track record's «*Location*» property.
Identify	Populates a track record's «*Identity*» property (eg "Hostile" or "Friendly").
Classify	Populates a track record's «*Classification*» property (eg "Airbus A380").
Assess	Populates a track record's «*Alive*» property (eg "Destroyed", "Damaged").
Target	Designate an object for prosecution by a sensor or weapon.
Systemneer	Select a system for use in some action. Generalisation of "weaponeering" to include sensors.
Aim	Select an aimpoint in the environment for prosecution.
Fuse Data	Fuse two or more data records. The operation is hidden unless it is highlighted for study.
Fuse Tracks	Fuse two or more track records. The operation is hidden unless it is highlighted for study.
Fuse Actions	Fuse two or more actions records. The operation is hidden unless it is highlighted for study.

The *super-DTA agent* is a DTA agent that can apply supervisory control to one or more DTA agents. The super-DTA agent is itself a DTA agent – it has containers for Data, Tracks and Actions, and can transact with other DTA agents. However, the super-DTA agent does not act into the external environment; rather, it acts by forming or shaping other agents. This is depicted through dashed, round-edged boxes that envelop the agents being programmed (Figure 12).

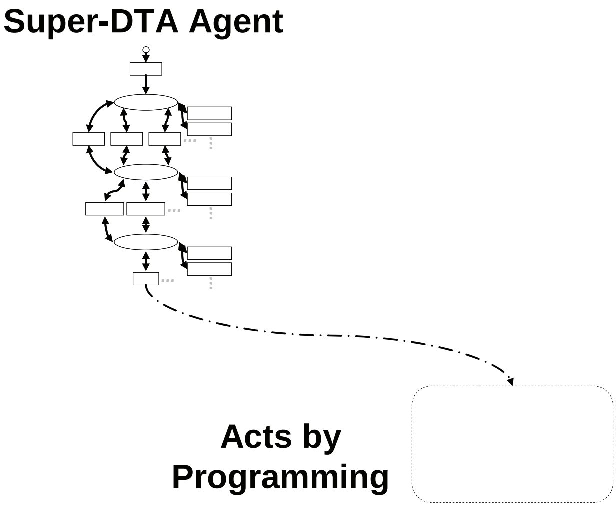
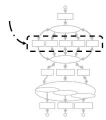
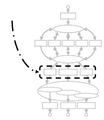
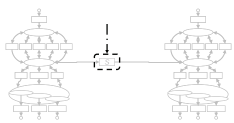
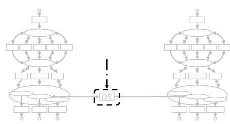


Figure 12. Super-DTA Agents Act By Programming

The super-DTA agents are domain-independent. When supervising Sensor-Shooter DTA agents, it is convenient to centre on three broad sets of actions (Table 5), for how the agents populate tracks, schedule actions and communicate with each other. This covers a number of C2 constructs including recognition criteria, Rules of Engagement, network connectivity and weapons release authorization.

Table 5. Supervising Sensor-Shooter DTA agents - Notable Cases

	Case	Representation
a.	**Recognition Criteria** The Super-DTA agent (re)programs the processes used to populate tracks. An important example is the criteria used to identify and classify objects in the battlespace (e.g. Interrogation Friend Foe codes).	
b.	**Rules of Engagement** The Super-DTA agent (re)programs the processes used to schedule actions. An important example is the criteria used to select targets and weapons (i.e. Rules of Engagement).	
c.	**Network Connectivity** The Super-DTA agent (re)connects one or more agents. For example, configuring a number of agents to share their situation awareness.	
d.	**Weapons Release Authorization** A particular case of network connectivity is in configuring an agent so that it can direct another agent to shoot weapons (i.e. Weapons Release Authorization). The same concept holds for configuring agents to direct sensors or maneuvers.	

Case Study - Field Artillery

Field artillery refers to cannon, rockets or mortars. Modern operations are characterized by *indirect fires*: the artillery does not have direct line-of-sight to the target, and fires under the direction of an observer. Indirect fires are thus inherently networked, and thus invite improvement through digital-tempo systems.

To this end, the Australian Army has selected the Advanced Field Artillery Tactical Data System (AFATDS) as its Battle Management System – Fires (BMS-F). The Australian Army has some experience with digital-tempo systems (from experimentation and coalition operations). There remains, however, considerable scope for redesigning the ADF's field artillery teams around the BMS-F. This manifests in choices on the quantity and mix of equipment to complement AFATDS, commensurate with the skills and roles.

One important aspect is the impact on field artillery agility. To consider this, we build DTA charts that focus on the connectivity between sensor and shooter.

In the baseline system (Figure 13), a Joint Fires Team (JFT) occupies an observation post overlooking a region of operations. The JFT is working to find, fix, identify and classify entities within this region. Structurally, when the JFT wants to call for fires, they call to the Joint Fires Effects Coordination Centre (JFECC), who patches them to an indirect fire asset. The JFT can then direct the fires asset to aim and shoot munitions. This sequence can be bypassed for most cases, under arrangements where a JFT is preconfigured to call to a particular fire asset. Nevertheless, the JFT may choose to call to the JFECC, to request more fire assets. The DTA chart thus depicts a point-to-point link between a JFT and a fire asset, put in place by the JFECC. The communication from JFT to fire asset occurs at voice tempos, and the JFECC forms and dissolves these links at voice tempos.

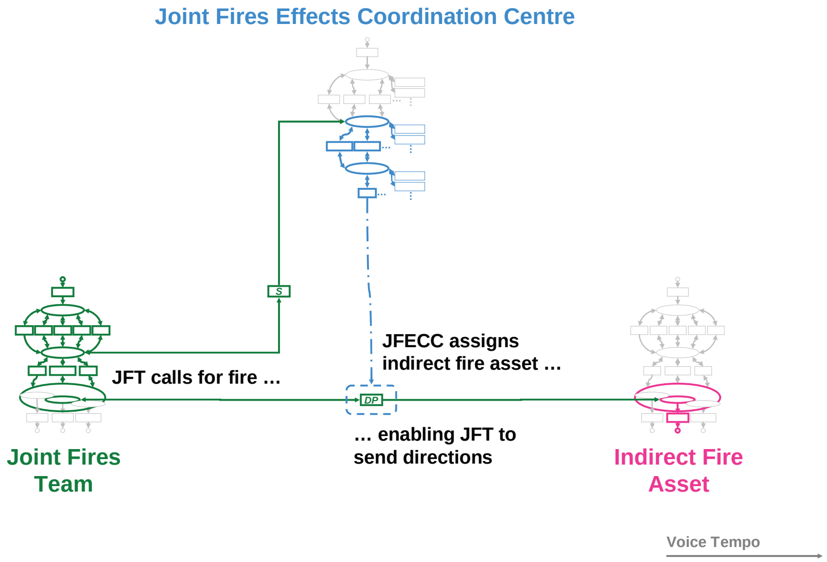


Figure 13. Field Artillery - Baseline

With AFATDS, fire assets are allocated by a computer algorithm, operating at digital tempos (Figure 14). The JFECC is in supervisory control, specifying the priorities to the scheduling algorithm. This is a stepping-stone into dynamic scheduling of individual attacks by precision-guided munitions, such as extended-range guided munitions and "Rockets in a Box" concepts (Figure 15). The added significance is in naval surface fire support, in improving the capacity for a single warship to support multiple JFT. The DTA chart thus depicts the BMS-F as a mediating artifact between multiple JFT and multiple fire assets. It pools the calls for fire, and assigns fire assets to those calls, under priorities set by the JFECC. The communications are at digital tempos, and the assignment priorities are specified at digitally-aided tempos.

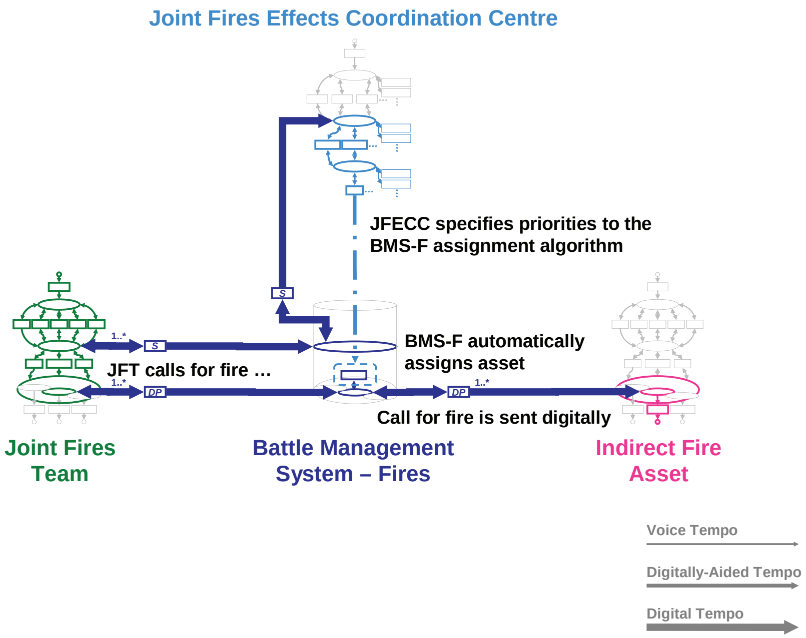


Figure 14. Field Artillery - Dynamically Assigning Shooters to Sensors

The DTA charts allow us to see how the BMS-F fostered agility in the field artillery system. Importantly, this aspect is seen as complementing, but distinct from, the improvements from digitizating the calls for fires and using the BMS-F as a near real-time intelligence tool (Hew, Byrne, and O'Neill In preparation).

Emergent Opportunities in C2 Teams and Technologies

In designing C2 teams for the future, we have to be cognizant of new technologies prompting new C2 structures. An important class of problems is in roles that change from being "in" the loop" to "on" the loop; that is, from being a Sensor-Shooter agent to being a supervisor of one-or-more such agents. We finish with two case studies to illustrate the issues, and propose this as an emergent opportunity for C2 research.

Case Study - Joint Terminal Attack Controllers and Joint Fires Observers

In 2005, US Joint Forces Command formalized the concept of a Joint Fires Observer (JFO) and its relationship with Joint Terminal Attack Controllers (JTAC) (US Department of Defense 2005). In certain contexts of mission and technology, the presence of a JFO can shift the JTAC and aircrew to being "on" the loop. This changes the nature of the decisions being made by JTAC and aircrew, and hence their information needs.

A JTAC is a certified service member who, from a forward position, directs the action of combat aircraft engaged in Close Air Support (CAS) and other air operations in a ground commander's operational area. JTACs provide the ground commander with recommendations on the use of CAS and its integration with ground maneuver. In contrast, a JFO is a certified service member who can request, adjust, and control surface-to-surface fires, provide targeting information in support of particular types of CAS (known as Type 2 and Type 3), and perform terminal-guidance operations (e.g., laser-designation of targets) (US Department of Defense 2009).

“Rocket-in-a-box” NLOS-LS Missile

Excalibur Extended-Range Guided Munition

Naval Surface Fire Support

JDAM-ER on Test Flight

Figure 15. Emergent Opportunities in Joint Fires[2]

Our interest is in weapons launched on GPS coordinates, from aircraft standing off outside the threat envelope. The prototypical example is the Joint Direct Attack Munition (JDAM), which has a range of 16-24 km; tests have been conducted on an Extended Range version, seeking a range of 64-96 km (Jane’s 2010) (Figure 15). At these ranges, the aircrew will not acquire the target visually. Doctrine has envisaged this situation under Type 2 or Type 3 control.

2. Picture credits: U.S. Army, Australian Department of Defence.
NLOS-LS Non Line-Of-Sight Launch System.
JDAM-ER Joint Direct Attack Munition - Extended Range.

There are two key points from a technological perspective. The first is that the systems and skills to generate a GPS aimpoint for air attack have high commonality with those used for precision-guided artillery (Kinne et al. 2006). This was a motivation for the JFO category, in leveraging existing capabilities to increase the number of personnel who could facilitate CAS (US Department of Defense 2005). The second point is that the JFO can communicate an aimpoint over machine-to-machine links, all the way into the aircraft's mission system and the weapon. This can prevent "fat fingered" errors (Kinne et al. 2006) that might otherwise arise from coordinates being manually transcribed across systems.

The DTA chart thus depicts the JTAC and aircrew as being "on"-the-loop (Figure 16), in contrast to the "in"-the-loop roles shown earlier. As described, the JFO's aimpoint is communicated into the weapon. The aircrew uses its SA to check that the coordinates are within an expected target area; that is, they are "on" the information flow from JFO to weapon. The JTAC is similarly "on" the loop from JFO to weapon – when they clear the attack, they are certifying that the loop from JFO to weapon is operating correctly.

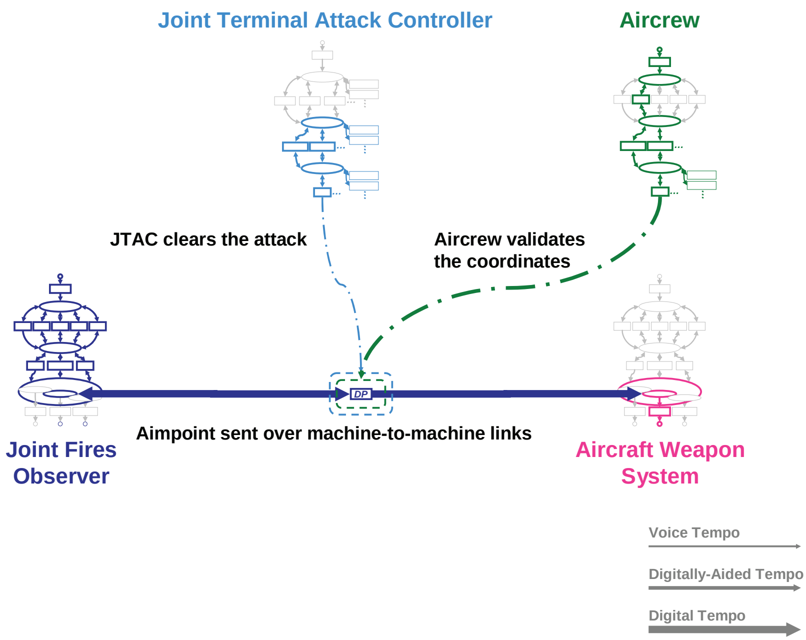


Figure 16. Close Air Support - "On" the Loop to Coordinates Sent Machine-to-Machine

The realization invites further examination of "on" versus "in" the loop roles around machine-to-machine systems – machines are efficient for handling information, but it takes humans to form the machines into meaningful workflows. Topics of research could include: the nature of SA for being "on" the loop (Hew et al. 2010), and the "social lubrication" that enables sensor-shooter information flows to work at aspirational tempos (Cheek 2003).

Case Study - Air Defence Systems and Airspace Management

Fratricide incidents in recent operations have highlighted concerns about air defense systems, and the adequacy of C2 arrangements. Analysis has called for increased attention to systems design for supervisory control (Hew et al. 2010) (Hawley, Mares, and Marcon 2010; Hawley and Mares To appear), especially over the processes by which contacts are identified and classified. This has implications for airspace management structures and practice.

The DTA chart depicts a number of issues and opportunities with regards to air defense systems (Figure 17). We have an air defense system (ADS), which collects data, processes it into tracks, and schedules its sensors and weapons against targets. Examples include Aegis and Patriot, which can be configured to automatically close the loop from sensors to weapons (Hew et al. 2010); in high-threat environments, their performance can be beyond conceivable human capabilities. The ADS could be further decomposed into distinct agents for sensor, weapon and other subsystems, as per the previous case studies.

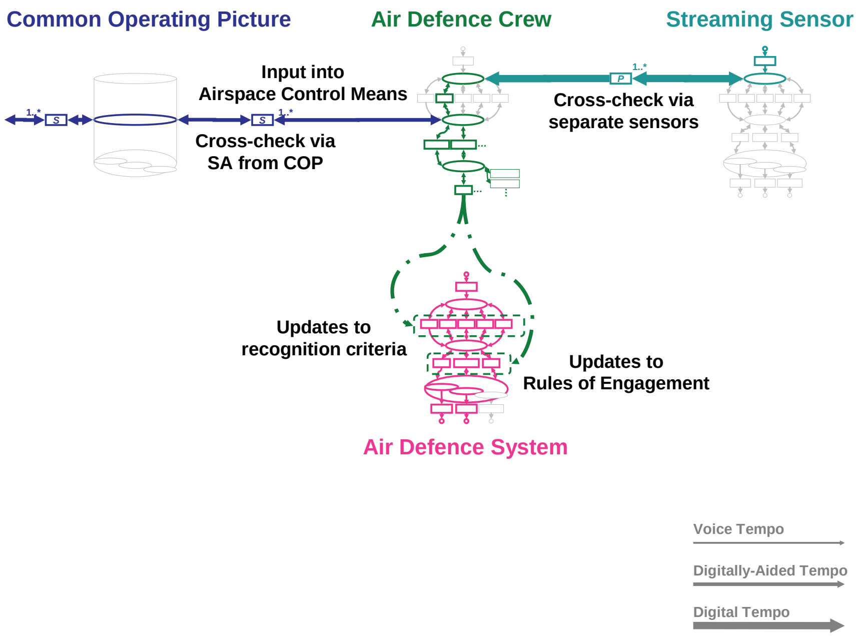


Figure 17. Air Defence - "On" the Loop To Recognition and Rules of Engagement

The air defense crew is "on" the loop to the ADS. They no-longer close the loop from sensors to weapons themselves (that is, "in" the loop); their role is to ensure that the loop is operating properly (they are "on" the loop). The role of being "on" the loop is not new, but it has not been well-articulated in historical or contemporary systems (Hew et al. 2010). Moreover, the role was previously held at a headquarters level, rather than at the crew level. The critical activities are in programming and updating recognition criteria and Rules of Engagement (ROE), so that the ADS discriminates contacts correctly and schedules actions appropriately. The challenge is in skilling and equipping the air defense crew to perform these activities.

The first opportunity is to improve the tempo at which recognition criteria and ROE can be updated. Currently, it can take years for the vendor and test authorities to develop and deploy a new software upload. This can place an air defense crew in the untenable position of being in supervisory control of a system with known flaws. Faster, incremental improvements bring commensurate reductions in risk.

Second, we can equip the air defense crew with sensors, as input to cross-checking the ADS. These would typically be streaming sensors, providing the crew with unprocessed data instead of tracks (e.g., electrooptical video). The crew need not be continuously monitoring this data feed, but can use it selectively to cross-check the ADS algorithms.

Finally, we can tie the air defense crew into the Common Operating Pictures (COP) for airspace management. This provides the crew with another information source for cross-checking the ADS, and input into the airspace control means (ACM). All ADS carry inherent risks of fratricide, but the risks can be managed through appropriate ACM (e.g., Restricted Operating Zones). The challenge is in negotiating the ACM with airspace users, cognizant of the capabilities and limitations of the ADS. Historically, the ACM could be formulated over months or even years, for a single theatre and under a static C2 structure (e.g., VII Corps operations in Western Europe during the Cold War). Modern conflicts see a need for ACM to be formulated at much faster tempos, in different theaters and across changing collections of airspace users.

Conclusion

DTA charts can help researchers to conceptualize C2 teams as they are now, and as they could be. They graphically depict how a team works, as afforded by technology, for analysis and design. They have helped the Australian Defence Force to conceptualize options for the future, informing decisions on investment, doctrine and training. Moreover, the prospect is for a deeper understanding of C2 teams in integrated air-land-sea operations, as manifestations of recurring concepts and structures.

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