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ABSTRACT

The Royal Navy uses Hawk jets to simulate sea-skimming missile attacks against vessels as part of their training regulations. However to best achieve these goals, pilots of the Hawk are required to fly at approximately 50 feet above sea level to accurately mimic the flight path of a missile. Despite this need the Hawk is not equipped with a radar altimeter and instead relies upon pilot skill to ensure the safe completion of the operation. Incidents whereby the Hawk jets have struck the water are however recorded, risking pilot safety. This paper explores the Hawk missile simulation task using a STAMP-STPA methodology to map the key stakeholders within this operation, explore areas of potential risk in the system and make a series of recommendations to improve overall systemic safety of the operation.

Key Words: STAMP-STPA; Systemic Safety; Royal Navy; Systems Thinking

During the Falklands War, 2nd April – 14th June 1982, the Royal Navy Type 42 destroyer, HMS Sheffield, was operating as part of a picket force ahead of the larger Royal Navy task force. On the 4th of May, 1982, an Exocet anti-ship missile, launched by an Argentine Navy Super Étendard fighter-bomber, struck the destroyer. The threat was not identified as a sea-skimming missile until crew aboard HMS Sheffield saw smoke rising from the missiles exhaust approximately five seconds before impact. Due to the lack of threat identification, HMS Sheffield failed to take any defensive or evasive manoeuvres to avoid the missile, and did not deploy any countermeasures, such as launching chaff or preparing defensive fire. Although evidence suggests that the missile did not detonate, heat from the missile ignited HMS Sheffield's fuel reserve and fire engulfed the ship. This extensive fire, combined with the initial impact of the missile, resulted in the death of 20 Royal Navy seamen and the eventual foundering of the vessel, the first Royal Navy vessel sunk since the Second World War (Board of Inquiry, 1982).

Following the sinking of HMS Sheffield, the Royal Navy instigated significant procedural changes for dealing with missile attacks, including the required manoeuvres that vessels should take and immediate defensive actions that should be followed. Significantly, a need was identified to focus on crew training to enable the crew to rapidly respond to the threat of a fast approaching sea-skimming missile, including detection of the incoming threat, and required countermeasures to attempt to avoid the impact of the missile. To facilitate this training, during live sea training operations, the Royal Navy utilises low flying Hawk T1/1A jets to mimic the flight path of a sea-skimming missile in order to realistically train ship radar operators and gunners (Royal Navy, 2012). This training operation is conducted by the Royal Navy, and its subsidiary

force, the Fleet Air Arm, without direct involvement of the Royal Air Force (RAF). The Hawk T1/1A, used in this training operation, originally known as the Hawker Siddeley, first entered service with the RAF in 1976. The Hawk T1/1A is a tandem-seat transonic ground-attack and training aircraft, with a max speed of 625mph at sea level. Traditionally flown by a forward pilot and rear seated trainer, the Hawk can also be flown and operated by a single pilot. As an older aircraft, the Hawk T1/1A does not possess a Head Up Display (HUD) and is reliant on primarily analogue gauges. The Hawk T1/1A jets used within missile training simulations have been made famous for its use by the RAF acrobatic team, the Red Arrows. Despite newer models of the Hawk being developed by BAE Systems, such as the Advanced Hawk, equipped with improved safety systems, including an integrated HUD, these are not available to the Fleet Air Arm for missile simulation training who maintain the use of previously retired RAF T1/1A Hawks.

In order to best mimic the approach of a sea-skimming missile the Hawk must be flown at very low altitudes, ideally less than 50 feet above sea level. Due to cost implications and original design specifications, the Hawk T1/1A is not fitted with a Radar Altimeter (Rad-Alt), which provides accurate measurement of the altitude of the aircraft above the sea. Indeed, to refit a single Hawk T1/1A with Rad-Alt would cost approximately £1 million, making such a refit financially unviable, particularly as the aircraft is being phased out of service. This makes flying the Hawk T1/1A at low altitude extremely difficult, and requires a high level of expertise to perform safely. This training operation therefore has significant safety implications. The pilot must rely upon visual cues to gauge altitude, whilst flying as low and as fast as possible to mimic the flight path of a missile. To illustrate the risk associated with this operation, in 2000, one Hawk T1/1A suffered a sea strike incident, whereby the jet struck the surface of the

sea during a training operation (Stanton & Harvey, 2017). Although there was no resulting loss of life, the aircraft involved suffered considerable damage to its underside. To mitigate the immanent Risk to Life (RtL), the Fleet Air Arm increased the minimum altitude for the Hawk during such operations. This risk mitigation however began to erode the realism of the training operations, as the aircraft would inevitably be detected earlier than would be the case of an incoming missile in an active combat zone, allowing radar and gunnery officers and crew greater time to respond to the encroaching threat.

Despite access to fast jet and fixed-wing aircraft, the primary focus of the Fleet Air Arm has traditionally been rotary-wing and Harrier jet operations. The Fleet Air Arm has therefore historically lacked pilots skilled in fast jet operations, a prerequisite for Hawk training simulations. To reduce the risk to Hawk pilots, Royal Navy vessels and attendant crew, retired RAF pilots, independently contracted by the Fleet Air Arm, were used to fly the Hawk jets used for missile simulation training operations. The commissioned pilots had extensive experience in military fast jets, including low altitude flight, gained from their previous service within the RAF. This experience acted to provide a level of mitigation against the pilots' RtL for the Hawk missile simulation task. Following an overhaul to British defense strategy (Strategic Defense and Security Review, October 2010), the British Government (2010) decided to retire the aging Harrier jet from active service. As a consequence of this decisions, trainee Fleet Air Arm pilots were diverted from Harrier training into Hawk training, leading to a high number of, albeit relatively inexperienced, pilots, becoming available to the Fleet Air Arm for training operations. Due the junior pilots' lack of experience, reassessment of the risks associated with the Hawk missile simulation task was deemed necessary. This reassessment was required to consider both the immediate risk to the

pilots operating the Hawk jets but also the long-term safety of the ships crew, who require training for live combat theatres in the future.

In addition to direct changes within the Fleet Air Arm, Hawk missile simulation exercises were significantly impacted by safety related cultural changes within the British Military. Following the catastrophic mid-air explosion of RAF Nimrod XV230 in 2006, which resulted in the total loss of the aircraft and the deaths of all 14 personnel on-board during a standard refueling procedure, the British Government requested a comprehensive review into the airworthiness and safe operation of the Nimrod aircraft and military operation more generally. This report was delivered by Haddon-Cave (2009) who concluded that safe military training operations were undermined by a safety culture that held assumptions of safety due to previous safe operations. The report suggested that a shift in organizational culture towards business and financial targets *'at the expense of functional values such as safety and airworthiness' (p. 355)* also negatively impacted the safe completion of operations (Haddon-Cave 2009). As a consequence, Haddon-Cave (2009) recommended the establishment of an independent Military Aviation Authority (MAA) to properly assess RtL and shape future safety culture within all British military aviation arms, including the RAF and Fleet Air Arm. As a consequence of the Haddon-Cave (2009) report a culture change was seen within British military aviation resulting in a decision to assign individual accountability for RtL assessments to 'Duty Holders' (DH), where previously responsibility for risk had been held at the organization level. The newly established MAA produced guidelines for the assessment of RtL, in the form of the Defense Aviation Hazard Risk Matrix (MAA, 2011), which supports the classification of single risks according to their estimated severity (catastrophic, critical, major,

minor) and likelihood (frequent, occasional, remote, improbable). The resulting risk level determines at which level of DH the risk is held.

The goal of safety management within the UK military is to reduce risk to a level which is As Low As Reasonably Practicable (ALARP): this is reached when *'the cost of further reduction is grossly disproportionate to the benefits of risk reduction'* (Ministry of Defence, 2007). In order to reduce the associated RtL of the Hawk missile simulation training exercise to a level that was ALARP, a decision was taken by the Royal Navy, with SME advice, to increase the minimum height above sea level that the Hawks were allowed to safely operate. Taken with previous altitude increases, this decision further degraded. By flying at an increased altitude, the Hawk can no longer accurately simulate sea-skimming missile attacks on surface ships thereby denigrating Royal Navy surface fleet and ships crew training against very low-level targets.

In addition to organisational changes, safety and risk assessment within British military aviation underwent a series of cultural changes following the Haddon-Cave (2009) report. Traditionally, the Royal Navy and Fleet Air Arm relied upon quantitative risk assessment techniques including Technique for Human Error Rate Prediction (THERP) (Swain, 1964; Swain & Guttmann, 1983; Boring, 2012) and Systematic Human Error Reduction and Prediction Approach (SHERPA) (Embrey, 1986). These techniques quantitatively model the probability of humans within the system making an error, reminiscent of Fault Tree Analysis (FTA; Barlow, 1973). Within the developing safety culture changes however, the British Military holds the growing acceptance that such methods can be seen as reductionist and can fail to actively attribute the risks associated with the interactions of different subsystems. This acceptance matches a wider trend in

safety research within academic research towards system-based approaches (Walker, Salmon, Bedinger, & Stanton, 2017; Salmon et al., 2017). To this end, the military has sought to increase the use of systemic approaches to safety to augment previously completed assessments. Of the developed systemic approaches within the larger academic literature, Systems Theoretic Accident Model and Process (STAMP) approach (Leveson, 2004) and its corresponding hazard analysis Systems-Theoretic Process Analysis (STPA) has become the most prolific and widely cited (Underwood & Waterson, 2012). STAMP-STPA has been used to explore system safety across a variety of domains including road transport (Salmon, Read, & Stevens, 2016) rail accidents (Underwood, & Waterson, 2014) and potential aviation accidents (Allison, Revell, Sears & Stanton, 2017).

Despite its clear domain agnostic utility, STAMP-STPA has been less used within the military domain (Pereira, Lee & Howard, 2006), especially in relationship to training paradigms. Indeed, development of the systemic approach to address safety within military systems of systems has been a significant challenge to date. Within STAMP-STPA, systems can be viewed as *"interrelated components that are kept in a state of dynamic equilibrium by feedback loops of information and control." (p. 250*, Leveson, 2004). STAMP-STPA can be seen as advantageous over the linear fault and error methods such as THERP and FTA previously used within the military domain in that it seeks to improve the safety of the system as a system as a whole, rather than attribute blame on individual personnel for an accident. To achieve this, STAMP-STPA considers the role of individuals, organizations and technology within the same analysis. This allows safety to be considered as a dynamic, as apposed to linear, process, characterised by feedforward and feedback, from both human, technological

and organizational agents. The identification of the non-linear, interactive, coupling between different stakeholders and the constraints imposed by the different stakeholders, makes STAMP-STPA ideal for understanding complex systems (Leveson, 2004) and systems of systems (Salmon et al., 2012; Harvey & Stanton, 2014; Allison et al., 2017). STAMP-STPA analysis therefore provides a model of potential accidents, which Leveson (2011) describes as an ideal basis for investigation, analysis, prevention and risk assessment

This paper aims to assess the risk to life that surrounds the Hawk missile simulation scenario and identify the primary stakeholders within the system of systems. To achieve these aims, a STAMP-STPA analysis of the Hawk missile simulation scenario was undertaken. As discussed, previous risk assessment strategies used by the Royal Navy have been viewed as reductionist and have historically failed to ensure safe operations. By offering an alternative approach to safety, it is argued that STAMP-STPA can provide novel safety insights, not offered by alternative methods. This work therefore offers a novel use of the STAMP-STPA methodology, a method with limited previous application within the military domain.

METHOD

SME INVOLVEMENT

Understanding of the Hawk RtL case study was gained through and initial workshop and subsequent interviews with subject matter experts (SMEs). An initial workshop was conducted with nine independent SMEs. Eight SMEs were military and industrial stakeholders who had a job role focused in developing

military safety culture following the Haddon-Cave (2009) report. The final SME participant was an independent industry Human Factors professional. During this workshop, the Hawk RtL scenario was explored and key stakeholders were identified.

To achieve a greater understanding, analysts were provided with detailed overview of the Hawk RtL scenario in a subsequent interview with an SME from Air Command, a senior Wing Commander. This resulted in a detailed account of the missile simulation task, which was further supplemented by information available within official documentation including Military Aviation Authority guidelines (MAA regulatory publications, 2016), and Flag Officer Sea Training (FOST) guidance (International Defence Training Royal Navy, *n.d.*). Two analysts completed a second, in-depth interview with the same Air Command SME for greater insight and clarification. During the second interview, the ten characteristics of a system of systems (Harvey & Stanton, 2014) were used to structure the discussion and elicit detailed information about Hawk operations for missile simulation training.

Upon completion of the analysis, findings were presented to an independent team of SMEs who had considerable experience working in the defence sector and with previous safety experience for review, comment and feedback.

CONSTRUCTION OF THE MODEL

Systems Theoretic Accident Model and Process (STAMP)

The cornerstone of the STAMP methodology is the identification of the stakeholders at all levels within the system, and the constraints that they impose on other stakeholders. The control structure represents the highest level of abstraction within the system of systems (Harvey & Stanton, 2014). By organising the layers of constraints that link these stakeholders, it is possible to develop a hierarchical control structure that maps the systems under investigation (Stanton et al., 2013). The initial step of the STAMP analysis therefore involves the construction of a high-level hierarchical control structure. The control structure maps the system of systems under investigation and identifies all the stakeholders that contribute to the system.

These stakeholders are linked by control actions, typically represented by labelled arrows. Control actions constitute the main source of feedback and interaction between the different stakeholders. Some control actions are continuously performed during the scenario under investigation whilst others denote intermittent actions, for example an action performed after an event has occurred.

Systems-Theoretic Process Analysis (STPA)

Systems-Theoretic Process Analysis (STPA, Leveson, 2004, 2011) is used to make predictions about the future safety of systems; based on control theory and the use of consistent guide sentences. STAMP-STPA views systems as interrelated components linked by loops, which control the flow of information within the system and, therefore, maintain a state of dynamic equilibrium (Leveson, 2011). A key concept in STAMP-STPA is that of constraints: accidents occur not due to the occurrence of an event; rather accidents are the result of a lack of appropriate constraints applied at points within the control structure (i.e. feed-forward and

feedback loops). Representing interactions within a system as a hierarchy of control loops allows these constraints to be identified. STPA maps these control loops and identifies potential unsafe control actions (UCAs) through the use of a standardised off-nominal taxonomy. The off-nominal taxonomy is driven by the use of four guide sentences:

1) Action required but not provided;

2) Unsafe action provided;

3) Incorrect timing / order;

4) Stopped too soon / applied too long.

These guide sentences are set as part of the standardised STPA methodology (Leveson, 2004) and are applied to each of the control actions that were identified in the initial stage. The guide sentences are designed to allow analysts to identify all potential UCAs within the system and elicit all the possible failings in order to create the complete failure taxonomy. When applying these guide sentences, each may generate multiple UCAs, equally when exploring some systems not all are applicable in all cases.

For the final stage of the analysis, the causes for the UCAs can be explored by constructing feedback loops for identified UCAs. This enables the researchers to examine how multiple UCAs can interact as well as explore the causal factors behind the UCAs. Once this stage is complete it is possible to begin to develop safety constraints for each of the potential UCAs. These are constraints that should be imposed on the system to prevent the UCAs from occurring, reducing the likelihood of an accident (Leveson, 2004). In this regard, the addition of novel

safety constraints allows the analysts to progress the STAMP-STPA methodology to allow for the development of potential mitigation strategies.

As discussed, STAMP-STPA follows an established step-by-step process to construct a control structure, identify 'unsafe control actions' (UCAs) and identify interactions and causal factors. Before this can be completed however, the primary hazards of the scenario under investigation must be identified. The STAMP model defines a hazard as "*A system state or set of conditions that, together with a particular set of worst-case environmental conditions, will lead to an accident (loss)"* (*p*14, Thomas, et al., 2013). As an example, an accident could be the exposure of people to toxic chemicals and the related hazard would be the release of toxic chemicals into the atmosphere (Thomas et al., 2013). Prior to the start of the analysis, the research team were required to define the potential hazards that could lead to an accident. In the Hawk RtL case study, a potential accident was defined as any event leading to death or injury, with the potential hazards being defined as:

- Hawk strikes the sea
- Hawk strikes the Frigate
- Inadequate training of Frigate crew for future missile attack

The initial risks relating to the Hawk are primarily concerned with the Hawk flying at low altitude. Should the Hawk strikes the sea, as occurred within the incident in 2000, the aircraft is likely to suffer considerable damage, risking the pilot's safety and the airworthiness of the aircraft. Should the aircraft strike the frigate, the Hawk itself is likely to suffer catastrophic damage, providing substantial risk to the pilot's safety. The Frigate is also likely to suffer significant damage, risking the lives of crew and potentially seaworthiness of the vessel. Should the Hawk fail to fly at low altitude, the Hawk will appear on the frigate's radar earlier than an incoming missile would. This

would result in the incomplete training of the frigates crew, potentially endangering the lives of the crew in future live fire conflict zones.

RESULTS AND DISCUSSION

Following STAMP-STPA procedure, the mapped control structure for Hawk missile simulation task is shown in Figure 1. The developed control structure takes a hierarchical form, with the addition of the 'Sea' component operating in parallel, linking to the pilot and frigate crew. Seven stakeholders were identified, Military Aviation Authority, who operates as regulator, Duty Holder, Pilot, Hawk Jet, Frigate, Crew and the Sea. Each of the seven stakeholders are linked by unique Control Actions, mapping the stakeholder relationships

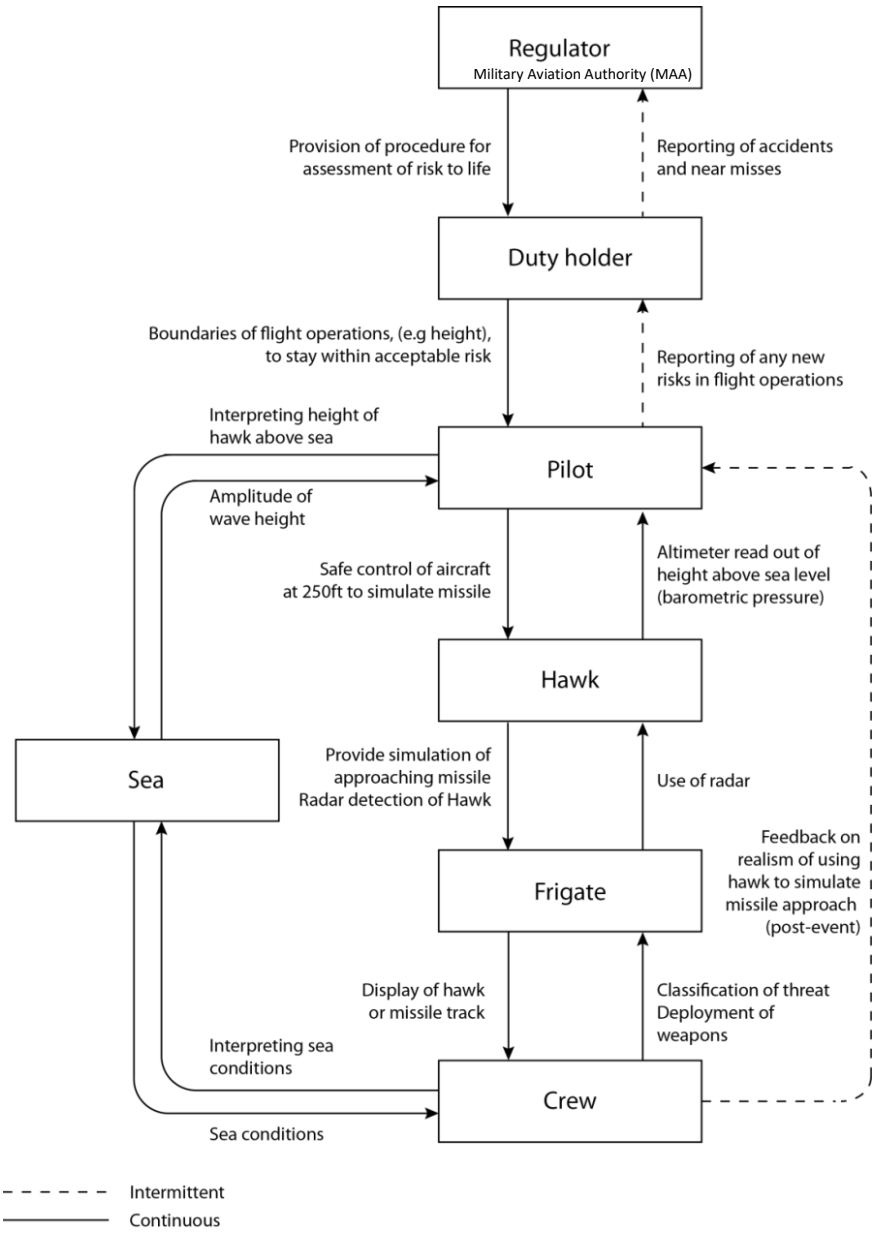

Figure 1 Control structure for the Hawk Risk to Life (RtL) case study

Working through the control structure presented in Figure 1, the Regulator, the Military Aviation Authority (MAA), provides the Duty Holder with assessment procedures for the Hawk RtL scenario. The MAA acts as the single regulatory authority responsible for regulating all aspects of air safety across British defense. The MAA has full oversight of all defence aviation activity, including the operation of the Hawk RtL scenario. A key directive of the MAA is to maintain appropriate

standards of air safety (ALARP) within defense operations. The duty holder's prime role is to take responsibility for implementing effective Aviation Safety Management Systems and ensuring that their air operations are at all times conducted at a level of safety that is at least ALARP, as laid out in MAA Regulatory Article 1022. In practical terms, the key role of the duty holder is to provide pilots with the boundaries of flight operations to stay within what is judged acceptable risk. The pilot is responsible for the safe control of the aircraft within these boundaries. The pilot is required to use readings provided by the on-board sensors to accurately simulate a potential missile attack and provide an accurate radar image to the frigate. The radar sensors of the frigate detect an object that is approaching the vessel rapidly. The crew of the frigate is required to classify an event like this as threat that requires preparation of its defense weapons. The frigate's radar continues to track the objects progress towards the vessel. During this time, the frigates crew executes all required defense operations. Once the exercise is complete, the pilot is required to report to the duty holder any new risks that have been identified within the missile simulation exercise. The Duty Holder has a responsibility to report to the Regulator any accidents or near misses. Operating in parallel to the primary control structure is the sea, which is a key stakeholder with the operation. The sea is not static during the simulation exercise but rather subject to different weather conditions. The pilot must frequently interpret the height of the Hawk above the sea to ensure safe operations . The sea also provides key conditional variable for the crew of the frigate to interpret. Sea conditions can impact the potential countermeasures available to avoid the simulated missile strike, whether the frigate is required to "destroy" the simulated missile, using on board defensive weapons or undertake maneuvers to avoid the strike.

Based on the control structure presented within Figure 1, each of the control actions were considered in turn to compile a failure taxonomy using the standardised STAMP-STPA method as discussed previously. In total, 88 UCAs were identified for the Hawk RtL case study. Examples of generated UCAs using each of the guide sentences are provided in Table 1.

Table 1 Example analysis of two control actions against STPA guide sentences

Control action	From	To	Guide sentence	Unsafe control action
Provision of procedures for assessment of RtL	Regulator	Duty Holder	*Action required but not provided*	Fail to provide procedures for RtL assessment
			Unsafe action provided	Provide wrong procedures for RtL assessment
			Incorrect order / timing	Provide RtL procedures too late
			Stopped too soon / applied too long	RtL process overly complex and bureaucratic
				RtL process too vague
Safe control of aircraft at 250 feet, to simulate missile	Pilot	Hawk	*Action required but not provided*	Failure to maintain safe control of the aircraft below 250 feet
			Action required but not provided	Failure to maintain safe control of the aircraft above 250 feet
			Stopped too soon / applied too long	Move out of safe altitude too early
			Stopped too soon / applied too long	Move out of safe altitude too late

*RtL Risk to Life

Safety constraints were defined for each of the identified UCAs. The safety constraints for the example UCAs presented in Table 1 are presented in Table 2. Safety constraints were however generated for all 88 identified UCAs, and are presented within the appendix.

Table 2 Example analysis of safety constraints assigned to UCAs

Unsafe Control Action	Safety Constraint
Fail to provide procedures for RtL assessment	Must provide procedures for RtL assessment
Provide wrong procedures for RtL assessment	Must provide correct procedures for RtL assessment
Provide RtL procedures too late	Must provide procedures for RtL assessment in sufficient time
RtL process overly complex and bureaucratic	RtL process should not be overly complex and bureaucratic
RtL process too vague	RtL process should not be too vague
Failure to maintain safe control of the aircraft below 250 feet	Must maintain safe control of aircraft
Failure to maintain safe control of the aircraft above 250 feet	Must maintain safe control of aircraft
Move out of safe altitude too early	Hawk must stay at correct altitude for appropriate duration
Move out of safe altitude too late	Hawk must stay at correct altitude for appropriate duration

*RtL Risk to Life

Example mapping of UCAs is illustrated for two of the UCAs described in Table 2 above: “fail to provide procedures for RtL” (Figure 2) and “failure to maintain safe control of the aircraft below 250 feet” (Figure 3). Figure 2 shows that for the UCA of “fail to provide procedures for RtL”, the regulator may fail to define procedures for RtL assessment due to an incorrect, incomplete or inconsistent process model relating to current regulations, previous incidents/ accidents, risk assessment procedures or the definition of risk likelihood or severity. This in turn can result in a failure to document procedures, and/ or a failure to provide the documentation to required parties. Further risks are identified in that the regulator, the MAA, is required to ensure that duty holders receive all appropriate documentation. Duty holders are required to use this documentation and establish suitable procedures for RtL assessments, and to ensure that RtL assessments are carried out. Mirroring the relationship between regulator and duty holder, the duty holder also has responsibility to feedback RtL assessments back

to the regulator. Within this example, no mechanical failure endangers the safety of either the pilot of the Hawk or the crew of the Frigate. Such a relationship would be traditionally not be considered by the safety approaches used within the British military. This relationship, highlighted by the STAMP-STPA analysis is however crucial for ensuring the safety of the overall training operation.

With the risk of "failure to maintain safe control of the aircraft below 250 feet" (Figure 3) the pilot may fail to understand or input the correct control actions to the Hawk due to an incorrect, incomplete or inconsistent process model relating to the required control inputs, feedback from the aircraft or safety regulations for flying below 250 feet. Alternatively, there could be a failure of aircraft controls, whereby the aircraft does not respond to the control inputs of the pilot. This lack of control response suggests a failure of aircraft components, and would result in the Hawks behaviour becoming unsafe. Further component failure could result in feedback not being received by the pilot, leading to, or reinforcing, the pilots misunderstanding of required control inputs. Although the failures identified within this example are not unique to the STAMP-STPA approach, this example does demonstrate the utility of the method. In addition to identifying potential areas of unsafe operations within stakeholder relationships, STAMP-STPA is also able to identify the risks and consequence of component failure.

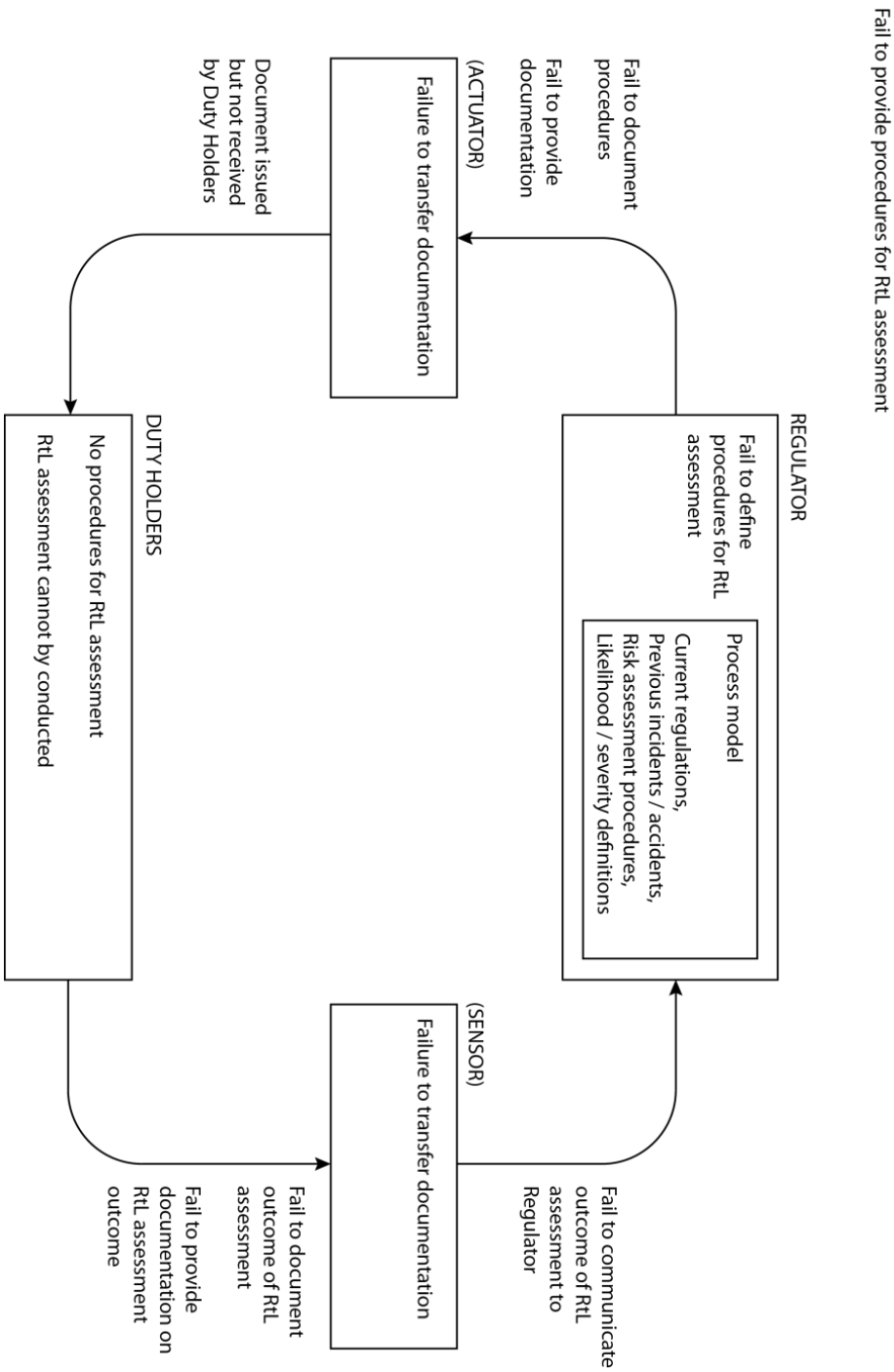

Figure 2. Causal factors identified for the UCA ‘fail to provide procedures for RtL assessment’, between the regulator and duty holder.

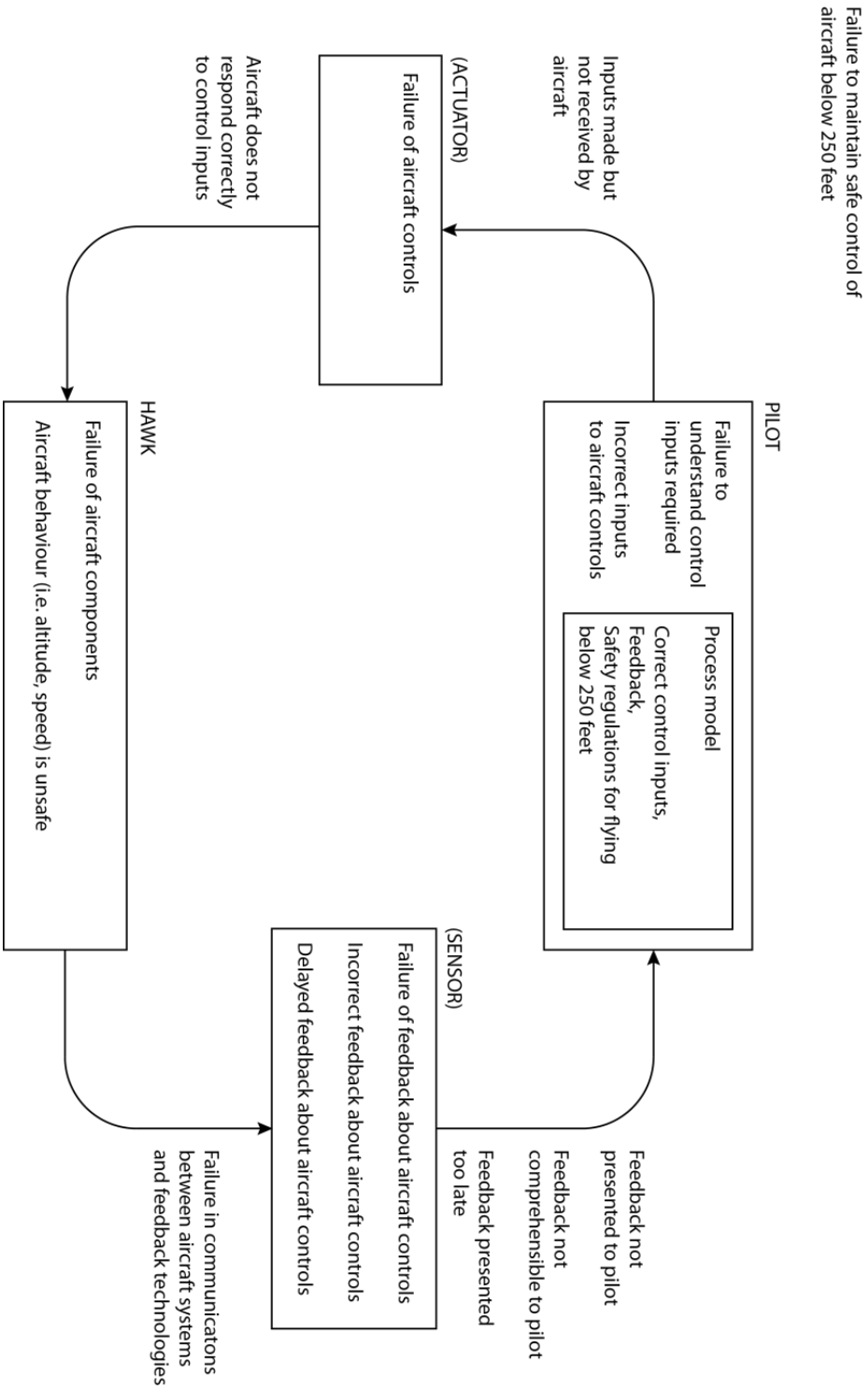

Figure 3. Causal factors identified for the UCA ‘failure to maintain safe control of aircraft below 250 feet’, between the pilot and hawk

Each of the 88 UCAs identified within this work lead to the generation of a corresponding safety constraint designed to minimise the likelihood of each UCA occurring. Each safety constraint is presented within the appendix. Generated safety constraints fell into three main categories: 1) ensuring proper adherence to established procedures; 2) ensuring operations are adequately followed; and 3) ensuring sufficient training and experience is both possessed and generated by individuals operating within the system. By adequately employing the generated safety constraints the likelihood of an incident or an accident occurring can be reduced (Leveson, 2004). Each of these categories, and how the application of exemplar safety constraints can be used to improve the safety of the system, will be discussed in turn.

Interviews with SMEs and official documentation revealed that extensive procedures are in place governing the Hawk missile simulation scenario, including predetermined minimum altitudes for the Hawk to operate. The present analysis highlighted that in order for the exercise to remain of value and safe, operational requirements must be followed. Within this scenario, the clearest example of this action is the pilot must ensure the "Safe control of the aircraft at approximately 250 feet to simulate missile". To achieve this goal it is essential that the pilot maintains safe control of the Hawk and must stay at a maximum 250 feet for the duration of the exercise. By flying higher than this altitude, the aircraft would appear on radar considerably sooner than would be the case of a sea-skimming missile, defeating the purpose of the exercise. Flying significantly lower than this level however risks the safety of the pilot and risks a repeat of the sea strike incident of 2000 (Stanton & Harvey, 2017), as discussed previously. Priority at all times must be given to the pilots' safety however, in order to ensure that the aircraft is under control.

The Hawk missile simulation task is associated with considerable risks. Immediate risk is placed upon the pilot, due to the need to fly low and fast over the sea, with no accurate reading of altitude available. The pilot is reliant on visual cues of wave height and information provided by the Hawk's barometric pressure altimeter, which can be inaccurate at very low altitude. To achieve these goals, the pilot must regularly interpret their height above the sea, allowing for sufficient time to respond to changes in wave amplitude and dynamics. Ensuring that Hawk pilots possess sufficient experience in fast, low altitude, operations is therefore essential in maintaining safety. As noted previously, retired RAF pilots are no longer commissioned to this training exercise but instead rather more junior Fleet Air Arm pilots are utilised. Appropriate procedures are essential in ensuring that the selected pilots possess the required experience to be able to complete these goals.

Secondary risk is placed upon the Frigate and its attending crew. Frigate and crew are at direct risk of potential impact with the Hawk, should the pilot collide with the ships superstructure, by flying too low. Equally the Frigate and crew are also at risk of not receiving sufficient training should the Hawk approach too high. The Hawk missile simulation task provides essential training for crew to be able to accurate classify and take suitable action against such potential incoming threats. By ensuring that crew training is adequate, future safety, including potentially within a live combat theatre, is improved. It is therefore essential that the Hawk missile simulation task generates sufficient experience and training for the crew of the frigate. The use and value of simulation training has seen across work domains and is now standard practice within aviation, medicine and the military (Salas, Wilson, Burke, & Priest, 2005). Ensuring the simulation is representative of the real event is however paramount, reinforcing the

Hawks requirement to fly as low and fast as possible to accurately mimic the flight profile of a sea-skimming missile.

The use of STAMP-STPA (Leveson, 2004; 2011) has provided a novel approach to examine where risk could emerge in the highly controlled Hawk missile simulation task. The use of a systemic approach to safety has allowed the researchers to consider a significantly wider array of risks, especially those relating to human-system interactions, than those previously identified using methods previously utilised by the Fleet Air Arm, including FTA (Barlow, 1973) and THERP (Swain, 1964 Swain & Guttmann, 1983; Boring, 2012). The use of the STAMP-STPA approach is however highly time consuming and reliant on the knowledge of both the SMEs available and the research team undertaking the analysis. Work is therefore needed within the safety community to provide support for systemic safety analysis, including STAMP-STPA to improve the availability of these tools. Dedicated software tools supporting such analysis are currently lacking and would be beneficial to increase the efficiency and level of fidelity of the analysis.

The STAMP-STPA framework (Leveson, 2004; 2011) has been deployed within this study to explore the Hawk missile simulation task from a highly abstract perspective, using declassified information. Future detailed work is needed to explore the individual stakeholders that operate within all levels of the system in order to ensure that each stakeholder is operating as safely as they can. The analysis can also be extended to explore the potential safety implication of alternative military training operations to examine whether the insights gained from the current investigation can be applied universally to other operations. Finally, it would be beneficial to directly compare the insights gained from STAMP-STPA to alternative systemic safety methods such as FRAM, (Hollnagel, 2012), Accimaps (Rasmussen, 1997), and Event

Analysis of Systemic Teamwork (EAST) (Stanton, Baber, & Harris, 2008; Stanton, Salmon & Walker, 2018). This is especially apt when considering that EAST Broken Links approach has previously been used to explore the same training scenario (Stanton & Harvey, 2017). Although Underwood and Waterson (2014) suggests that STAMP-STPA offers the most comprehensive approach to exploring systemic safety, it would be negligent to suggest that other methods do not add additional benefit. Underwood and Waterson (2014) undertook an extensive comparison between STAMP-STPA and Accimaps and found that despite considerable differences between the two approaches, both offered unique insights when examining a rail accident. It would therefore be prudent to utilise alternative metrics to examine the relative benefits and limitation of different approaches.

CONCLUSIONS

The current work has applied the STAMP-STPA framework to examine Royal Navy Hawk missile simulation training. An evolving safety culture within the British Military as well as previous incidents within this specific training exercise have highlighted the need for modern approaches to safety within this domain.

A control structure, mapping all key stakeholders within the Hawk missile simulation exercise was generated within STAMP. This was furthered to elicit 88 potential UCAs using STPA. Finally, initial safety constraints have been provided for each identified UCA in order to reduce the likelihood of each UCA occurring and improve overall systemic safety. The developed safety constraints focused on ensuring adherence to require procedures; ensuring required operations are safely completed; and ensuring adequate training for all agents within the system. It is

argued that the STAMP-STPA approach offered qualitatively different insights that would be offered using traditional safety tools currently used within the military domain, highlighting the importance of pre-existing relationships and interactions between different stakeholders. Acting as a case study for use of the STAMP-STPA approach in the military domain, it is argued that systemic approaches can act to enhance overall safety.

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APPENDIX

STPA safety constraints assigned to all control actions identified in the Hawk Risk to life case study

Control action	From	To	*Guide sentence*	Unsafe control action	Safety constraint
Provision of procedures for assessment of risk to life (RtL)	Regulator	Duty Holder	*Action or feedback required but not provided*	Fail to provide procedures for Risk to life assessment	Must provide procedures for Risk to life assessment
			Unsafe action or feedback provided	Provide wrong procedures for Risk to life assessment	Must provide correct procedures for Risk to life assessment
			Incorrect timing or order	Provide Risk to life procedures too late	Must provide procedures for Risk to life assessment in sufficient time
			Stopped too soon / Applied too long	Risk to life process overly complex and bureaucratic	Risk to life process should not be overly complex and bureaucratic
			Stopped too soon / Applied too long	Risk to life process too vague	Risk to life process should not be too vague
Reporting of accidents and near misses	Duty Holder	Regulator	*Action or feedback required but not provided*	Fail to report accident or near miss	Must report all accidents or near misses
			Unsafe action or feedback provided	Wrong cause for accident or near miss reported	Right cause for accident or near miss must be reported
			Unsafe action or feedback provided	Wrong consequence for accident or near miss reported	Right consequence for accident or near miss must be reported
			Incorrect timing or order	Accident or near miss reported too late (to be acted upon)	Must report accident or near miss in sufficient time to be acted upon
			Stopped too soon / Applied too long	Incomplete report of accident or near miss	Must ensure complete report of accident or near miss
			Stopped too soon / Applied too long	Too much detail in reporting so salient points are masked	Must avoid over-reporting of detail

Control action	From	To	*Guide sentence*	Unsafe control action	Safety constraint
Report performance against risk boundaries	Duty Holder	Regulator	*Action or feedback required but not provided*	Fail to report performance against risk boundaries	Must report performance against risk boundaries
			Unsafe action or feedback provided	Report performance against risk boundaries incorrectly	Must report performance against risk boundaries correctly
			Incorrect timing or order	Report performance against risk boundaries too late	Report performance against risk boundaries with sufficient time to act
			Stopped too soon / Applied too long	Fail to report performance sufficiently against all risk boundaries	Report performance sufficiently against all risk boundaries
Identify hazards within Risk to life assessment process	Duty Holder	Pilot	*Action or feedback required but not provided*	Fail to define the hazards for flight operations to stay within acceptable risk	Hazards for flight operations must be defined
			Unsafe action or feedback provided	Setting incorrect hazards for flight operations to stay within acceptable risk	Right hazards for flight operations must be set
			Incorrect timing or order	Defining the hazards too late for the pilot to act	Must define hazards in sufficient time for pilot to act
			Incorrect timing or order	Fail to define all of the appropriate hazards for safe flight operations	Hazards must be set when sufficient information is available
			Stopped too soon / Applied too long	Hazards defined too early based on insufficient information	Hazards for flight operations must be defined
			Stopped too soon / Applied too long	Too many hazards defined, making the Risk to life advice overly complex	Hazards for flight operations must be defined to an appropriate level of detail too avoid complexity
Assign severity and criticality levels of risks	Duty Holder	Pilot	*Action or feedback required but not provided*	Fail to assign severity and criticality levels for risks	Must assign severity and criticality levels for risks
			Unsafe action or feedback provided	Wrong criticality or severity assigned to risk	Right criticality or severity must be assigned to risk
			Incorrect timing or order	Assign severity and criticality levels for risks too late	Must assign severity and criticality levels for risks with sufficient time

Control action	From	To	*Guide sentence*	Unsafe control action	Safety constraint
			Incorrect timing or order	Assign severity and criticality levels for risks too early, without complete information	Must assign severity and criticality levels for risks when all information about reported risks is known
			Stopped too soon / Applied too long	Fail to complete assignment of severity and criticality to risks	Must complete assignment of severity and criticality to risks
Reporting of any new risks in flight operations	Pilot	Duty Holder	*Action or feedback required but not provided*	Failure to report any new risks to flight operations	Must report any new risks
			Unsafe action or feedback provided	Wrong risks reported	Right risks must be reported
			Incorrect timing or order	Risks reported too late (to be acted upon)	Risks must be reported in sufficient time to be acted upon
			Stopped too soon / Applied too long	Not reporting all the risks (only reporting partial information)	All risks must be reported
			Stopped too soon / Applied too long	Over-reporting of risks, resulting in trivial risks reported	Trivial risks must not be reported
Safe control of aircraft at 250 feet to simulate missile	Pilot	Hawk	*Action or feedback required but not provided*	Failure to maintain safe control or the aircraft (flying below 250 feet)	Must maintain safe control of aircraft
			Action or feedback required but not provided	Failure to maintain safe control or the aircraft (flying above 250 feet)	Must maintain safe control of aircraft
			Stopped too soon / Applied too long	Move out of safe altitude too early (not held 250 feet for the time necessary for Frigate to track as simulated missile)	Hawk must stay at 250ft for appropriate duration
			Stopped too soon / Applied too long	Move out of safe altitude too late	Hawk must stay at 250ft for appropriate duration
Altimeter readout of altitude	Hawk	Pilot	*Action or feedback required but not provided*	Altimeter fails to provide height above sea level	Provide accurate reference to altitude above sea level
			Unsafe action or feedback provided	Error in altimeter reading	Accurate height reference must be provided

Control action	From	To	*Guide sentence*	Unsafe control action	Safety constraint
(barometric pressure)			*Incorrect timing or order*	Pilot reads altimeter too late	Pilot must read altimeter in sufficient time to respond
Interpreting altitude of Hawk	Pilot	Sea	*Action or feedback required but not provided*	Pilot fails to look at sea	Pilot must look at sea
			Action or feedback required but not provided	Pilot cannot see sea (poor visibility)	Provide visual representation of sea under poor conditions
			Action or feedback required but not provided	Pilot fails to interpret height of Hawk above sea	Pilot must correctly interpret the height of the Hawk above sea
			Unsafe action or feedback provided	Pilot interprets wrong height of Hawk above sea	Pilot must interpret height above sea accurately
			Incorrect timing or order	Pilot interprets height above sea too late	Pilot must interpret height above sea in sufficient time to respond
			Stopped too soon / Applied too long	Pilot fails to monitor height above sea for adequate amount of time to see changes	Pilot must monitor height for adequate amount of time to see changes
			Stopped too soon / Applied too long	Pilot takes too long to interpret height of Hawk above sea	Pilot must not take too long to interpret height of Hawk above sea
Amplitude of wave height	Sea	Pilot	*Action or feedback required but not provided*	No wave amplitude (flat sea)	N/A
			Unsafe action or feedback provided	Amplitude of waves insufficient to judge height accurately	N/A
Provide simulation of approaching missile	Hawk	Frigate	*Action or feedback required but not provided*	Simulation of missile not provided	Provide simulation of missile
			Unsafe action or feedback provided	Not an accurate representation of a missile approach (e.g., see aircraft take-off from base)	Must provide accurate representation of missile approach
			Incorrect timing or order	Simulated missile approach too fast or too slow	Hawk must approach at appropriate speed to simulate missile accurately

Control action	From	To	*Guide sentence*	Unsafe control action	Safety constraint
			Stopped too soon / Applied too long	Simulated approach abandoned too early	Pilot must not abandon approach too early
			Stopped too soon / Applied too long	Simulated approach carries on too late	Pilot must not continue approach too late
Radar detection of Hawk	Hawk	Frigate	*Action or feedback required but not provided*	Fail to detect Hawk	Ensure success of detection by radar
			Unsafe action or feedback provided	Inaccurate identification of Hawk	Must accurately identify Hawk
			Incorrect timing or order	Detect Hawk too late	Hawk must be detected as early as possible
Use of radar	Frigate	Hawk	*Action or feedback required but not provided*	Fail to use radar	Radar must be used by crew
			Unsafe action or feedback provided	Fail to use appropriate radar	Must use appropriate radar
			Incorrect timing or order	Switch radar on too early	Radar must be switched on at appropriate time
			Stopped too soon / Applied too long	Switch radar off to early	Radar must not be switched off too early
			Stopped too soon / Applied too long	Switch radar off too late	Radar must not be switched off too late
Feedback on realism of using Hawk to simulate a missile approach (post-event)	Crew	Pilot	*Action or feedback required but not provided*	Fail to provide feedback on realism of simulation	Provide feedback on realism of simulation
			Unsafe action or feedback provided	Provide incorrect feedback on simulation	Must provide correct feedback on simulation
			Incorrect timing or order	Provide feedback on simulation too late	Must provide feedback on simulation in sufficient time to be acted upon
			Stopped too soon / Applied too long	Provide insufficient feedback on simulation	Must provide sufficient feedback on simulation
			Stopped too soon / Applied too long	Over-reporting of feedback, resulting in trivial feedback reported, and essential feedback being lost	Must report essential and not trivial feedback

Control action	From	To	*Guide sentence*	Unsafe control action	Safety constraint
Transmission of information about Hawk or missile track	Frigate	Crew	*Action or feedback required but not provided*	Fail to display Hawk or missile track	Frigate must be capable of displaying Hawk or missile track
			Unsafe action or feedback provided	Inaccurate display of Hawk or missile track	Must display accurate display of hawk or missile track
			Incorrect timing or order	Display of Hawk or missile track too late to act upon	Missile track must be displayed in sufficient time to be acted upon
			Stopped too soon / Applied too long	Transmission stopped too soon	Must not stop transmission to soon
			Stopped too soon / Applied too long	Transmission applied too long	Must not apply transmission too long
Classification of threat	Crew	Frigate	*Action or feedback required but not provided*	Fail to classify threat	Crew must classify threat
			Unsafe action or feedback provided	Misclassification of threat	Must provide accurate classification of threat
			Incorrect timing or order	Classification of threat too early based on insufficient information	Classification of threat must be done in sufficient time to be acted upon
			Incorrect timing or order	Classification of threat too late	Classification of threat must be done in sufficient time to be acted upon
			Stopped too soon / Applied too long	Classification stopped to soon leading to inaccuracies due to incomplete information	Must not stop classification too soon
			Stopped too soon / Applied too long	Too much time spent in classification, delays response	Must not spend too much time in classification
Deployment of weapons	Crew	Frigate	*Action or feedback required but not provided*	Fail to deploy weapons	Weapons must be deployed by crew
			Unsafe action or feedback provided	Deployment of wrong weapons	Must deploy correct weapons
			Incorrect timing or order	Deployment of weapons too early	Weapons must be deployed at the correct time
			Incorrect timing or order	Deployment of weapons too late	Weapons must be deployed at the correct time

Control action	From	To	*Guide sentence*	Unsafe control action	Safety constraint
			Stopped too soon / Applied too long	Stop deployment of weapons before target destroyed	Deployment of weapons must continue until target is destroyed
			Stopped too soon / Applied too long	Deployment of weapons at a redundant target, waste of weapons	Deployment of weapons must not continue after target is destroyed
Interpreting sea conditions	Crew	Sea	*Action or feedback required but not provided*	Crew fails to look at sea	Crew must look at sea
			Action or feedback required but not provided	Crew cannot see sea (poor visibility)	Provide visual representation of sea under poor conditions
			Incorrect timing or order	Crew interprets sea conditions too late	Crew must interpret height above sea in sufficient time to respond
			Stopped too soon / Applied too long	Crew fails to monitor sea conditions for an adequate amount of time to see changes	Crew must monitor sea conditions for adequate amount of time to see changes
			Stopped too soon / Applied too long	Crew takes too long to interpret sea conditions	Crew must not take too long to interpret sea conditions
Sea conditions	Sea	Crew	*Unsafe action or feedback provided*	Sea conditions present a danger to safe control of the Frigate	Crew should not operate the Frigate in dangerous sea conditions