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New Paths from Sensor to Shooter: How Digitization can Change the Formability and Topology of Information Flows in Systems that Acquire and Prosecute Targets

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ABSTRACT

The question of how emerging technologies create a radical improvement in capabilities for distributed fires is integral to Defence. Data (from sensors) can be exploited into actions (for shooters) over different paths, and sensors connected to shooters just-in-time vs just-in-case. The analysis combines cognitive ergonomics with network theory via the US Department of Defence Architecture Framework for systems engineering. The work is supported by case studies in indirect fires, close air support, naval surface fires and suppression of enemy air defences. This report will be of interest to operations and systems analysts who are studying the impact of emerging technologies on sensor-to-shooter operations.

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Executive Summary

The Australian Defence Force anticipates a capability advantage from so-called *digitization*, namely the conveyance of information at substantially faster rates than before. But networks and communications are hardly new to military operations, so why should faster communications lead to 'step changes' in capability? This report explores two answers:

1. *Data (from sensors) can be exploited into actions (for shooters) over different paths*. Even if communications are slow, it is possible to tell someone to do something at tactically useful tempos. But to provide them with 'dots on maps' requires faster communications; imagery and video require even faster communications. As sufficiently-fast communications become available, new and potentially-superior exploitation paths become possible.

2. *Sensors are more easily connected to shooters just-in-time rather than just-in-case.* 'Just-in-time' processes can allow assets to be used more efficiently, as opposed to sitting on standby (but idle) 'just-in-case' they are needed. While the 24 hour deliberate targeting cycle is a 'just-in-time' process, it only works against slow-moving targets. Current processes for dynamic targets are 'just-in-case', but faster communications could allow new processes that are 'just-in-time'.

This report provides methods for understanding the network topology that underpins a sensor-to-shooter system, understanding the wider structures that assemble a given sensor-to-shooter system, and asking questions about what the topology and structures could be or should be. The methods can be applied by a systems analyst who is familiar with the US Department of Defense Architecture Framework (DoDAF v2). The work synthesizes the current best practices in cognitive ergonomics, network theory and systems engineering. Case studies are provided from indirect fires, close air support, naval surface fires and suppression of enemy air defence.

This report will be of interest to operations and systems analysts who want to understand the potential impact of emerging technologies on sensor-to-shooter operations. It provides an insight into the total set of sensor-to-shooter systems that are possible, rather than just the ones that have been used in recent operations or are promoted by particular vendors.

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Acronyms

DoDAF	US Department of Defense Architecture Framework
EFFBD	Enhanced Functional Flow Block Diagram
IDEF0	Integrated Computer Aided Manufacturing Definition for Function Modelling 0
OODA	Observe-Orient-Decide-Act decision cycle
OV	Operational View
TOGAF	The Open Group Architecture Framework

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1. Introduction

The Australian Defence Force anticipates a capability advantage from so-called *digitization*; namely the conveyance of information at substantially faster rates than before. Networks and communications are hardly new to military operations. Moreover, when technologies improve by marginal amounts, then improvements in capability can be expected to be at-most linear (for example, a 10 percent improvement in technology would be expected to yield an improved capability on the order of 10 percent). But with digitization offering orders-of-magnitude improvements in technology, there arises the possibility of beyond-linear 'step changes' in capability.

How do we characterize the 'step changes' to capability that are offered by digitization, and what does this mean for operational systems? This report explores two answers:

1. *Data (from sensors) can be exploited into actions (for shooters) over different paths*. Even if communications are slow, it is possible to tell someone to do something at tactically useful tempos. But to provide them with 'dots on maps' requires faster communications; imagery and video require even faster communications. As sufficiently-fast communications become available, new and potentially-superior exploitation paths become possible.
2. *Sensors are more easily connected to shooters just-in-time rather than just-in-case*. 'Just-in-time' processes can allow assets to be used more efficiently, as opposed to sitting on standby (but idle) 'just-in-case' they are needed. While the 24 hour deliberate targeting cycle is a 'just-in-time' process, it only works against slow-moving targets. Current processes for dynamic targets are 'just-in-case', but faster communications could allow new processes that are 'just-in-time'.

The analysis is underpinned by a nascent 'unified theory' that accounts for the structure and formation of sensor-to-shooter systems. The proposed theory builds on earlier work on cognition in human-machine systems, supervisory control, and topology from network theory, and uses systems engineering to bring everything together with precision.

This report will be of interest to operations and systems analysts who want to understand the potential impact of emerging technologies on sensor-to-shooter operations. The concepts of 'Revolution in Military Affairs', 'Network-Centric Warfare', and digitization were heralded for their potential to allow operations to be conducted in structurally superior ways (see Cebrowski and Garstka (1998) and Alberts, Garstka, and Stein (2000) as seminal works). It is accepted that introducing technology can change the way that people work (Militello et al., 2014; Russ et al., 2010), but what are the precise changes that occur? While performance may improve (Bass, Baumgart, & Shepley, 2013; Ophir-Arbelle, Oron-Gilad, Borowsky, & Parmet, 2013), what are the structural changes that underpin that performance? Indeed the structure of human-machine systems remains an active topic of research in cognitive ergonomics / human factors (Flach, Carroll, Dainoff, & Hamilton, 2015; Fleştea, Fodor, Curşeu, & Miclea, 2016; Hettinger, Kirlik, Goh, & Buckle, 2015; Plant & Stanton, 2016; Stanton, 2013; Stanton & Bessell, 2013).

The analysis in this report is an extension and unification of studies that the author led or was involved with during 2007-11, in distributed fires and electronic warfare (P. Hew, 2011b; P. Hew, Byrne, & O'Neill, 2012; P. C. Hew, 2009; P. C. Hew & Flahive, 2011; P. C. Hew & Kingston, 2008). The examples of operations are based on publically-released material, vendor literature, discussions with operators and subject matter experts, human-in-loop experiments (Jessee, Hill, & Flahive, 2013) and a field visit to a live-fire exercise (Byrne, Hew, Lewis, & O'Neill, 2009).

1.1 Terms and Notation

This report uses the US Department of Defense Architecture Framework (DoDAF v2) (Department of Defense (U.S.), 2015), with simplifications for readability: An *activity* is something to be done, without specifying how. A *function* is something that is done via some specified means. Activities are *implemented* as functions that are *performed* by one or more humans or machines, and this *allocates* the activities to those humans or machines. *Items* convey information. *Needlines* denote the need to exchange information.

The report will also use the following charts:

- Enhanced Functional Flow Block Diagrams (EFFBD – Figure 1) depict the order in which activities occur, the logic of moving from one activity to another, and the flow of information that occurs. Activities are drawn in square-cornered boxes, while items (of information) are shown in round-cornered boxes. Arrows between the square-cornered boxes show the sequence of activities. *Inputs* are shown as arrows from item to an activity, and *outputs* as arrows from an activity to an item. Circles denote the logic for the occurrence of activities, as defined by the text enclosed by the circle. In particular, AND marks activities that occur in parallel, and LP marks activities that are *looped* (iterated).
- Integrated Computer Aided Manufacturing Definition for Function Modelling 0 charts (IDEF0 – Figure 2) depict the flow of information, who/what performs the activities, and what governs those activities. Activities are drawn in boxes. *Inputs* to activities are shown as arrows entering the left edge, and *outputs* as arrows leaving the right edge. Activities are governed by *controls*, shown as arrows entering the top edge. An activity’s *performers* are shown by arrows into the bottom edge. An IDEF0 chart does *not* say anything about time order in which activities occur, nor the logic of moving from one activity to another.
- Event traces (Figure 3) show the history of a system’s behaviour. The activities that could be performed are listed by row. Time proceeds from left to right. Rectangles highlight the times when a given activity is performed. Arrows denote the times when information is transmitted and then received, from one activity to another.

Further details may be found in Long (1995). While the diagram names use the word ‘Function’, they may be used to depict activities or functions.

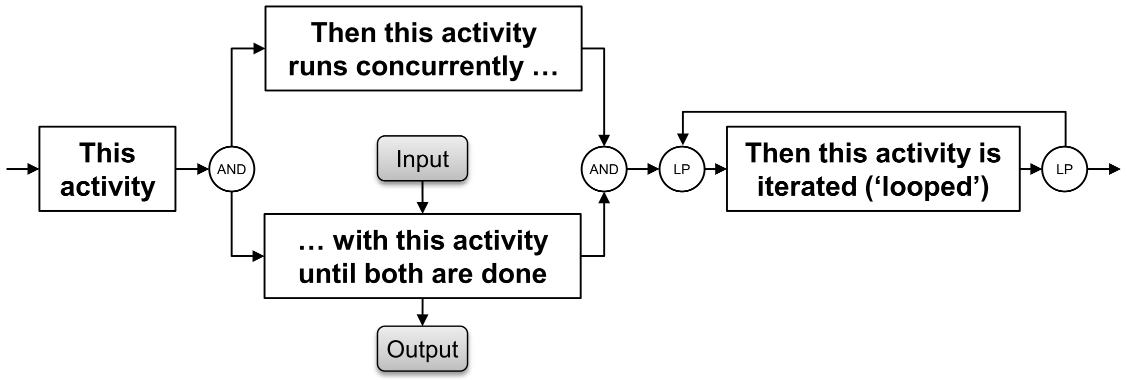

Figure 1 *Enhanced Function Flow Block Diagram (EFFBD) – summary of notation used in this report. Activities are drawn in square-cornered boxes, while items are shown in round-cornered boxes. Arrows between the square-cornered boxes show the sequence of activities. Inputs are shown as arrows from item to an activity, and outputs as arrows from an activity to an item. Circles denote the logic for the occurrence of activities, as defined by the text enclosed by the circle. In particular,* AND *marks activities that occur in parallel, and* LP *marks activities that are looped (iterated).*

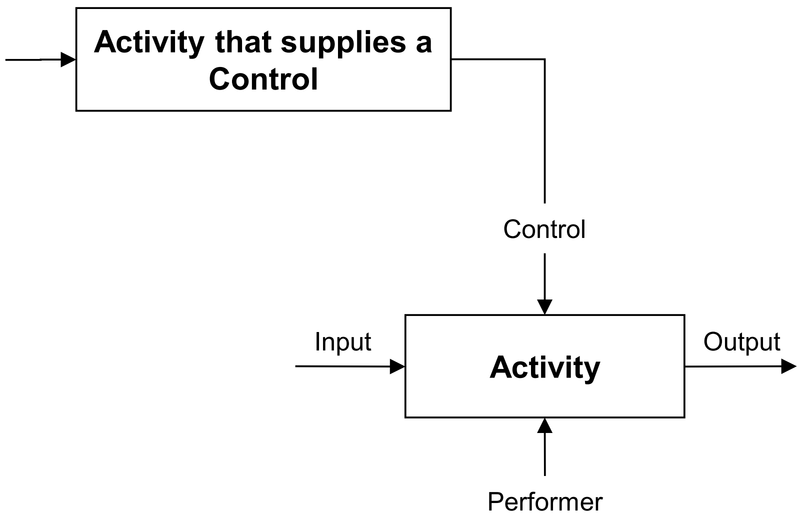

Figure 2 *Integrated Computer Aided Manufacturing Definition for Function Modelling 0 (IDEF0) – summary of notation used in this report. Activities are drawn in boxes. Inputs to activities are shown as arrows entering the left edge, and outputs as arrows leaving the right edge. Activities are governed by controls, shown as arrows entering the top edge. An activity's performers are shown by arrows into the bottom edge.*

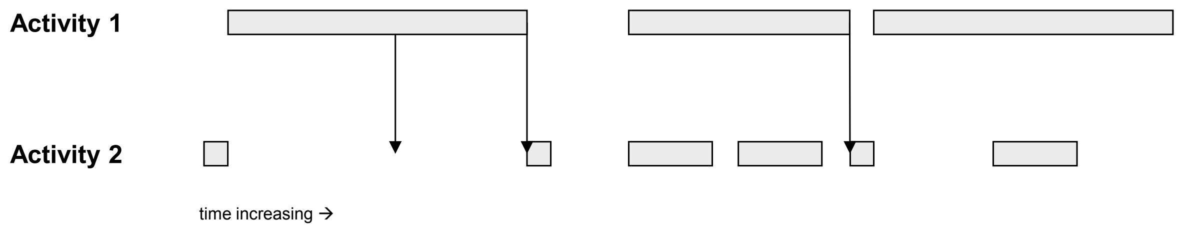

Figure 3 Event trace – summary of notation used in this report. The activities that could be performed are listed by row. Time proceeds from left to right. Rectangles highlight the times when a given activity is performed. Arrows denote the times when information is transmitted and then received, from one activity to another.

2. How is Sensor Data Exploited into Shooter Actions?

This chapter explores the *exploitation paths* from sensor to shooter, namely the paths over which data from sensors is exploited into actions for shooters. It does so by providing a method for understanding the exploitation paths, and for asking questions about the paths that become possible under digitization.

In outline, the chapter proposes a model for an exploitation path from sensor to shooter. A suitably-equipped individual can implement the entire path. Larger systems can have one or more paths, where individuals in the system perform one or more path fragments. But to assemble the fragments across individuals, we will need communications that are sufficiently fast. The ideas are formalized in systems engineering, and the chapter provides a method for viewing the exploitation paths' network topology ('who/what takes inputs and makes outputs'). It considers examples from operations, and finishes with conclusions for future investigations.

2.1 Exploiting Data into Actions

The central idea is that a sensor-to-shooter system has one or more exploitation paths, where individuals (human or machine) in the system perform fragments of the paths. But to assemble fragments at a given point in the exploitation path, we will need communications that are fast enough for the velocity of information at that point.

Figure 4 provides three examples of exploiting data into actions, illustrating the pattern that we will formalize into a model. First consider a radar warning receiver on a single-seat aircraft (Figure 4.a). The equipment measures the ambient intensity in the radiofrequency bands. If there is a source of power that has a pattern that can be recognised, then the equipment infers that there is a radio transmitter. It reports the transmitters' existence to the pilot (by visual or audio means), who makes decisions on it that include decisions to manoeuvre the aircraft, or employ weapons or other subsystems.

The human vision system does the same thing in the visible spectrum (Figure 4.b): the eye starts with measurements of the ambient red-green-blue intensity and finishes (by means that are yet to be fully understood) with inferences about the existence of objects and the properties of those objects. The pattern holds for other sensors, even if the operating principle is very different. For example, radar uses echo-location: it illuminates the environment with radio frequency energy and uses the echoes to make inferences about objects (Figure 4.c).

The velocity of information increases as we move upstream (from right to left). If we want to assemble path fragments that are upstream in the exploitation path, we will need communications that are fast enough. For example (Figure 4.b), an artillery observer can send corrections by voice within seconds ('Drop 200', 'Fire for effect'). That is, the corrections can be encoded in a small number of bits. But to provide a 'dots-on-maps' display of objects in the battlespace, each object is described by a number of values (typically: latitude, longitude, altitude) and those values have to be refreshed. We thus have a larger number of bits that need to be transmitted more frequently. Imagery and video takes the principle even further, as every pixel must be described and refreshed.

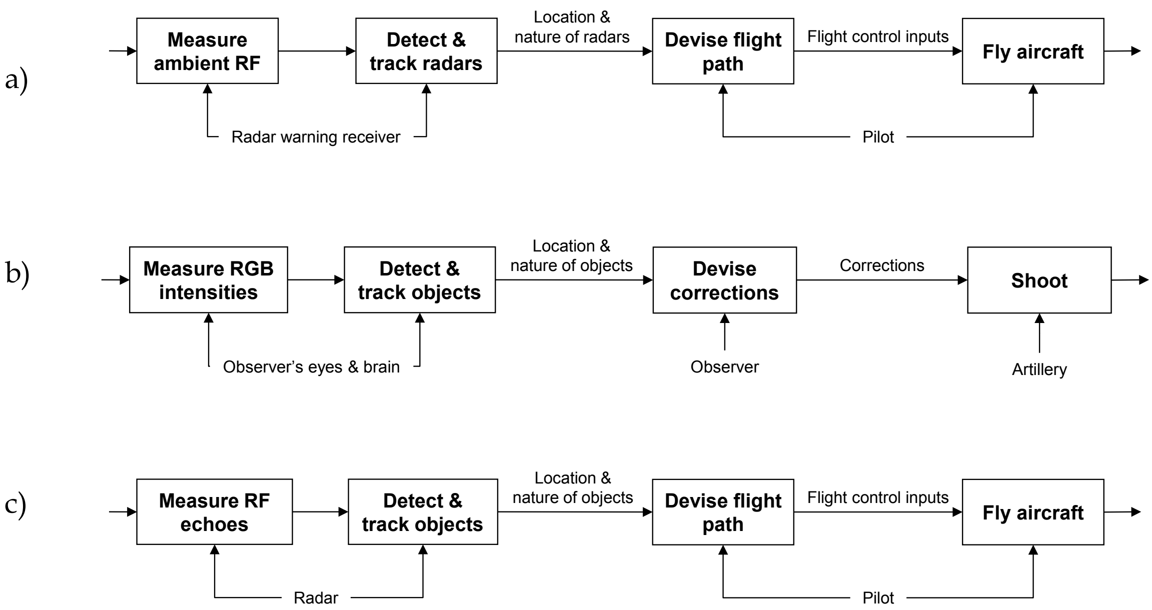

Figure 4: Exploitation paths (information flow in IDEF0 format) a) Radar warning receiver on a single-seat aircraft b) Forward Observer using visual observations to guide artillery c) Radar on an aircraft. In each case, there is a process that measures a physical quantity(s), and a process that infers the existence of objects and the objects' properties. The velocity of information increases as we move upstream (from right to left). Abbreviations: RF = radiofrequency, RGB = red-green-blue.

2.2 Understanding the Exploitation Paths from Sensor to Shooter

We now formalize the ideas that were introduced in the previous section.

2.2.1 Template for Modelling an Individual

Figure 5 presents the template for modelling an individual in a sensor-to-shooter system. The items and activities are specified at Table 1 and Table 2. The activities *measure*, *track*, *decide*, and *act* are modelled as occurring in parallel, where they are continually polling for inputs and intermittently generating outputs. Figure 6 shows a typical event trace.

The model poses three items of information, namely *measurements*, *tracks* and *actions*. As an aid to intuitions, we have the following examples for each kind of item:

- *Measurements*: A pixel in a digital image, measuring the red-green-blue intensity at a location and time. Likewise the measurements of radiofrequency energy at the antenna of a radar warning receiver or radar.

- *Tracks*: Belief-in-existence ('I have detected this object'), location, velocity, identification (friend/foe/non-combatant), classification, assessment-of-health ('damaged', 'destroyed', as in battle damage assessment).
- *Actions*: Slewing a sensor to look at a location, moving to a location, shooting a weapon at an object.

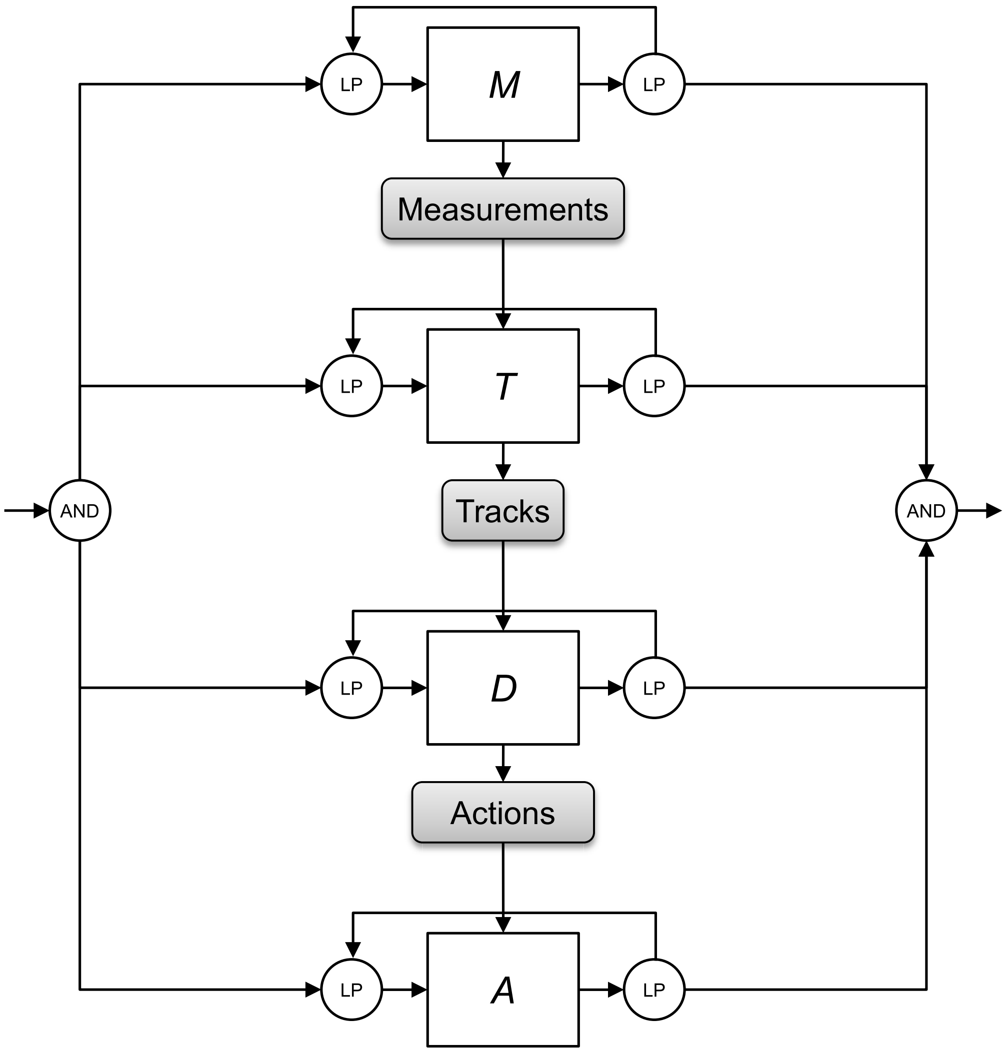

Figure 5 Template for an individual performer within a sensor-to-shooter system. The template is shown as an Enhanced Functional Flow Block Diagram. The activities are abbreviated: M = Measure, T = Track, D = Decide, A = Act. The activities are iterated continually and in parallel. Measurements are progressively taken and accumulated into tracks, leading to decisions that specify actions. In a given sensor-to-shooter system, a given performer will perform some or all of measure, track, decide and act. The individual performers are assembled into a system through their exchanges of information, namely measurements, tracks and/or actions.

Table 1 Items of information exchanged within sensor-to-shooter systems. Portions delimited by «…» are replaced by particular values. Portions delimited by […] are optional.

Item	**Template**
Measurement	«Location» at «Time» was measured as «Measurement»
Track	Over «Time Interval», «Object» has / will have «Property» with «Value»
Action	[At «Time»] [«Performer»] will «Act» [on «Target Object»] [using «Subsystem»] [directed at «Location»]

Table 2 Activities performed by constituents in a sensor-to-shooter system.

Activity	**Description**
Measure	The activity of generating *measurement* items.
Track	The activity of polling for *measurement* items and generating / updating *tracks*.
Decide	The activity of taking *tracks* and generating *actions*.
Act	The activity of doing *actions*.

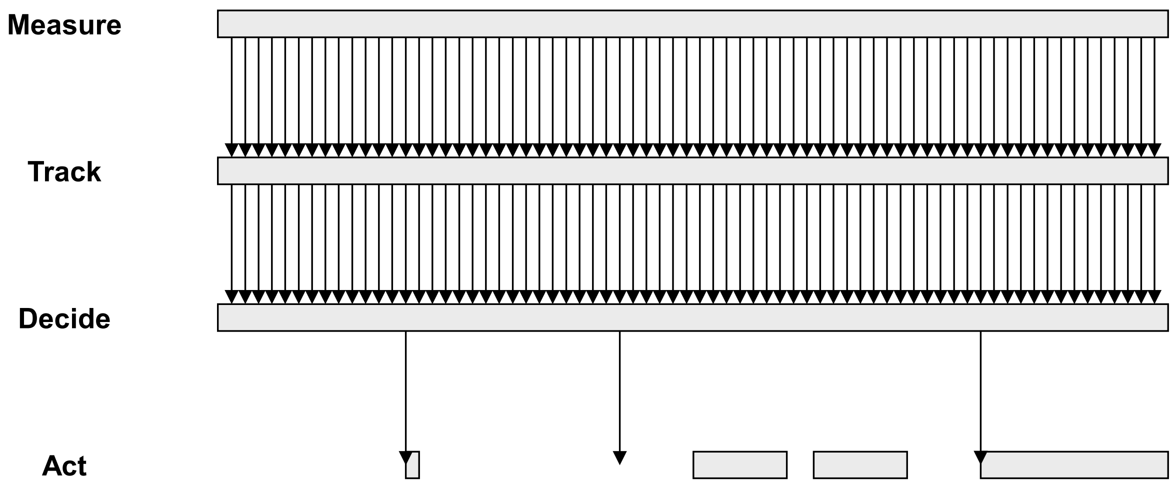

Figure 6 Typical event trace for an individual performer within a sensor-to-shooter system. The activities are iterated continually and in parallel. Measurements are made and accumulated into tracks, leading to decisions that specify actions. Note that the time when an action is performed may differ from when it is specified (arrow from decide to act may or may not lead to an immediate action).

An exploitation chain takes *measurements*, accumulates them into *tracks*, and this leads to decisions that specify *actions*. The logic by which a given set of *measurements* yields one or more *tracks* can be very sophisticated, and likewise for *tracks* into *actions*. The model treats the logic as a black box, and merely asserts that the activities occur (it defines the activity, but leaves open their implementation as functions).

There are six points that are worth emphasizing about the model:

- *Scope*. We model the acquisition and prosecution of targets. We leave aside the wider system that brings a sensor and shooter together at some time, location and circumstance (see next chapter). Likewise the effects of the actions are implied, but are not covered by the model.
- *The activities occur in parallel, consistent with real-world systems*. For example, a rifleman continually scans their locale for threats, in parallel with thinking about what they will do. In terms of the model, the rifleman continually obtains *measurements*. The measurements yield inferences about objects in the battlespace, as *tracks*. At various times, they make decisions that create *actions* to be performed.
- *Exploitation paths work in conjunction with other activities and information*. The model is a template for understanding the exploitation paths in a system. The possibilities are left open for other activities and information. Indeed, each of the *measure-track-decide-act* activities could be affected by other information.
- *The principal feedback loop is through the battlespace*. When *actions* are performed, there will be changes to the individual, to other individuals, and/or effects in the battlespace. For example, the action may be to look at a different location using a sensor. This will change the *measurements* taken by that sensor.
- *Accounts for an individual human*. A suitably-equipped individual can be a sensor-to-shooter system on their own. Exemplars are a soldier with a rifle, or a fighter pilot in an aircraft.
- *Accounts for machines*. A suitably-equipped machine can be a sensor-to-shooter system on its own. Prototypical is the Phalanx Close-In Weapon System for defence against anti-ship missiles, which has been in service for over three decades (Jane's, 2010). The model needs to cover such possibilities, and indeed a sensor-to-shooter system built from humans and/or machines in any allocation. To emphasize: in describing an activity, there cannot be any prejudice about allocating the activity to human or machine.

2.2.2 Charting the Exploitation Topology

We now treat Figure 5 as a 'building block' for assembling individuals (humans or machines) into a sensor-to-shooter system. We assert the following principles:

1. In a given system, an individual will perform some or all of *measure*, *track*, *decide* and *act*.
2. The individuals are assembled into a system through exchanges of information, namely *measurements*, *tracks* and/or *actions*.

Given these principles, a sensor-to-shooter system can be charted under the scheme given using the template provided by Figure 7. The charts are based on IDEF0, with changes to emphasize the features that will be of interest. Recall that IDEF0 charts draw activities in boxes. *Inputs* to activities are shown as arrows entering the left edge, and *outputs* as arrows leaving the right edge. Activities are governed by *controls*, shown as arrows entering the top edge. In IDEF0 charts, an activity's *performers* are shown by arrows into the bottom edge. We divert from this practice by drawing the activities for a given performer in a 'swimlane' (running across the page). Hence in a given 'swimlane', each of the activities *measure*, *track*, *decide* and *act* are either present or absent (following the first modelling principle). *Measurements*, *tracks* or *actions* can be sent across 'swimlanes' (following the second modelling principle).

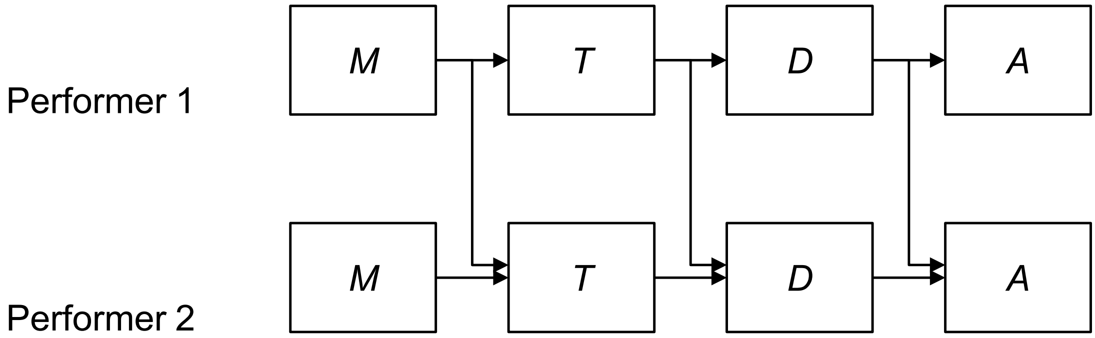

Figure 7 Charting scheme for viewing a sensor-to-shooter system's exploitation topology. The charts are based on IDEF0: Activities are depicted in rectangles. Inputs are shown as arrows entering the left edge, and outputs as arrows leaving the right edge. An activity is governed by controls, as arrows entering the top edge (not shown here, but inherited from IDEF0). Performers are listed by row, and the activities that they perform are shown in their 'swimlanes', running left to right. The activities are abbreviated: M = Measure, T = Track, D = Decide, A = Act.

A chart produced under the scheme of Figure 7 will be called the *exploitation topology* of a sensor-to-shooter system. Likewise, we say that two systems have the *same exploitation topology* if their charts are the same, up to a relabelling of the performers. The idea corresponds with studies of network topology, in which two networks are the same if they have the same nodes and vertices.

Exploitation topologies allow us to formalize our intuitions about exploitation chains. To recall, an *action* can be encoded in a small number of bits, and conveyed once every tens of seconds. Conveying *tracks* at an operationally-acceptable latency can necessitate a data bandwidth that is several decimal orders of magnitude greater. *Measurements* (especially imagery and full-motion video) can be many orders of magnitude greater again. Hence a system's exploitation topology provides an immediate appreciation of the kind of communications technology that will be needed to make that system work.

We emphasize that, as for IDEF0 charts, an exploitation topology chart does *not* say anything about time order in which activities occur, nor the logic of moving from one activity to another. This information is suppressed so that the exploitation topology is easier to see. If we want to see how a performer performs their activities, we can take the activities from their 'swimlane' and generate the full depiction as per Figure 5: each performer performs their activities (one or more of *measure*, *track*, *decide*, *act*) concurrently, where each activity continually polls for inputs and intermittently generating outputs.

For readers who are familiar with systems engineering practices, we note that the charts may be regarded as OV-2 and/or OV-5b.[1] We also see that sensor-to-shooter systems have 'sequential interdependence' between individuals (Arthur, Edwards, Bell, Villado, & Bennett, 2005): work flows from one member to another in the team, but mostly in one direction (that is, *measurements* are progressively accumulated into *tracks* and thus *actions*).

2.3 Comparison with Previous Models

2.3.1 Derivation from the Parasuraman-Sheridan-Wickens Model

The proposed model derives heavily from the four-stage model of information processing proposed by Parasuraman, Sheridan, and Wickens (2000). This model proposes activities for 'information acquisition', 'information analysis', 'decision and action selection', and 'action implementation'. The proposed model equates *decide* with 'decision and action selection', and *act* with 'action implementation'. *Measure* and *track* are inspired by 'information acquisition', 'information analysis', but they do not align exactly. Parasuraman et al. (2000) described 'information acquisition' and 'information analysis' through loose analogies. For our purposes, it is desirable to distinguish *measurements* from *tracks*, as this tells us something about the communications speeds that will be needed. The activities *measure* and *track* are then defined from those information items.

2.3.2 Compatibility with Boyd's Observe-Orient-Decide-Act Loops

The proposed model can be regarded as a specialization of the Observe-Orient-Decide-Act decision cycle proposed by Boyd (see Osinga (2006). Specifically, the *measure-track-decide-act* activities can be respectively taken as specializations of Observe-Orient-Decide-Act. We only claim that our model is a specialization of OODA, to avoid potential conflicts with

[1] An Operational View 2 (OV-2) Operational Resource Flow Description depicts *needlines* that indicate a need to exchange resources. It can define a need to exchange items between activities. An Operational View 5b (OV-5b) Operational Activity Model describes the activities that are conducted in the course of achieving a mission, and the flows into and out of those activities. The OV-2 and OV-5b are complementary descriptions; the OV-2 emphasizes the flows while the OV-5 emphasizes the activities (Department of Defense (U.S.), 2015). DoDAF does not endorse a specific method for producing views, so our charts may be regarded as OV-2. They also (arguably) constitute OV-5b, to the extent of describing the inputs/outputs to activities.

other usages. Indeed, we acknowledge that Boyd's OODA is a very sophisticated model of decision-making, and that our analysis only uses a fraction of this sophistication.[2]

2.3.3 Compatibility with Endsley's Model of Situation Awareness

We also consider the classical model of situation awareness proposed by Endsley (1995). The model postulates activities for 'situation assessment', 'decide' and 'act'. 'Situation assessment' is the process for achieving, acquiring and/or maintaining situation awareness. *Situation awareness* is defined as a state of knowledge, namely the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.

We decline to adopt the model for our purposes after a close reading of (Endsley, 1995). Specifically, the model constructs situation awareness as a state of knowledge *in humans*. Under the model, information is taken from the real world into machines ('system knowledge'), and presented to the operator(s) through some user interface ('interface knowledge'). This information feeds the operator(s)' situation awareness.

As argued earlier, our model needs to cover systems constituted from humans and/or machines in any allocation. If we adapt Endsley's model to our purposes, then we would have to input situation awareness as something that can be held by machines and transacted between parties. We are aware of such formulations (P. Hew, 2011a; Stanton, Salmon, Walker, & Jenkins, 2009), but they appear to rest on redefining situation awareness such that it overlaps with 'system knowledge' and/or 'interface knowledge' as defined by Endsley. There is little apparent advantage in doing so, and considerable risk to the conceptual clarity of the classical model.

We can retain the important features of Endsley's model by postulating a function called 'situation assessment' that is implemented by humans, and that combines with other functions in human implementations of *decide*.

2.4 Case Studies

2.4.1 Observed Indirect Fires

We start with observed indirect fires (Figure 8), the prototypical case for land artillery and naval surface fire support. There are two performers, an Observer and Artillery. We study the system from the 'fire mission' call in land artillery, or the 'Guns Up Ready to Fire' in naval surface fire support. The Observer performs the *measure* and *track* activities against objects in the battlespace and *decides* what to do. The Observer sends *actions* to the

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[2] At time of writing, there does not appear to be a 'canonical' formalization of OODA in systems engineering terms; that is, a formalization that is universally accepted as definitive by the systems engineering community. The analysis in this chapter needs the precision in definitions as made for *measure* and *track*, but we do not claim that this is the entirety of Observe and Orient.

Artillery, who carries them out. The chief characteristic is that Artillery cannot see the target (thus 'indirect'), and acts on directions from the Observer (thus 'observed').

Historically, the Observer used their eyes (with binoculars) to *measure* and their mind to *track*. *Actions* were sent verbally, in accordance with specified terms and definitions ('Drop 200', 'Fire for effect'). With recent technology, *tracking* is supplemented by laser-rangefinding. Then with computerized mensuration and satellite navigation, the resulting *action* can specify a geographical location to an artillery round.

We reemphasize that the *measure*, *track*, *decide* and *act* activities are parallel and concurrent. In a naïve model of observed indirect fires, we might say that there is a temporal sequence of *measure* and then *track* and then *decide* and then *act*. If we accept this model then in the interval of time when the Artillery is *acting*, the Observer is doing nothing. This conclusion is not supported empirically – in reality the Observer does not stop what they are doing. We *do* have a progression from *measurements* into *tracks* and thus *actions*, and our interest is in the topology of that progression.

2.4.2 Close Air Support

We contrast observed indirect fires with the prototypical case from close air support (Figure 9). The system retains an Observer, but now has an Aircraft. We study the system from the point in time when the Observer calls for support, namely the '9 line brief'. At this point in time, the Aircraft is at some distance away from the Observer, and very possibly out of sight. The Observer performs *measure* and *track* activities against objects in the battlespace and *decides* on a target. In older approaches to close air support, the Observer would verbally 'talk on' the Aircraft, to convey critical *tracks* and specify *actions*. The Aircraft's crew would then perform their own *measure* and *track* activities, *decide* on a target, and perform *actions* against it.

The relationship of Observer to Artillery can thus be very different to that for Observer to Aircraft. The Aircraft's crew can see objects in the battlespace, and can make their own choices on which ones to engage. Artillery cannot do this. Thus an Aircrew can perform the *decide* activity to generate *actions* (in particular, on where and how to shoot), and/or it can take the *actions* as supplied to them by the Observer. Likewise the Aircrew's decisions are based on the *tracks* as received from the Observer *and* the ones that they develop themselves. In contrast, Artillery merely polls for *actions* from the Observer.

An obvious potential problem is if the target selected by the Aircraft is different to the one selected by the Observer. This has motivated interest in supplementing the verbal 'talk on'. One approach automates the provision of *tracks*, so that the Aircraft has a 'dots on heads-up display' picture of where friendly forces are located (the Situation Awareness DataLink (Jane's, 2013) is one example). A second approach adopts the technologies described for observed indirect fires, treating the Aircraft as Artillery (in the charts, see how Figure 9 covers Figure 8 while adding further paths).

2.4.3 Full Motion Video

We now consider the approach to close air support that emerged during operations in Afghanistan and Iraq post-2001, using imagery collected by the Aircraft (Figure 10). The imagery is collected by an electro-optic video camera working in the visible and infra-red spectra. The Aircraft is equipped to stream the imagery as full-motion video, where 'full-motion' means that objects appear to move continuously. The Observer is equipped to receive and view the video (using a Remotely Operated Video Enhanced Receiver (Jane's, 2017) for example), and to transmit markups that can be viewed by the Aircraft's crew. Thus the Observer can see the battlespace through the Aircraft's 'eyes' as well as their own, and convey *tracks* and *actions* from that shared perspective.

Full-motion video can enable shooters to see targets. Consider for example a Ship in naval surface fires, operating an Unmanned Aircraft equipped with a video camera (Figure 11). The resulting exploitation flow can be regarded as an opposite to the one for Observer to Artillery, in the allocation of the *track* and *decide* activities. We will consider the idea of equipping the Unmanned Aircraft to *track* in a later example.

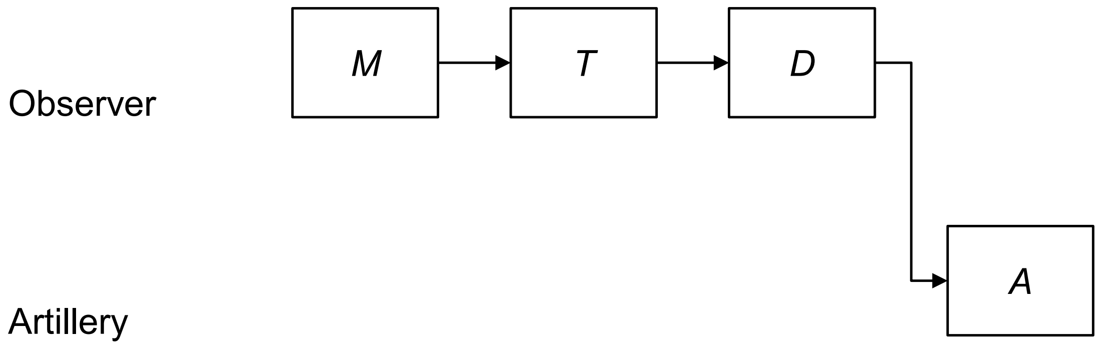

Figure 8 Observed indirect fires (prototypical). The Observer performs the measure and track activities against objects in the battlespace and decides what to do. The Observer sends actions to the Artillery, who carries them out. The chief characteristic is that Artillery does not have a line of sight to the target (thus 'indirect'), and acts on directions from the Observer (thus 'observed'). In historical operations, the Observer used their eyes (with binoculars) to measure and their mind to track. Actions were sent verbally, in accordance with specified terms and definitions ('Drop 200', 'Fire for effect'). In one application of the new technologies, tracking is supplemented by laser-rangefinding. Then with computerized mensuration and satellite navigation, the resulting action can specify a geographical location to an artillery round.

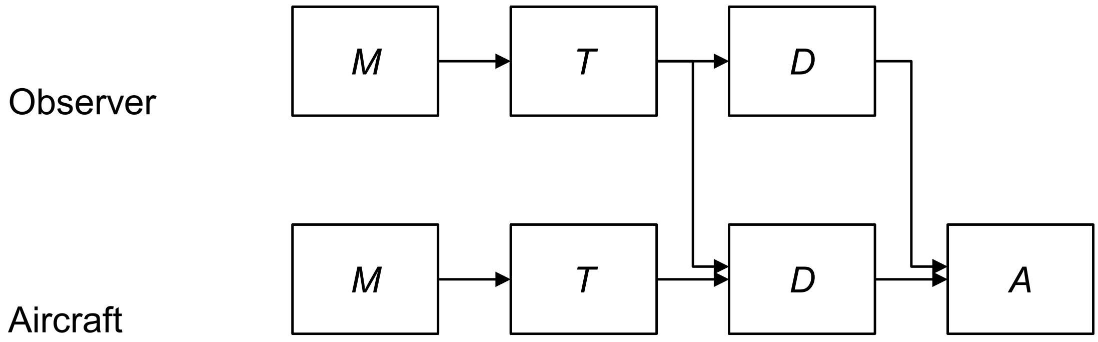

Figure 9 Close air support (prototypical). The Observer performs measure and track activities against objects in the battlespace, decides on a target. In historical operations, the Observer would verbally 'talk on' the Aircraft, to convey critical tracks (arrow from Observer tracking activity to Aircraft deciding) and specify actions (arrow from Observer deciding to Aircraft acting). The Aircraft's crew would then perform their own measure and track activities, decide on a target, and perform actions against it. An obvious potential problem is if the target selected by the Aircraft is different to the one selected by the Observer. This has motivated interest in supplementing the verbal 'talk on'. One approach automates the provision of tracks, so that the Aircraft has a 'dots on heads-up display' picture of where friendly forces are located. Another adopts the technologies described for observed indirect fires, treating the Aircraft as Artillery.

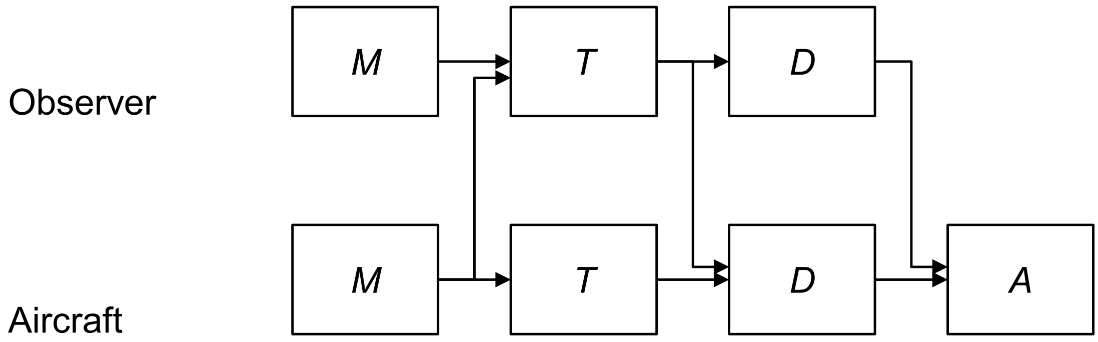

Figure 10 Close air support supplemented by full-motion video. The Aircraft collects imagery using a video camera, and streams it to the Observer (arrow from Aircraft measuring to Observer tracking). The Observer views the video, and transmits markups that can be viewed by the Aircraft's crew (arrow from Observer tracking to Aircraft deciding). Thus the Observer can see the battlespace through the Aircraft's 'eyes' as well as their own, and convey tracks and actions from that shared perspective.

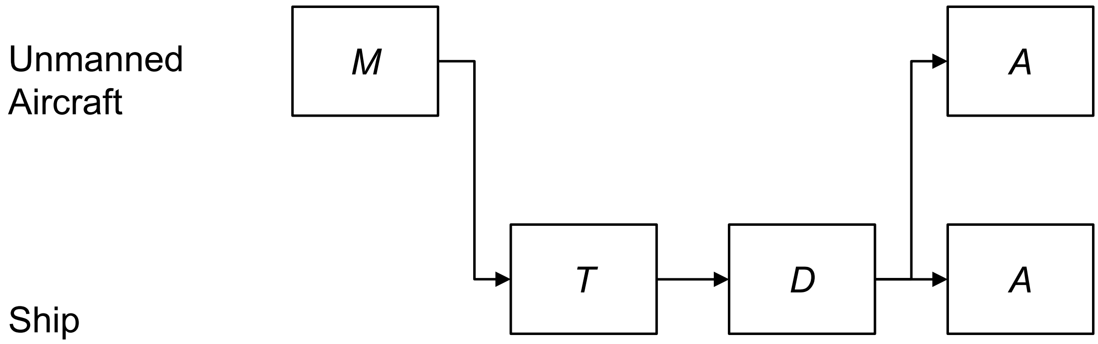

Figure 11 Full-motion video can provide a line of sight equivalent to shooters that can otherwise only be indirect fire assets. Prototypically we might consider a Ship in naval surface fires, operating an Unmanned Aircraft equipped with a video camera.

2.4.4 Target Designation

There are situations where an Observer arranges for a marker to be placed into the battlespace: coloured smoke and laser spots being two examples. While the Aircraft performs *measure* and *track* as before, the marker makes this easier by being readily visible to the aircrew or aircraft equipment. For modelling, we declared a Marker as a performer (for consistency with laser designation – see next paragraph). Smoke markers, for example, can be used in many ways (Figure 12). They can be used as reference points for conveying *tracks*: the Observer and Aircraft can both see the smoke, thus the Observer can 'talk on' the aircrew from smoke to target. They can also be used as reference points for *actions*, where Observer tells the Aircraft to shoot at the markers or at a point relative to them.

Laser designation (projecting a laser spot onto a target) can be treated in the same way, taking the laser spot as the Marker. The Observer can move the laser spot by manipulating the laser designator (in terms of the model: send a 'move' action to the laser spot). Moreover, a laser-guided munition can *measure* in the band of light occupied by the laser spot, and can use those measurements to *track* the spot. In a so-called 'lock-on after-launch', an Observer can tell an Aircraft to launch a Munition, which will then acquire the laser spot and home in (Figure 13). In drawing the chart, we show the Aircraft controlling the Munition's *act* activity (the arrow into the top edge). The Aircraft launches the Munition, but from then on the Munition *decides* where it will fly.

The options afforded by emergent technologies are thus quite rich, even in the restricted case of equipping a soldier to be a ground-based Observer working with Aircraft, Artillery and Ships. At the same time, the modelling provides a sense in which the options are constrained. Information topologies provide a precise way to make statements such as 'Using laser designation is like using smoke markers except for …' or 'Using full-motion video is quite different because …'.

2.4.5 Larger Example

We consider a notional sensor-to-shooter system for suppression and destruction of enemy air defences (Figure 14). An Unmanned Reconnaissance Aircraft loiters in the battlespace, sending imagery to a Ground Station. Analysts use the imagery to seek out the defences, and otherwise tell the Unmanned Reconnaissance Aircraft where to fly. If an enemy's air-defence radar is spotted, the Ground Station tells a Strike Aircraft to attack, and the Strike Aircraft launches an Anti-Radiation Missile. The Anti-Radiation Missile is programmed to recognize the emission characteristics of the air-defence radar, to which it listens for and homes in.

The analysis prompts questions about possible variations (depicted in dashed lines). Should we equip the Unmanned Reconnaissance Aircraft with *tracking* capabilities? For example, sensors for precision navigation and rangefinding could allow a target's location to be inferred. A further option is aided/automated target recognition, to automatically infer the existence and properties of targets. Similarly, should the Strike Aircraft launch the Anti-Radiation Missile purely on cueing from the Ground Station, or close with the target and perform its own *measuring* and *tracking*? Doing so may be necessary if the Missile is to have an up-to-date characterization of the targeted radar's emission characteristics.

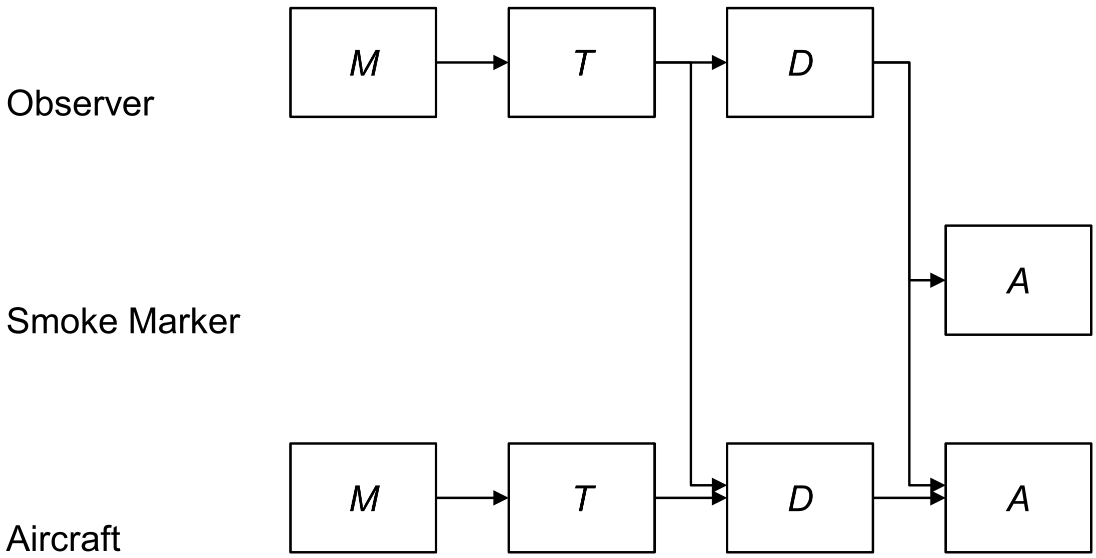

Figure 12 Smoke markers are placed into the battlespace. The model treats a marker as an enduring object that can be told to move by the Observer (in actuality, smoke markers burn out after some duration. They are put into the battlespace by various means, including by hand, artillery or from aircraft). A marker can be used in many ways. One is as a reference point for conveying tracks (arrow from Observer tracking to Aircraft deciding): the Observer and Aircraft can both see the smoke, thus the Observer can 'talk on' the aircrew from smoke to target. Another is as a reference point for actions (arrow from Observer Deciding to Aircraft acting), where Observer tells the Aircraft to shoot at the markers or at a point relative to them.

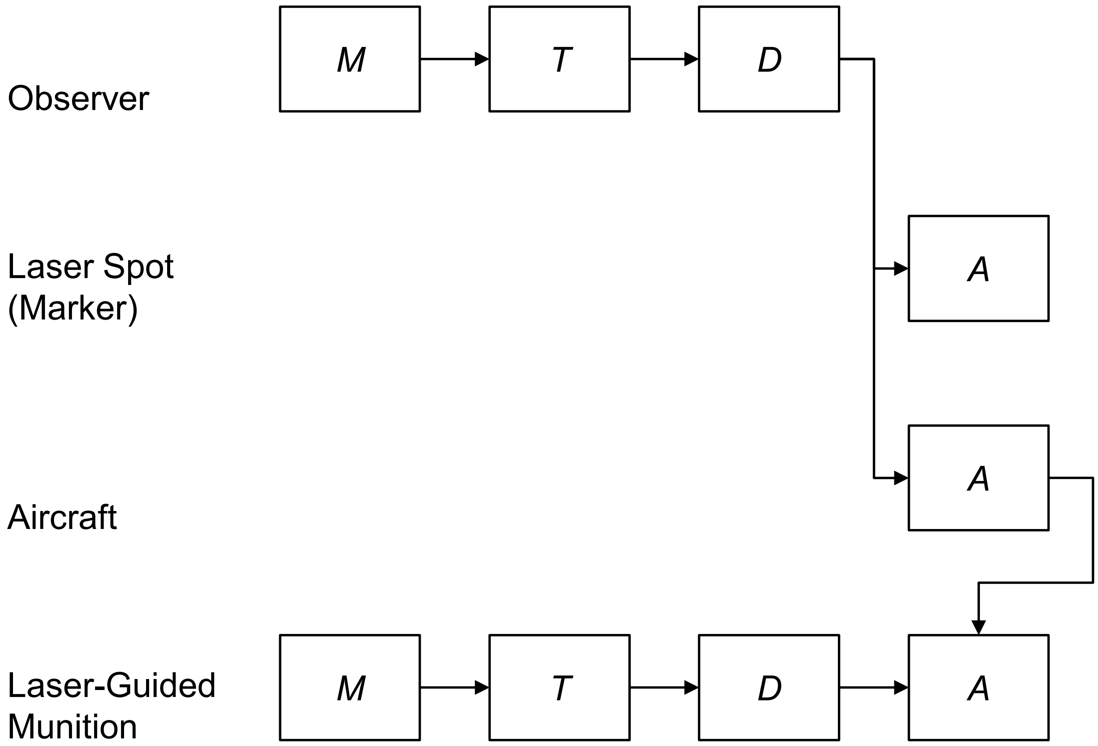

Figure 13 Laser designation with 'lock-on after-launch'. The Observer can move the laser spot by manipulating the laser designator (in terms of the model: send a 'move' action to the laser spot). The Observer tells an Aircraft to launch a Munition, which will then acquire the laser spot and home in. We show the Aircraft governing the Munition's act activity (the arrow into the top edge). The Aircraft launches the Munition, but from then on the Munition decides where it will fly.

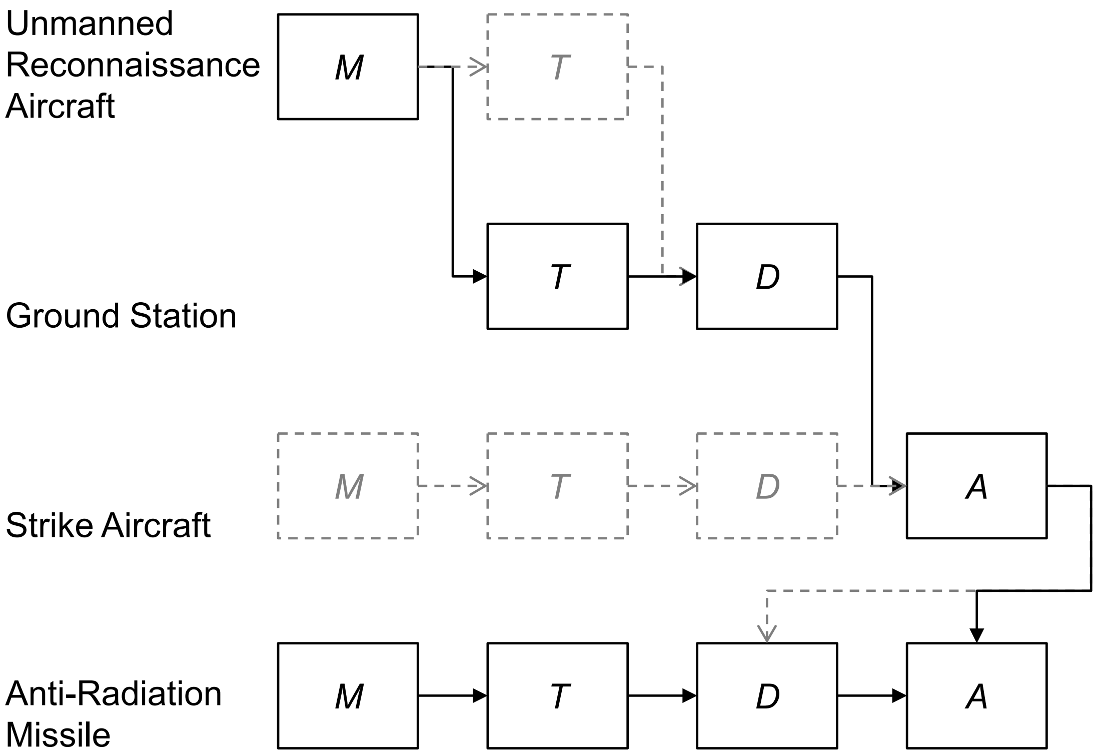

Figure 14 Notional sensor-to-shooter system for suppression and destruction of enemy air defences. An Unmanned Reconnaissance Aircraft loiters in the battlespace, sending imagery to a Ground Station. Analysts use the imagery to seek out the defences, and otherwise tell the Unmanned Reconnaissance Aircraft where to fly. If an enemy's air-defence radar is spotted, the Ground Station tells a Strike Aircraft to attack, and the Strike Aircraft launches an Anti-Radiation Missile. The Anti-Radiation Missile is programmed to the emission characteristics of the air-defence radar, to which it listens for and homes in. Variations shown in dashed lines: Unmanned Reconnaissance Aircraft is equipped with an automated tracking capability, Strike Aircraft closes with the target and performs its own measuring and tracking.

2.5 Conclusion

We finish this chapter with the following ambit claim: that the exploitation paths for any sensor-to-shooter system can be modelled via the template for the charting scheme that we have described. By understanding sensor-to-shooter systems as being assembled from a 'building block' under known rules, we gain an insight into the total set of sensor-to-shooter systems that are possible, rather than just the ones that have been used in recent operations or are promoted by particular vendors.

Exploitation topologies are of most relevance during the systems architecting phase, for generating and developing options. As illustrated in the case studies, we can describe an option precisely and detail its differences with other options. Indeed if an exploitation topology has exchanges of measurements (at high speed), it will require a communications bandwidth that is orders of magnitude more than one that exchanges at-most tracks, which in turn requires much more bandwidth than one that only exchanges actions.

The method can be applied by a systems analyst who is familiar with the US Department of Defense Architecture Framework (DoDAF v2). The analyst uses a template to model the humans and machines in the system that they are studying. The analyst then views the system in a particular way to see the exploitation topology. The template was informed by the best-available models in cognitive ergonomics (Parasuraman et al. (2000), Boyd OODA and Endsley situation awareness). Likewise the viewing procedure adopts best-practices from systems engineering. While network representations and methods have been previously applied to the study of sensor-to-shooter operations (see (Stanton, Baber, & Harris, 2008; Stanton, P., et al., 2009) as just two examples), the proposed method includes the formalizations needed to study the network topology of the exploitation paths.

The proposed approach can be adapted to handle systems other than sensor-to-shooter ones. The main change is the activities' definitions to match them to the domain of interest. This applies to the *act* activity especially. We otherwise retain the focus on information topologies. In working with DoDAF v2, we charted the system in a manner that could be used as either an OV-2 or OV-5b. If we were applying The Open Group Architecture Framework (TOGAF v9), we might use a logical data diagram. Likewise under the Zachman Framework, we might use a data model diagram. The approach can be regarded as a form of social network analysis, where the flow of information between performers is mediated as a flow across the workflow's activities.

We also offer the *measure-track-decide-act* model as a refinement of the Parasuraman-Sheridan-Wickens model. Our refinement replaces the earlier model's loose analogies and examples with precise formalisms.

3. How are Sensor-to-Shooter Systems Assembled?

This chapter investigates the possibility of connecting sensors to shooters 'just in time' instead of 'just in case'. It does so by providing a systems analysis of how sensor-to-shooter systems are put together.

In outline, the chapter introduces the distinction between the speed at which parties can be connected and disconnected (*formability*), and the speed at which information is conveyed from one party to another (*propagability*). It details a concept of operations based on forming sensor-to-shooter chains within seconds. It then looks at where and how sensor-to-shooter chains are formed in current practices. It finishes with implications for studies of sensor-to-shooter systems especially and digitization in general.

The key finding is that current practices actually try to avoid the need to reform sensor-to-shooter chains within seconds. The capability's utility is therefore an open question, and earlier studies (to be discussed) are neither as pertinent nor complete as may first appear.

Throughout this chapter, terms used in doctrine (Department of Defence (Australia), 2009a, 2009b; Department of Defense (U.S.), 2013, 2014)., are enclosed in "double quotes like this". Definitions are otherwise shown in *italics*, as per usual practice.

3.1 Formability vs Propagability

The central idea is that sensor-to-shooter systems need to be put together so that there is a complete chain from inputs to effects. Thus we are interested in the *formability* of systems, namely the speed at which parties can be connected and/or disconnected. Formability is different from *propagability*, which is the velocity at which information is conveyed from one party to another (the previous chapter investigates the impact of propagability on sensor-to-shooter systems).

Figure 15 provides three examples that illustrate the difference between formability and propagability. First consider naval surface fire support, with a forward observer on land and a warship providing fires. There are two distinct processes:

- *Tasking a warship to come on station and connect to the observer*. This process culminates when the warship reports that it is 'Guns Up Ready to Fire'.
- *Calling for fire on targets and providing adjustments*, where the observer and warship iterate through a cycle of adjusting and shooting.

The same processes can be seen in close air support and land artillery – while the actors and procedures change, there is still a process for *connecting a sensor to a shooter*, and a process where the *sensor tells the shooter what to do*.

The second process (*sensor tells the shooter what to do*, see previous chapter) has received far more attention than the first process (*connecting a sensor to a shooter*). Moreover in current operations, the first process takes place over relatively long time intervals. The tempo is dominated by the speed at which vehicles can move – ships and land vehicles can take days to come on station, whereas aircraft dispatched from ground or airborne alert can be on station within minutes.

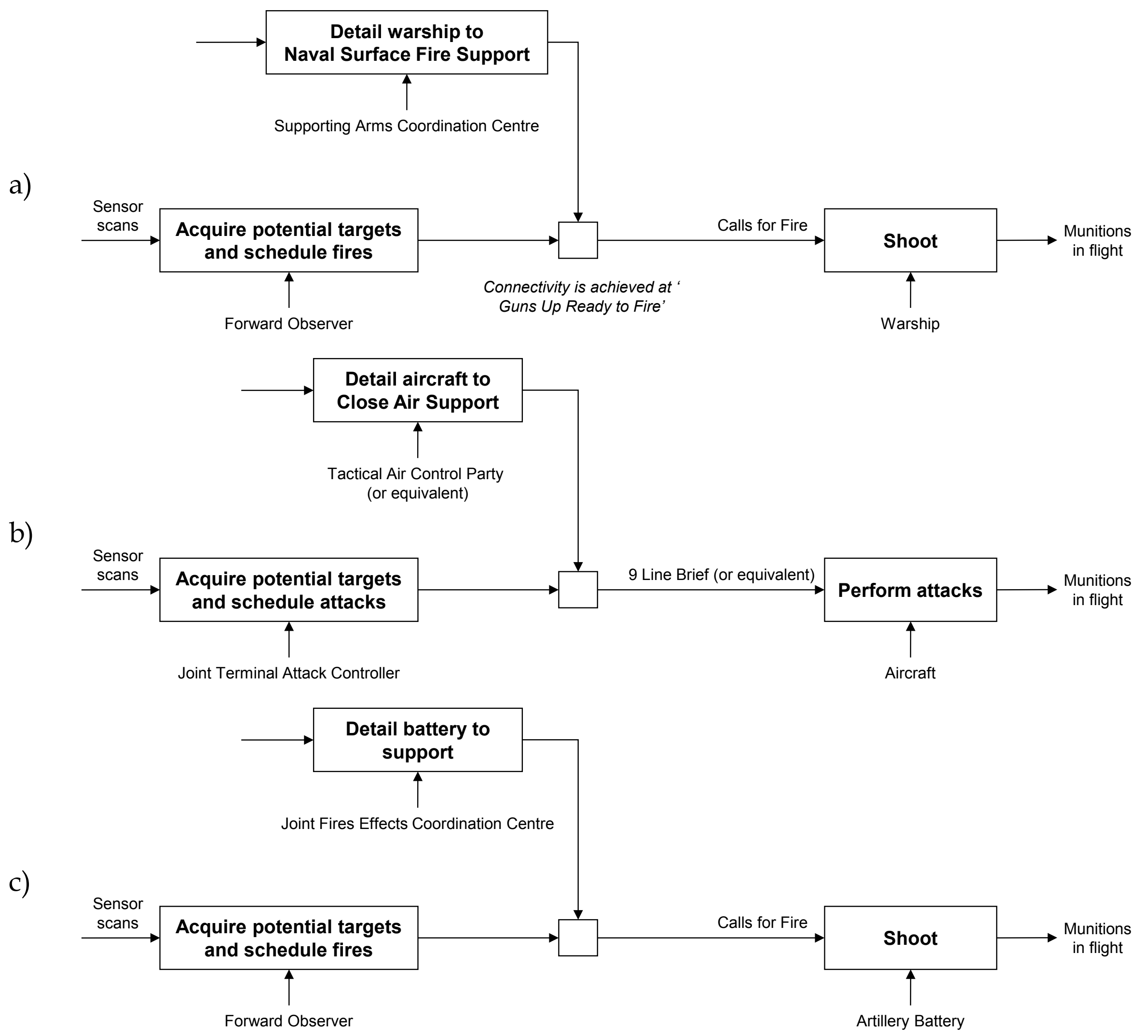

Figure 15: Forming a sensor-to-shooter system (information flow in IDEF0 format) a) Forward Observer – Warship for naval surface fires support b) Joint Terminal Attack Controller – Aircraft for close air support c) Forward Observer – Battery for land artillery. In each case, there is a process for connecting a sensor to a shooter (upper half of each chart), and a process where the sensor tells the shooter where to shoot (lower half of each chart). The activity between parties (the small empty rectangle) is a switch that passes information if and only if the parties are connected. The depicted activities (Acquire …, Detail …, Shoot) are composed from sub-activities. Close Air Support has Perform Attacks rather than Shoot, as aircrew are not necessarily constrained to shooting at locations picked by others; indeed they can often find and select their own targets (see previous chapter, case studies for observed indirect fires vs close air support).

3.2 Forming Sensor-to-Shooter Chains within Seconds

At first glance, if sensor-to-shooter chains could be formed more quickly then coverage would increase. Weapons are increasing in range, so they could reach targets acquired by sensors at increasingly dispersed locations – but only if those sensors are connected.

Likewise the utilization for sensors and shooters could be increased. Notionally, we could have situations in which a sensor has acquired a valid target, and there is a shooter that could reach it, but the target escapes because the sensor is not connected to the shooter.

We turn to formalizing and analyzing these intuitions.

3.2.1 Proposed Concept of Operations

Suppose that we register every sensor and shooter onto a common digital network such that a chain could be constructed from any sensor(s) to any shooter? A sensor could thus be connected to a shooter in fractions of a second, just as a telephone network connects caller to receiver. Sensors and shooters could be de-registered from the network if they were not to be assembled into chains. Formally, we propose a system that has information flows as depicted at Figure 16 and activities flow as depicted at Figure 17.

We define a *sensor unit* as anything that performs the activity **Acquire potential targets** and a *shooter unit* as anything that could **Engage targets**. We propose that a *scheduling unit* would **Schedule targets for engagement** under the control of some *engagement criteria*, such that *if* the sensor acquires a valid target, *then* the shooter will engage. Criterion could include the *null* 'do not engage anything', but if the criterion was *non-null* then we declare the sensor as *connected* to the shooter (or vice versa for shooter to sensor). We equate the act of *establishing* a chain with supplying a sensor-to-shooter chain with non-null engagement criteria. A *switching unit* would **Establish sensor-to-shooter chains** under the control of some *connections policy*. For example, a connections policy might say that if a sensor is north of some line, then it can be connected to a certain set of shooters. The activity to **Devise policy for sensor-to-shooter chaining** is performed by a human who is 'on' the loop.[3]

In real life, the engagement criteria and connections policy manifest in a number of artifacts, including among them the Rules of Engagement, the Attack Guidance Matrix and Fire Support Coordination Measures. The model covers systems where humans are 'in' the loop from sensor to shooter, and also systems that automatically acquire and engage a target without human intervention. We would model such systems as having machines for the sensor, shooter and scheduling units. We leave aside the question of whether a given set of engagement criteria is adequate for real-world conditions; the point is that automated scheduling of shooters to targets is possible. Likewise, sensor-to-shooter chains could be established by a machine.

[3] 'on' the loop is different from 'in' the loop. If a human is 'in' the loop, then they are performing an activity (strictly: they are performing a function that implements an activity). If a human is 'on' the loop, they are in a supervisory role that controls the activity. See (P. C. Hew, 2016) for details.

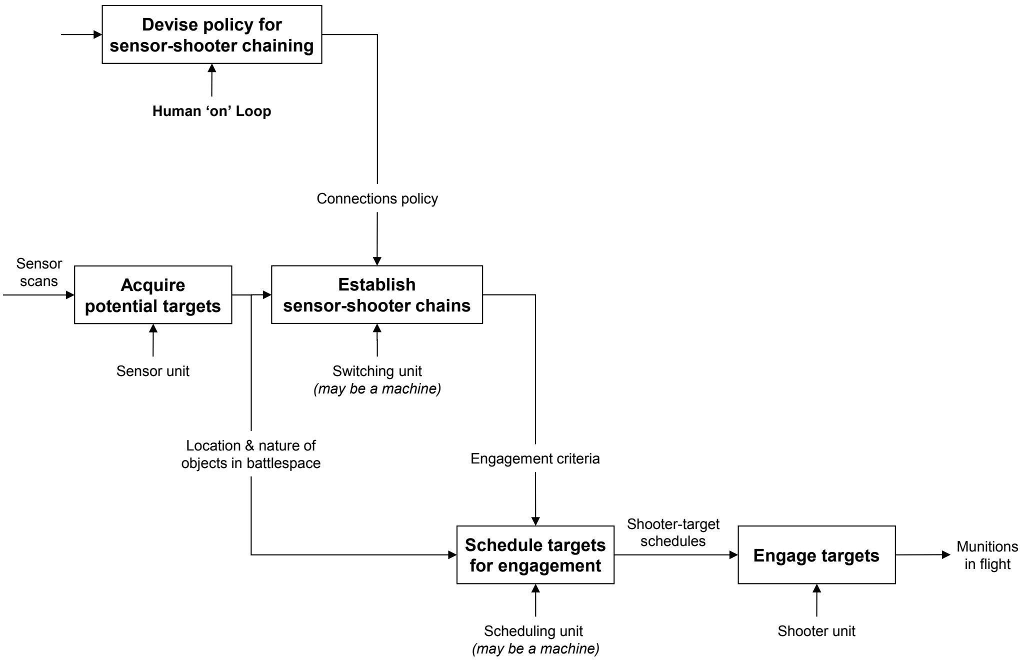

Figure 16 Concept of operations – assembling a sensor-to-shooter chain to acquire and engage targets (information flow in IDEF0 format).

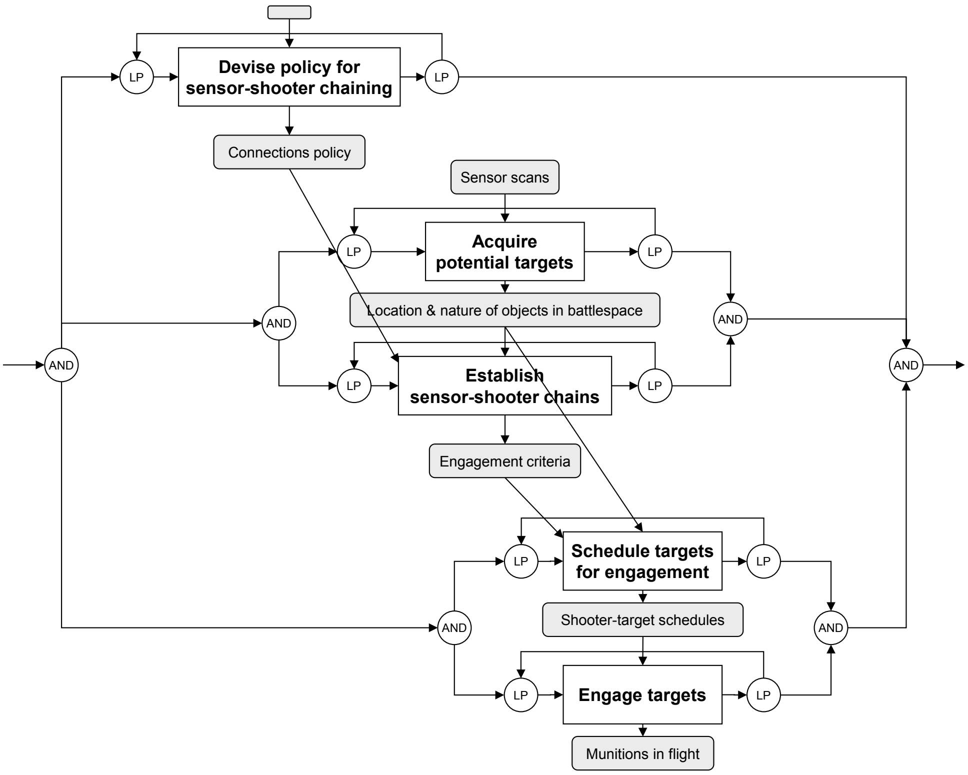

Figure 17 Concept of operations – assembling a sensor-to-shooter chain to acquire and engage targets (activities flow as an Enhanced Functional Flow Block Diagram).

The proposed concept and technologies are not new. The US Army experimented with them during the 1990s (Alberts et al., 2000, pp. 180-182), and an elegant description is given in Driscoll and Pohl (2002). Indeed, the capability is present in the Advanced Field Artillery Tactical Data System (Boatner, 2002), a battle management system that has seen two decades of service with the US Army and Marine Corps, and that entered service with the Australian Army in 2011. See (P. C. Hew, 2016) for details on how the proposed concept was deduced.

Our questions are about the concept's operational utility. Calbert (2000) quantified the utility of being able to engage more frequently in any time interval. An immutable sensor-to-shooter network could provide such a capability if it covered the battlespace. Our question is: What if the connections are formed when they are needed?

3.2.2 How do we Analyze the Proposed Concept's Operational Utility?

The modelling in Figure 16 and Figure 17 prompts the following question: should chains be established *before* or *after* targets are acquired by a sensor? Indeed, we see two paths for information and activity that can flow from **Acquiring potential targets**:

- *After*. A target could trigger the formation of a chain that would prosecute it (in Figure 16, follow the arrow out of **Acquiring potential targets** into **Establish sensor-to-shooter chains** and then down into **Schedule targets for engagement**). This is a 'just in time' approach – having found a target, establish the chain quickly before the target escapes.
- *Before*. The chains could be established up-front and then left alone to acquire and engage targets (again in Figure 16, follow the arrow out of **Acquiring potential targets** into **Schedule targets for engagement**, but do not use the arrow from **Acquiring potential targets** into **Establish sensor-to-shooter chains**). This is a 'just in case' approach, where sensor-to-shooter chains are set up as mousetraps.

Targets thus have two properties of interest. The first is *fleetingness*: a target has a *fleetingness of greater than X* if it must be engaged within duration *X* of being acquired, for any prospect of success. Conversely a *fleetingness of less than X* means that engagement can be deferred up to duration *X* after being acquired, for the same prospect of success. The term matches the usage of 'fleeting' in doctrine – the more fleeting a target, the harder it is to prosecute.[4]

The second property is *anticipability*: a target has *anticipability of greater than X* if its location from now to *X* can be constrained to a region smaller than the combined field-of-view of the available sensors. Conversely an *anticipability of less than X* means that no such region

[4] We cannot use 'time sensitivity' as it has a meaning in doctrine: a "time sensitive target" is one that is of such high importance, or presents such a threat, that the campaign-level commander dedicates assets to acquire and engage it (or is willing to divert assets away from other targets to do so). In most cases, time sensitive targets require immediate response because they pose (or will soon pose) a direct danger to friendly forces and/or noncombatants, or are highly lucrative, fleeting targets of opportunity. Thus time sensitive targets are a category of targets, characterized by high fleetingness and other features.

can be constructed. In practical terms, if we have correctly anticipated the target then our sensors will have covered every place that it could appear. The term is derived from 'anticipated' and its usage in doctrine (to be covered later in this chapter).

3.3 Current Practices

Current practices are best understood in terms of a default process that reforms the sensor-to-shooter chains every 24 hours, and then two variations from the default. The differences come from the capabilities of the sensor and shooter units, the speed at which they can be assembled into sensor-to-shooter chains, and the targets' fleetingness and anticipability.

3.3.1 Default Process (Air Force Deliberate Targeting)

The default process is essentially an air force construct. It assumes that targets have a fleetingness of less than 24 hours. Thus if a target is acquired in one 24 hour cycle, it is feasible to engage the target in a subsequent 24 hour cycle (Figure 18). In this sense, the sensor-to-shooter chains are formed 'just in time'.

Each 24 hour cycle is thus punctuated by a plan (the Air Tasking Order), scheduling the shooters to engage targets and sensors to search for further targets. To emphasize, the shooters are engaging targets that were detected in previous cycles, while sensors search for new targets. The duration to engage each target is dominated by the time taken by aircraft to fly to their objectives.

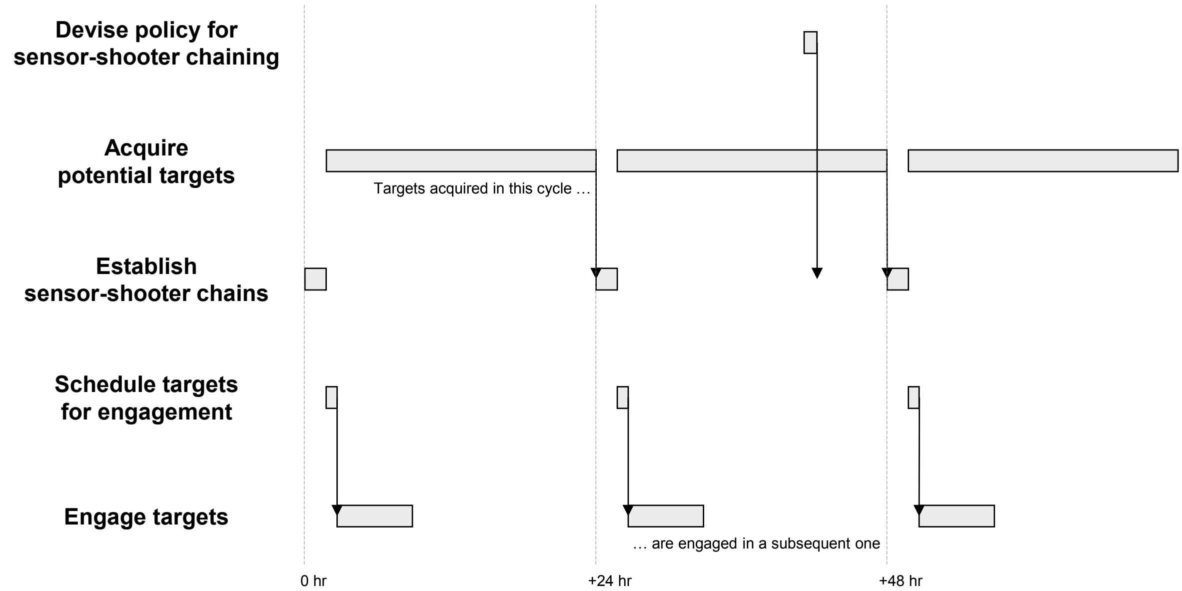

Figure 18 Current practice, default (typical event trace) – Air forces can reform sensor-to-shooter chains against targets with a fleetingness of less than 24 hours. The duration to engage each target is dominated by the need to fly to the target.

3.3.2 Variant 1 (Army and Navy Dynamic Targeting)

By contrast, armies and navies typically assume that the adversary can flee faster than they can redeploy (Figure 19). This assumption leads to the first variation, in which sensor-to-shooter chains are deployed to cover regions where targets are anticipated. The sensor-to-shooter chains may thus be thought of as mousetraps that are deployed 'just in case' – on acquisition of a target, the chain can react within tens of seconds.

The targets' anticipability must exceed the duration to redeploy, typically days/weeks for land vehicles and ships. There are provisions to reform chains in a matter of minutes/hours, for targets that were not anticipated.

3.3.3 Variant 2 (Air Force Dynamic Targeting)

Air forces can similarly reserve assets in anticipation of targets that have a fleetingness of more than 24 hours (Figure 20). Thus the second variation; when a sensor acquires a target, a shooter-equipped aircraft is dispatched from standby and established into a sensor-to-shooter chain. Note that the aircraft have been placed on standby 'just in case'.

The closer the aircraft, the more quickly the chain can establish (and then execute). Otherwise, if a target was not anticipated at the last planning cycle, assets might still be redirected from other missions. Doing so will disrupt those missions, and rests anyway on those assets being in favorable locations.

3.3.4 Alternate Interpretation in Terms of Planning Cycles

The practices can equally be understood in terms of a planning cycle, albeit with care as to choices made in the cycle's construction. First, planning must be viewed in its historical context of 'fire plans' for artillery: A target is "planned" in a given cycle if engagement actions are promulgated in the plan for that cycle. Moreover a target can be "unplanned" but anticipated, in that engagement actions were not promulgated in that cycle, but assets were put on standby in case the target appeared. An "unanticipated" target is one where no provisions were made.

Second, the planning cycle is a structure imposed by the commander onto their forces as a means of control. Thus "deliberate targeting" is applied to targets that can be deferred into a future cycle of planning versus "dynamic targeting" for targets that cannot wait. The interval between plans is a further choice (usually 24 hours in contemporary operations).

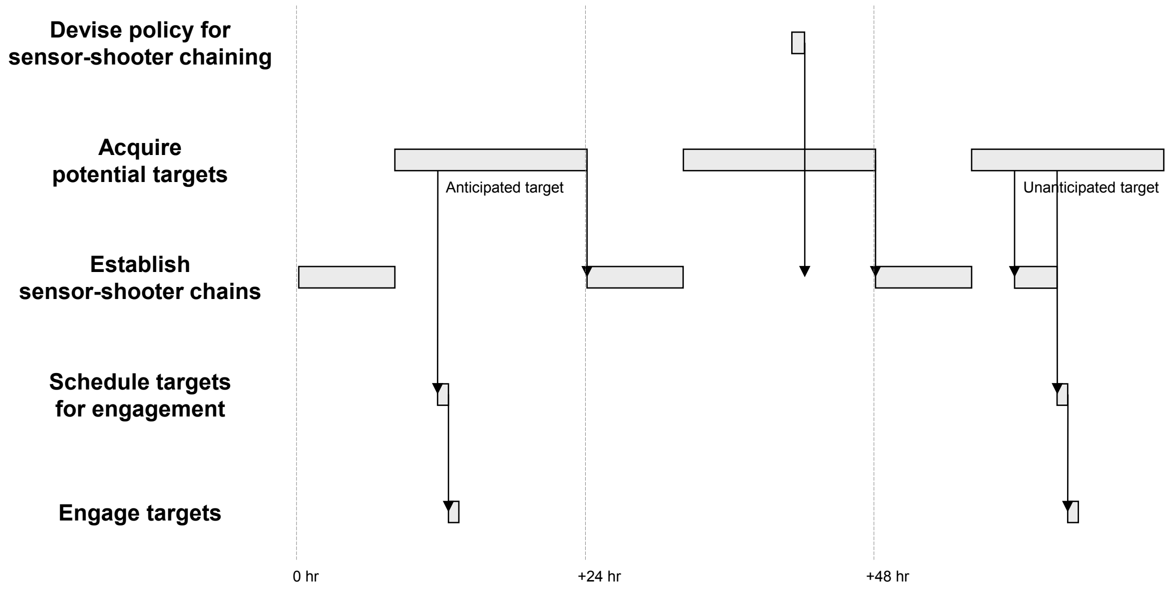

Figure 19 Current practice, variant 1 (typical event trace) – Armies and navies deploy sensor-to-shooter chains for targets that are anticipated, with a capacity to reform for targets that were not anticipated. In this way (unlike Figure 18), a target acquired in one 24 hr period can be engaged in that same period.

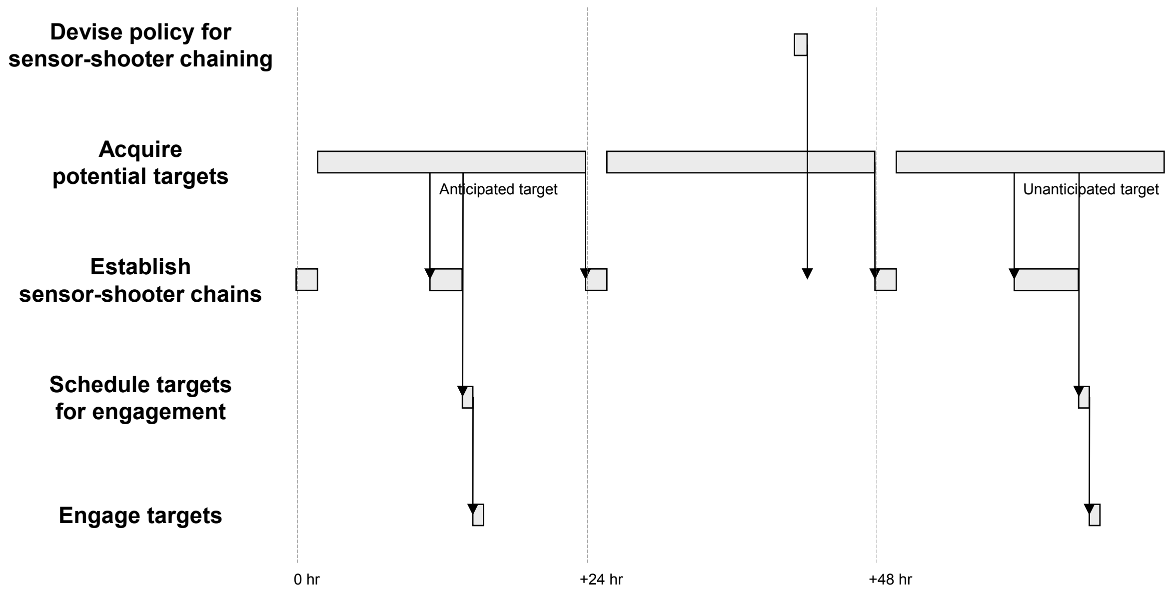

Figure 20 Current practice, variant 2 (typical event trace) – Air forces can place assets on standby in anticipation of with a fleetingness of greater than 24 hours, or otherwise redirect assets to targets that were not anticipated at the last planning cycle. In this way (unlike Figure 18), a target acquired in one 24 hr period can be engaged in that same period.

3.4 Proposed Practice vs Avoid Reforming Sensor-to-Shooter Chains?

If we are looking to (re)form a sensor-to-shooter chain within seconds, it is against a target that has fallen through the two processes – the target's fleetingness is greater than 24 hours but its anticipability is less than 24 hours. As noted, such targets are "unanticipated".

Fleetingness greater than 24 hours is not difficult to achieve. Anticipability of less than 24 hours is, however, more questionable. The issue is not about the capabilities of threats, but about how the friendly force plans and operates. Namely: Would we ever deploy sensors and shooters into locations where the shooters can cover the sensors, but *without* correctly anticipating which of those sensors ought to be connected (to those shooters)?

It is unclear that such a situation would arise. For example, an obvious alternative is to only deploy a sensor unit if it can be covered by a shooter (or if the sensor is expendable!). That is, the commander only deploys sensors if they have put in place the measures for exploiting the information that is obtained by those sensors.

3.5 Conclusion

The utility of reforming sensor-to-shooter chains within seconds is an open question. On the one hand, it is 'obvious' that coverage and utilization of sensors and shooters could be improved, and targets could be engaged where they would otherwise escape. On the other hand, current practices avoid the need to reform sensor-to-shooter chains within seconds. Hence the proposed practice could improve sensor-to-shooter operations, but (potentially) only in a contingency that is being avoided.

The proposed concept of operations solves the problem that was identified for it: to engage a target that has been acquired, before that target can flee. The insight is that the problem is dissolved by current practices. As explored in the analysis, the formability of sensor-to-shooter chains is dominated by the physical mobility – the speed of land vehicles, ships and aircraft. It has become technologically possible to assemble the *information exchange aspects* of a sensor-to-shooter chain within seconds, but the need for physical proximity is unchanged. If the demands of physical proximity are satisfied (by current practices, say), then improved formability via digitization could be a useful refinement.

Earlier studies are therefore not as pertinent or complete as may first appear. This author was unable to retrieve the experiments cited by (Alberts et al., 2000, pp. 180-182) as work by the US Army, and could not therefore see the assumptions made about the targets. The UK/US Sensor-to-Shooter Study series looked at targets with high fleetingness (Ansell, 2001), but excluded the possibilities for anticipating them. Other studies allocated shooters to target *assuming that* the targets can be engaged before they can flee (see (Ahuja, Kumar, Jha, & Orlin, 2007; Rosenberger et al., 2005) for example), or that aircraft are being dispatched from standby (Calbert, 2001; Mishra, Batta, & Szczerba, 2004).

Generalizing from sensor-to-shooter systems to networked systems in general, we note that extant studies largely assume that the networks and chains are static. The closest diversion is in systems dynamics (Radzicki & Taylor, 1997), where the networks vertices are fixed but can be regulated in flow rate. There are precedents in the study of logistics systems that can cope with disruptions or are laid out to anticipate contingencies (E J Lodree Jr & Taskin, 2008; Görmez, Köksalan, & Salman, 2010; Lefebvre, 2009; Melo, Nickel, & Saldanha-da-Gama, 2009). Supply chain management has recognized the need to adapt the chains to evolving circumstances (Gattorna, 2008; H. L. Lee, 2004).

Second, the assembly and dissolution of chains raises an intuitive connection to adaptability, in the idea of adapting chains to evolving circumstances. That said, network formability has yet to feature in studies of agility, adaptivity and related notions. Previous researchers have inferred that adaptivity is generically desirable (from precedents in nature and studies of computer simulations), and therefore sought to foster adaptivity into organizations (Alberts, 2011; JSA Action Group 14 Complex Adaptive Systems for Defence, 2010). The gap is in acknowledging the costs of being ready to adapt, as in holding aircraft on standby so as to establish a sensor-to-shooter chain.

We draw a speculative connection with cyber-physical systems, or systems where physical processes affect computations and vice versa (E. A. Lee, 2008). A case in point is monitoring a central-processing unit for overheating, and thereby adjusting the rate or nature of computations performed (Wolf, 2009). The term is typically applied to embedded systems, but could the distributed fires system constitute a cyber-physical system? It performs a computation, to allocate sensors and shooters to targets and/or anticipated target regions. The default process is a time-bounded optimization, over successive 24 hour intervals. As target fleetingness increases, the default approach fails and alternative computations need to be applied; in particular, ones based on pre-allocation. The connection is (we speculate) more than just an analogy, and could lead to new ways of conducting operations.

Finally, having accepted that sensor-to-shooter systems need to be formed, we also accept that there is recursion: there's the system that forms a sensor-to-shooter system, a super-system that forms the first system, a super-super-system that forms the second system, and so on. This recursion is reminiscent of the structures examined in (P. C. Hew, 2016).

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19. ABSTRACT

The question of how emerging technologies create a radical improvement in capabilities for distributed fires is integral to Defence. Data (from sensors) can be exploited into actions (for shooters) over different paths, and sensors connected to shooters just-in-time vs just-in-case. The analysis combines cognitive ergonomics with network theory via the US Department of Defence Architecture Framework for systems engineering. The work is supported by case studies in indirect fires, close air support, naval surface fires and suppression of enemy air defences. This report will be of interest to operations and systems analysts who are studying the impact of emerging technologies on sensor-to-shooter operations.