Progress in Aerospace Sciences 102 (2018) 1–46

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

Avionics Human-Machine Interfaces and Interactions for Manned and Unmanned Aircraft

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ARTICLE INFO

Keywords:
Adaptive systems
Avionics
Cognitive ergonomics
Human factors engineering
Human-machine interface and interaction
Human performance assessment
Unmanned aerial vehicle
Unmanned aircraft system
Trusted autonomy
Remotely piloted aircraft
Remotely piloted aircraft system

ABSTRACT

Technological advances in avionics systems and components have facilitated the introduction of progressively more integrated and automated Human-Machine Interfaces and Interactions (HMI^2) on-board civil and military aircraft. A detailed review of these HMI^2 evolutions is presented, addressing both manned aircraft (fixed and rotary wing) and Remotely Piloted Aircraft System (RPAS) specificities for the most fundamental flight tasks: aviate, navigate, communicate and manage. Due to the large variability in mission requirements, greater emphasis is given to safety-critical displays, command and control functions as well as associated technology developments. Additionally, a top-level definition of RPAS mission-essential functionalities is provided, addressing planning and real-time decision support for single and multi-aircraft operations. While current displays are able to integrate and fuse information from several sources to perform a range of different functions, these displays have limited adaptability. Further development to increase HMI^2 adaptiveness has significant potential to enhance the human operator's effectiveness, thereby contributing to safer and more efficient operations. The adaptive HMI^2 concepts in the literature contain three common elements. These elements comprise the ability to assess the system and environmental states; the ability to assess the operator states; and the ability to adapt the HMI^2 according to the first two elements. While still an emerging area of research, HMI^2 adaptation driven by human performance and cognition has the potential to greatly enhance human-machine teaming through varying the system support according to the user's needs. However, one of the outstanding challenges in the design of such adaptive systems is the development of suitable models and algorithms to describe human performance and cognitive states based on real-time sensor measurements. After reviewing the state-of-research in human performance assessment and adaptation techniques, detailed recommendations are provided to support the integration of such techniques in the HMI^2 of future Communications, Navigations, Surveillance (CNS), Air Traffic Management (CNS/ATM) and Avionics (CNS + A) systems.

1. Introduction

Ongoing developments in avionics have introduced a number of systems on-board civil aircraft, such as terrain and traffic alerting systems, engine and system monitoring and alerting systems, flight planning and management systems, data-link communication systems, as well as electronic information management and flight instrumentation systems. These technological innovations have supported higher degrees of automation, allowing a shift from manual control towards supervisory management in the flight deck. Increasingly, machine intelligence and autonomy is propelling the next generation of technological advances in human-machine interfaces, particularly in the domain of unmanned/remotely piloted aircraft. While automated systems are characterised by a set of predefined responses to planned events, autonomous systems are able to sense, learn and adapt to changes in the environment. This paradigm shift represents an evolution in the human-machine interaction: human-machine interactions with automated systems are typically limited to top-down supervisory control, but human-machine

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https://doi.org/10.1016/j.paerosci.2018.05.002
Received 9 April 2018; Received in revised form 8 May 2018; Accepted 9 May 2018
Available online 3 August 2018

interactions with autonomous systems will emphasize collaboration through human-machine teaming. Autonomous systems have the potential to contribute to improvements in operational safety, efficiency and effectiveness but have also introduced additional Human Factors Engineering (HFE) considerations to the design of the associated Human-Machine Interfaces and Interactions (HMI^2). The HMI^2 needs to be user-centric by providing the human user with appropriate and timely information and support, while avoiding overloading the human user with excessive clutter and information. At the same time, excessive automation can lead to underloading of the human user, leading to automation misuse, complacency and loss of situational awareness. More importantly, appropriate design of the HMI^2 can help to establish trust between human users and automated systems, which promotes more effective human-machine teaming.

Ongoing research concepts envisage the use of associate systems, which enhance operator capabilities by appropriate adaptations of the HMI^2. Associate systems are able to recognize situations when the human operator requires assistance and provide the necessary support. Basic associate systems are typically composed of task management, operator assessment and interface adaptation modules. The task management module monitors environmental and system conditions to determine what actions are required by human operators. The operator assessment module monitors the functional state and performance of the operator to determine if additional support is required. Information from the two modules is communicated to the interface adaptation module, which reconfigures the HMI^2 according to predetermined decision logics.

Although there exists a substantial volume of literature on operator state assessment, there are still significant challenges towards implementing associate systems that are able to assess the operator functional state reliably within the operational environment. Much of the literature points towards the use of human performance assessment techniques for assessing certain cognitive states of the human operator correlated to human performance. The use of cognitive states to drive adaptation in HMI^2 (termed as Cognitive HMI^2, or CHMI^2) has been demonstrated to be feasible and opens up many avenues in the area of human-machine teaming.

In addition to reviewing current HMI^2 developments, this article provides the state-of-the-art in CHMI^2 techniques, identifying the main challenges and opportunities in this field of research. In particular, the application of CHMI^2 in the Communication, Navigation, Surveillance (CNS), Air Traffic Management (CNS/ATM) and Avionics (CNS + A) context has the potential to support a number of emerging operational concepts. These include operational concepts include the management of complex trajectories, the continuous monitoring of system performance, increased air-ground collaboration, the inclusion of unmanned or Remotely Piloted Aircraft Systems (RPAS) in non-segregated airspace, as well as the command and control of multiple unmanned platforms.

The term "Unmanned Aircraft System" (UAS) refers to the combination of an uninhabited aircraft and its ground control elements [1]. The UAS is differentiated from the actual aircraft, which is itself a component of the UAS and is often referred to as the "Unmanned Aerial Vehicle" (UAV). More recently, the terms "Remotely Piloted Aircraft System" (RPAS) and "Remotely Piloted Aircraft" (RPA) have been introduced to provide a more accurate description of such systems [2,3], since the aircraft is typically not completely "unmanned" but it is controlled by remote crew members. However, at present, the terms UAS and RPAS are used interchangeably in the literature. For the sake of consistency, the acronym RPAS will be used in this article to describe the system in its entirety, while RPA will be used to describe the aircraft platform.

2. Developments in manned and unmanned HMI^2

This section presents an overview of the HMI^2 for manned and unmanned/remotely piloted aircraft. The evolution of civil flight decks is first presented, followed by a brief overview of military cockpits, and finally some emerging concepts for Single-Pilot Operations (SPO) as well as for the control and coordination of RPA platforms. Early human factors research originated between WWI and WWII, and was characterised by the development of methods for pilot selection and training, as well as in aerospace medicine and physiology. Developments in flight deck automation between the late-1930s to the 1960s shifted the focus of human factors research towards physical ergonomics and aviation psychology, which helped to guide the design, configuration and layout of the controls and display instrumentation in crew stations. In the late-1970s, Crew Resource Management (CRM) was introduced to aviation human factors, targeted at reducing human error and improving flight crew performance. With the introduction of glass cockpits in the late-1980s, human factors research has increasingly focused on cognitive ergonomics, particularly on the cognitive processes involved in higher-level information processing, decision making and automation management. As next generation flight decks trend towards human-machine interactions with autonomous and unmanned platforms, human factors research will need to address the important challenges surrounding trusted autonomy and human autonomy teaming. Fig. 1 illustrates this historical development across the three flight deck eras – mechanical, electro-mechanical and electro-optical – as described by Jukes [4], Jacobsen et al. [5], Moir et al. [6] and Abbott [7], along with the shift in the focus of human factors research [8]. This review focuses on the HMI design in "classic" electro-mechanical flight decks, as well as the first, second and third generations of electro-optical ("glass") flight decks.

2.1. Classic flight decks

The evolution of modern flight decks can be traced back to the classic flight decks of the 1960s, such as the Boeing 727-200 (Fig. 2). These flight decks feature electro-mechanical instrumentation requiring the operation of three to five crew members (comprising the pilot, co-pilot, flight engineer, as well as navigator and radio operator). HMI^2 on classic flight decks are characterised by low levels of information integration and low levels of automation. Early warning systems introduced in the 1970s, such as the Ground Proximity Warning System (GPWS), provided limited automated monitoring functionalities. Gradual advances in flight deck autonomy have led to de-crewing, with the navigator and radio operator roles being taken over by advanced functions in the late-1970s.

2.1.1. Basic six

The basic six set of flight instruments are meant to support pilots in maintaining awareness of their aircraft's essential flight states and are depicted in Fig. 3. These instruments have traditionally been either gyroscopic or air pressure-based and comprise:

– Airspeed Indicator (ASI), which provides information on the indicated airspeed (in knots) of the aircraft. Markings are used to provide indications of critical airspeed limits such as take-off, stall, cruise and maximum speeds.
– Attitude Indicator, which indicates the aircraft's pitch and roll. Information is displayed as an artificial horizon (coloured to represent the sky, ground and horizon) with markings to indicate the pitch and bank angles.
– Altimeter, which functions as a barometer to indicate the altitude (feet) of the aircraft. To account for variations in atmospheric pressure, the pilot calibrates the altimeter by using an adjustment knob to set the local pressure, which is displayed on a Kollsman Window. The local pressure is obtained through advisories from Air Traffic Control (ATC) or weather reporting stations.
– Turn and Slip Indicator, which provides information on the roll and yaw of the aircraft and is used to perform a coordinated turn.
– Heading Indicator, which provides heading information independent of the magnetic compass. Errors caused by precession due to friction lead to heading drift. The rotation of the earth also leads to wander in the gyroscope. The error can be corrected by slaving the indicator to a

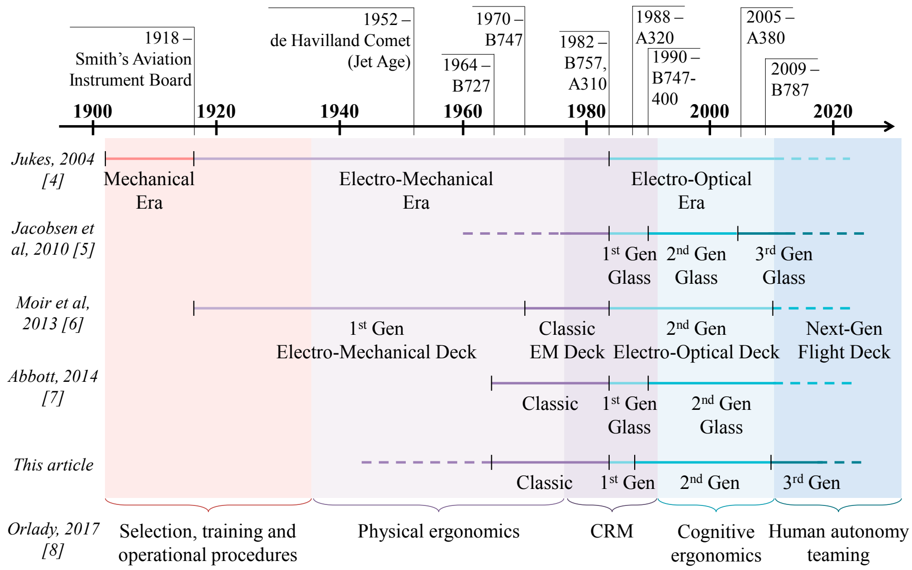

Fig. 1. Historical evolution of civil flight decks.

Fig. 2. Boeing 727 classic flight deck.

Fig. 3. Basic six flight instruments, [9].

magnetic sensor, which allows the heading to be constantly corrected; otherwise, pilots will need to manually realign the indicator once every ten to 15 min.

– Vertical Speed Indicator (VSI), which indicates the rate-of-climb (feet per minute) of the aircraft.

2.1.2. Attitude Directional Indicator and Horizontal Situation Indicator

The Attitude Directional Indicator (ADI) as illustrated in Fig. 4 is an evolution of the attitude indicator. Besides providing basic attitude information, the ADI incorporates flight director overlays to provide instruction on intercepting and maintaining the desired flight path. To support Instrument Landing System (ILS) approaches the ADI also displays glideslope, localizer, speed deviation and decision height information. The flight director display is connected to a flight director computer, which computes the necessary guidance instructions from altitude, airspeed, attitude, heading, navigation, navigation aid (NAV-AID) data (e.g., from VOR/DME) as well as autopilot mode inputs. Inclinometers, used in the Turn and Slip Indicator, are an additional component of ADI to assist the pilot in coordinating turns.

The Horizontal Situation Indicator (HSI), depicted in Fig. 5, is an evolution of the heading indicator. In addition to providing basic heading information, the HSI also includes a Course Deviation Indicator (CDI) overlay to support radio-based navigation. When the aircraft's Very High Frequency (VHF) Omnidirectional Range (VOR) receiver is tuned to the frequency of a selected VOR station, the course select knob on the HSI can be tuned to intercept a chosen radial from the VOR station. The selected course is indicated on the course select pointer. The TO/FROM indicator is used to show if the aircraft is flying towards (if pointing in the same direction as the course select pointer) or away from (if pointing in the opposite direction as the course select pointer) the VOR station. The

Fig. 4. Attitude directional indicator.

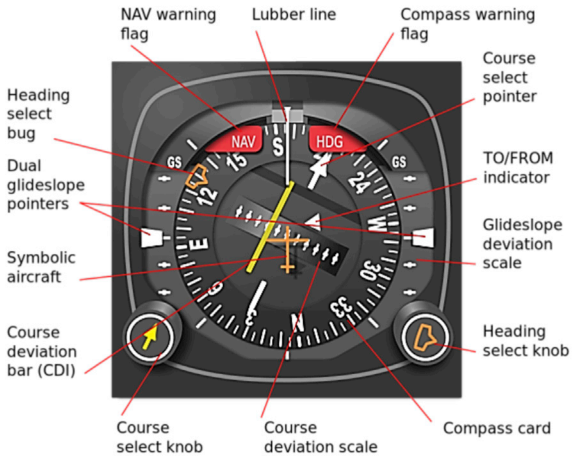

Fig. 5. Horizontal Situation Indicator, [10].

course deviation bar indicates left/right deviations from the selected course; each interval on the course deviation scale corresponds to a deviation of 2°. The HSI is also used in ILS approaches, but instead of indicating VOR information, the CDI overlay now shows the course deviation on the localizer. Glideslope pointers are also displayed on the HSI during ILS approaches.

2.1.3. Ground Proximity Warning System

The Ground Proximity Warning System (GPWS) is an implementation of the Terrain Awareness and Warning System (TAWS), which is meant to provide pilots with predictive cautions and warnings to avoid Controlled Flight Into Terrain (CFIT) incidents. GPWS primarily uses a low range radio altimeter to calculate the altitude of the aircraft above ground level. Other inputs to GPWS may include air data (altitude, altitude rate, speed) or glideslope deviation. Table 1 describes the five operating modes of GPWS and the associated audio and display elements.

2.2. First generation flight decks

Avionics developments in the mid-1970s allowed significant digitalisation of flight deck systems, leading to the consolidation of a number of legacy interfaces into combined electronic displays. Fig. 6 illustrates the historical evolution of first, second and third generation electro-optical deck displays, which included the Electronic Attitude Director Indicator (EADI) and Electronic Horizontal Situation Indicator (EHSI); Electronic Centralised Aircraft Monitor (ECAM) or Engine-Indicating and Crew-Alerting System (EICAS); as well as Multipurpose Control and Display Unit (MCDU) of the Flight Management System (FMS). The Boeing 757 (shown in Fig. 7) and Airbus A310 were among the first aircraft to feature these electronic displays.

2.2.1. Traffic Collision Avoidance Systems

Traffic Collision Avoidance Systems (TCAS) belong to a family of airborne systems providing traffic advisories and collision avoidance protection independently from ground-based ATC. TCAS I only provides Traffic Advisories (TA) to alert pilots of nearby aircraft, whereas TCAS II also provides Resolution Advisories (RA) in addition to TA and is used by the majority of commercial aviation aircraft. A TCAS display shows the location of proximate traffic. TA provide cautions and warnings to indicate possible conflicts with proximate aircraft, while RA recommend vertical manoeuvers (either a climb or descent) to the pilot for avoiding the conflict, coordinated between the two TCAS II-equipped aircraft when possible. The major components of TCAS II are: the TCAS computer unit, Mode S Transponder as well as the TCAS control panel and the cockpit display [13]. Fig. 8 shows a typical TCAS display containing both TA and RA information. Other target aircraft are depicted using geometric symbols. The type of symbol used depends on the threat status:

- Unfilled cyan or white diamond: non-threat traffic;
- Filled cyan or white diamond: proximate traffic within 6 nmi and ±1200 ft from own aircraft;
- Amber or yellow circle: intruders triggering a TA;
- Filled red square: intruders triggering a RA.

Additional information is provided for each target aircraft:

- Relative altitude of the target aircraft to own aircraft, given in hundreds of feet. If the target aircraft is above own aircraft, the relative altitude is preceded by a '+' (plus) sign. If the target aircraft is below own aircraft, the relative altitude is preceded by a '–' (minus) sign.
- Up (↑) or down (↓) arrows to indicate if the target aircraft is climbing or descending at more than 500 fpm.

A vertical speed tape is used to indicate the current vertical speed (by a vertical speed needle), as well as the vertical speeds to be avoided (red

Table 1
GPWS alerts, adapted from Ref. [11].

Mode	Danger			Voice message	Red blinking light	Amber blinking light	"Master" warning
1	Excessive diving speed	Caution		"Sink rate"		✓	
		Warning		"Whoop, pull up"	✓		✓
2A	Excessive rate of closure	Flaps retracted	Caution	"Terrain, terrain"		✓	
			Warning	"Whoop, pull up"	✓		✓
			Recovery	"Terrain, terrain"		✓	
2B		Flaps extended		"Terrain, terrain"	✓		
3	Loss of altitude following take-off			"Don't sink"		✓	
4A	Insufficient terrain clearance when aircraft is not in the proper landing configuration	Landing gear retracted	Airspeed is low (e.g., <190 kts)	"Too low, gear"		✓	
			Airspeed is high (e.g., >190 kts)	"Too low, terrain"			
4B		Landing gear extended but flaps not in landing position	Airspeed is low (e.g., <154 kts)	"Too low, flaps"		✓	
			Airspeed is high (e.g., >154 kts)	"Too low, terrain"		✓	
5	Excessive deviation below the glideslope			"Glide slope"		✓	

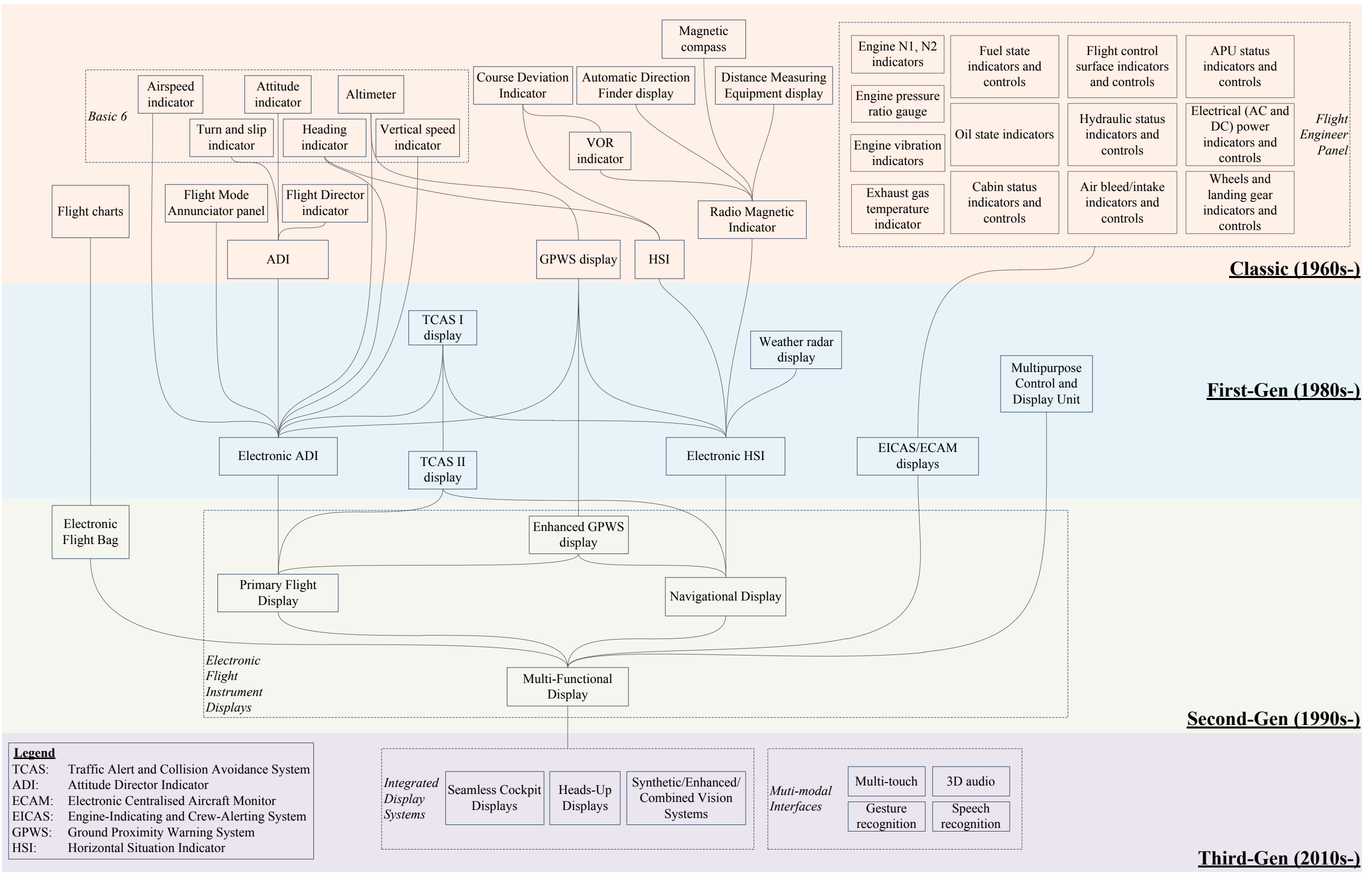

Fig. 6. Evolution of flight deck displays.

Fig. 7. Boeing 757, first generation flight deck, [12].

Fig. 8. TCAS display.

band) and to be flown (green band). The information displayed on the TCAS display is also typically shown on other glass displays (e.g., pitch, altitude and climb rate cues can be displayed on the EADI while traffic information can be displayed on the EHSI).

A number of human factors concerns have emerged early on in the use of TCAS, which include [14–16]:

–False alarms or nuisance alerts might lead to an erosion of trust, causing pilots to disregard future alerts;

– Advisories are issued under high time pressure, usually within a minute to collision (e.g., RA tau values range from 15 to 35 s), leading to high pilot stress and workload whenever advisories are triggered;
– RA are not shared with ATC or other (conflicting) aircraft (instead requiring pilots to manually report RA occurences to ATC). This might result in decreased awareness on the ATC's part and lead to conflicting instructions;
– Incorrect response to weakening or negative RA (i.e., RA requiring a reduction in an existing vertical speed, such as “Reduce climb, reduce climb” or “Adjust vertical speed, adjust”);
– Reversal (e.g., a descend RA reverses to a climb RA) and crossing (i.e., requiring the manoeuver of own aircraft to pass through the altitude intruder aircraft, leading to a crossing of flight paths) RA are challenging to execute and contribute to pilot workload and stress.

A number of changes to the TCAS system over time have supported the mitigation of these issues. The changes include:

– Improved TCAS logic (e.g., tau-based alerting leads to reduced false alarms at low altitudes);
– Additional TCAS advisories (e.g., RA reversals to prevent collisions in scenarios involving conflicting ATC instructions or unresponsive intruder aircraft);
– Modifications to the presentation of information (e.g., negative and weakening RA have been re-worded for increased clarity);
– Proposed downlinking or sharing TCAS information (e.g., following the Uberlingen mid-air collision accident, one of the recommendations made in the German Federal Bureau of Aircraft Accidents Investigation report was the down-linking of RA to ATC [17]).

2.2.2. Electronic ADI and Electronic HSI

The Electronic ADI (EADI) and Electronic HSI (EHSI) serve as electronic replacements of the ADI and HSI. The EADI and EHSI integrate salient flight information on a central display, thereby reducing the need for the flight crew to cross scan between multiple instruments. The EADI and EHSI also interface with other avionic systems, such as the Mode Control Panel/Flight Control Unit (MCP/FCU) or the FMS to provide navigation and guidance information in addition to basic control information.

In addition to ADI information, the EADI displays airspeed, vertical speed, altitude and heading information, effectively replacing the Basic Six as the primary source of flight information. The EADI contains a flight mode annunciator to display the flight and autopilot modes traditionally displayed on the MCP/FCU. Depending on the phase of flight, EADI elements are toggled on/off to reduce unnecessary clutter (e.g., the decision height and glideslope are only toggled on during the approach phase).

The EHSI combines the functionalities of the different electromechanical navigation instruments used in classic flight decks (e.g., HSI and RMI) with additional functionalities by virtue of FMS integration. Depending on the information required by the pilot, the EHSI can be switched between different modes. The main modes include:

– MAP (or NAV): used for most phases of flight, different toggles can be used to display NAVAID, route, airport or waypoint information, as well as VNAV path deviation;
– APP (or ILS): used for approaches, display depends on the type of approach being performed (e.g., localizer and glideslope information is provided for ILS approaches);
– VOR: used for VOR navigation, displays the VOR indicator on top of a compass rose;
– PLN: used for flight planning in conjunction with the FMS.

The EADI and EHSI also integrate surveillance data from a number of aircraft systems (e.g., TCAS, weather radar and GPWS) to provide pilots with enhanced awareness of the surrounding environment (e.g., traffic, weather and terrain).

2.2.3. Flight Management System

The Flight Management System (FMS) was first introduced on the Airbus A310 and Boeing 767 in the 1980s and has become a key avionic system on-board modern airliners. The FMS has been described as the heart of an airplane's flight planning and navigation function [18], integrating data from a number of subsystems including guidance, navigation, control, aircraft performance, systems management as well as air-ground communication. A typical FMS consists of one or more Flight Management Guidance Computers (FMGC) and Control Display Units (CDU). The tasks performed by the FMS include performance calculations, trajectory prediction, flight planning and optimisation, as well as vertical/lateral guidance. While early functionality was limited to lateral navigation and vertical guidance, later versions of the FMS have incorporated additional functionalities including flight planning, wind and temperature modelling, performance prediction, integration with Global Navigation Satellite System (GNSS) data as well as Controller Pilot Data Link Communications (CPDLC) capabilities [19]. Fig. 9 illustrates a Boeing-style Multifunction Control Display Unit (MCDU).

The MCDU contains multiple pages, which allow the flight crew to access different FMS functions. Pages are selected by pressing the page keys. Line select and skew keys allow the user to navigate within and between pages. The main pages on the Airbus MCDU are:

– DIR: used to initiate a direct flight to a waypoint not in the programmed flight plan;
– PROG: provides flight information (e.g., optimum and maximum cruise flight levels) corresponding to the flight phase that is currently in progress;
– PERF: provides performance data associated with the active flight phase;
– INIT: used for pre-flight initialisation of the flight plan;
– DATA: aircraft and navigation sensor status, as well as FMGC data bases and stored data;
– F-PLN: used to view and make revisions to the lateral and vertical elements of the flight plan;
– RAD NAV: displays the NAVAIDs tuned by the FMGC or selected by the pilot;
– FUEL PRED: used for fuel prediction and management;
– SEC F-PLN: used to access the secondary flight plan;
– ATC COMM: used for text-based communications between the flight crew and ATC.

The main pages on the Boeing Future Air Navigation System (FANS) (second generation flight deck) MCDU are:

– INIT REF: used in initializing aircraft identification, position of the Inertial Reference System (IRS), performance, takeoff, approach and navigation settings as well as providing reference data;
– RTE: used to view, input or change origin, destination or route;
– DEP ARR: for viewing and changing departure and arrival procedures;
– ATC: used for text-based communications between the flight crew and ATC;

Fig. 9. Boeing-style MCDU.

- VNAV: used to provide vertical performance guidance through different phases of flight;
- FIX: used to create fixes on the map from known waypoints, using radials and distances from the waypoint;
- LEGS: used to set lateral and vertical route data;
- HOLD: used to create holding patterns and add holding procedures to the active flight plan;
- FMC COMM: used for text-based communications between the flight crew and the company's airline operations centre;
- PROG: shows dynamic flight information (e.g., time, distance or fuel consumption) of the flight progress;
- N1 LIMIT: for viewing the N1 thrust limit as controlled by the FMGC or selecting from the N1 limit from a number of options including go-around, maximum continuous, climb and cruise).

In line with the concepts originally envisioned by the Advisory Group for Aerospace Research and Development (AGARD) and by the FANS committee of the International Civil Aviation Organization (ICAO), future FMS evolutions are expected to allow aircraft to generate optimal 4-dimensional (4D) trajectories, negotiate these trajectories with Air Traffic Management (ATM) operators, and also support Separation Assurance and Collision Avoidance (SA&CA) functionalities [20].

2.2.4. Crew Alerting Systems

The 1980s also saw the introduction of Crew Alerting Systems (CAS) such as the Electronic Centralised Aircraft Monitor (ECAM), shown in Fig. 10, and the Engine-Indicating and Crew-Alerting System (EICAS). The ECAM was developed by Airbus and first used on the A310 while the EICAS was developed by Boeing and first used on-board the 767. While there are slight differences between the two displays, both the EICAS and ECAM essentially serve the same purpose of monitoring multiple aircraft systems, consolidating monitoring data into integrated displays, alerting the flight crew of any abnormal conditions, as well as providing relevant advisories. Indications are classified in increasing importance: as memos (used to recall normal or automatic selection of functions), advisories (used when a monitored parameter drifts out of its normal operational range), cautions (used for events requiring crew awareness but not immediate action) or warnings (used for events requiring immediate crew action). In the event of multiple faults or failures, the relevant indications are prioritised according to their level of importance.

Typically, EICAS/ECAM displays are situated in the middle of the flight deck and are composed of an upper and lower display. The top display provides information relevant to primary systems (mainly engine parameters), such as:

- Primary engine parameters (thrust limit mode, N1, exhaust gas temperature, N2, fuel flow, etc.);
- Total and static air temperature;
- Quantity of fuel-on-board;
- Slat and flap position;
- Landing gear position;
- Summary messages or remedial instructions.

The lower unit typically contains secondary engine data, the status of secondary systems in the aircraft, or remedial procedures in the event of system malfunctions or failures. Information is displayed on multiple pages, which can include:

- Secondary engine parameters (fuel used, oil quantity, oil pressure, oil temperature, engine vibration, engine bleed pressure, etc.);

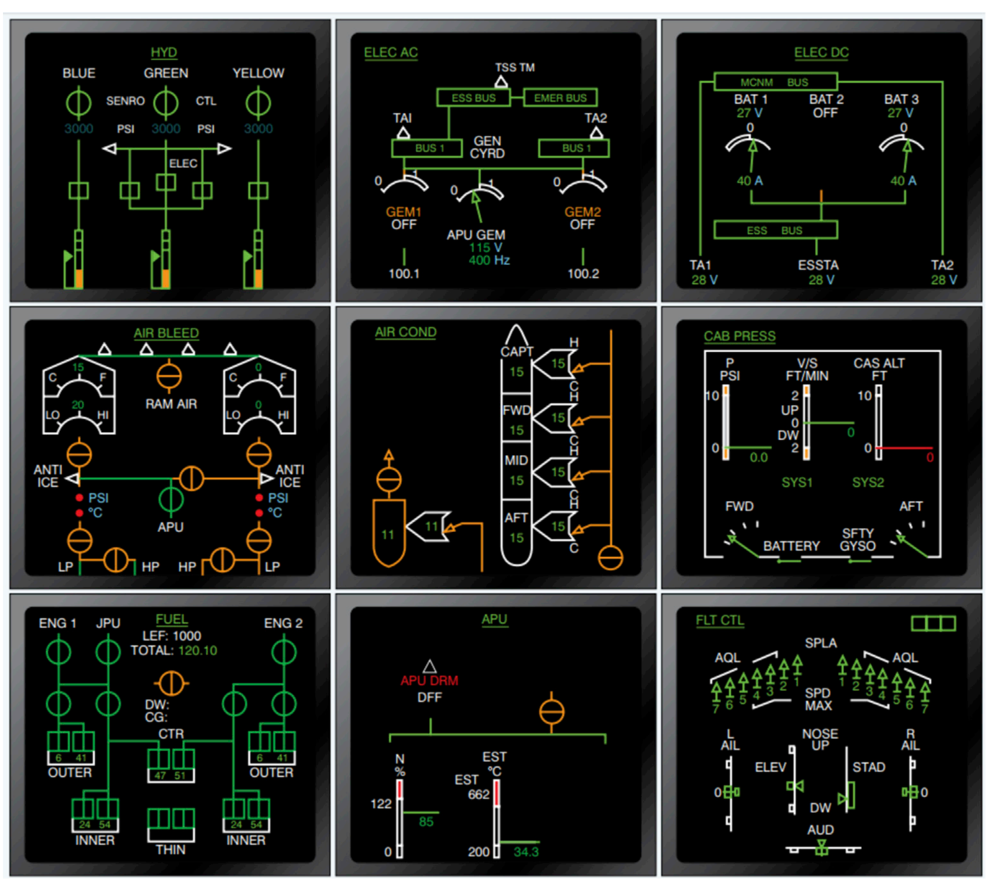

Fig. 10. ECAM status pages for different systems, image courtesy of FAA [21].

– System status and synoptics (AC/DC electrical power, auxiliary power unit, bleed air, cabin pressurisation and oxygen, flight control systems, hydraulics, doors, landing gear, etc.);
– Remedial procedures in the form of electronic checklists.

EICAS/ECAM reduces the need for pilots to constantly monitor system parameters and individual alerts, while providing decision support in abnormal and emergency situations by presenting appropriate caution, warning and advisory messages in the event of system failures or malfunctions. EICAS/ECAM has effectively superseded the flight engineer's function and enabled the transition from previous three-crew to current two-pilot flight decks.

2.3. Second generation flight decks

Second generation flight decks, such as the A320 and Boeing 747-400 (Fig. 11), are characterised by additional integration of avionics systems, allowing further consolidation of the displays used in first generation decks. The Electronic Flight Instrument System (EFIS) is a general term referring to the set of all electronic display systems used on-board second generation flight decks. EFIS displays typically include the Primary Flight Display (PFD) and Navigation Display (ND) but can also refer to ECAM/EICAS displays, the MCDU, as well as the Electronic Flight Bag (EFB). While the terms EADI/PFD, as well as the terms EHSI/ND are used interchangeably, PFD and ND typically refer to the displays used on a newer generation of aircraft (such as the Airbus A350-XWB [22] or the Boeing 747-400 [23]). As the EFIS uses standard display units, each display unit is inherently reconfigurable and interchangeable between different display modes. Such displays can perform multiple functions and are therefore known as Multi-Functional Displays (MFD).

2.3.1. Enhanced GPWS

The Enhanced GPWS (EGPWS) was introduced in 1996, nearly two decades after the development of the classic GPWS [25]. The EGPWS augments the classic GPWS with an internal database comprising terrain, obstacle and airport runways as well as the capability to relate the aircraft position to these databases, thereby providing predictive alerting and display functionalities. The added functionalities of the EGPWS includes two additional operating modes (Modes 6 and 7) as well as a number of enhanced functions (e.g., envelope modulation, terrain display, terrain look ahead alerting, terrain clearance floor) [26,27].

Mode 6 (advisory callouts) provides altitude and bank angle callouts. Altitude callouts include decision height-based callouts as well as altitude-based callouts; a Smart 500 Foot callout is also available during non-precision approaches. Bank angle callouts provide excessive bank angle advisories based on a bank angle envelope; different envelopes are defined for different classes of aircraft. Some of the EGPWS callouts (such as the decision height-based callouts) have been traditionally made by the Pilot Not Flying (PNF). Automating these callouts enhances flight crew awareness and allows the PNF to concentrate on other tasks during the approach and take-off phases.

Fig. 11. Boeing 747-400, second generation flight deck, [24].

Mode 7 (windshear) provides windshear alerts during take-off and approach. An envelope is defined based on a combination of head/tailwind as well as up/downdraft conditions. Windshear cautions (“Caution, windshear”) are given if an increasing headwind (or decreasing tailwind) and/or a severe updraft is detected to exceed the defined envelope. Windshear warnings (an aural siren followed by “Windshear, windshear, windshear”) are given if a decreasing headwind (or increasing tailwind) and/or a severe downdraft is detected to exceed the defined envelope.

Envelope modulation is an enhanced function to modulate the EGPWS envelope for special approach and landing cases. When using the classic GPWS, terrain features near specific airports around the world have resulted in nuisance or missed alerts during approach or radar vectoring situations. To circumvent this issue, EGPWS stores a database of these problem areas and adjusts the alerting envelope when operating at these locations. For example, envelope modulation desensitises Modes 1, 2 and 4 to minimize nuisance alerts due to unusual terrain or approach procedures.

Terrain display is an enhanced function for depicting surrounding terrain on compatible and enabled displays (e.g., EFIS displays). In the plan view display, relative terrain elevation is represented by various colours and intensities (primarily black, green, yellow and red).

Terrain look ahead alerting is an enhanced function, which provides more time for the flight crew to react to alerts, which are issued typically 60 s (cautions) or 30 s (warnings) prior to a predicted terrain conflict. The EGPWS compares the aircraft's position, flight path angle, track and speed against an internal terrain database to determine possible conflicts. Additionally, the ability to vary the look-ahead region as a function of the flight path angle, track and altitude prevents undesired alerts when taking off or landing. Different alerts are also given terrain or obstacle conflicts.

Terrain clearance floor is an enhanced function, which alerts pilots of possible premature descent during non-precision approaches. Using runway position data, a protective envelope is first defined around all runways. During approach, if the aircraft descends below these envelopes, the voice alert “Too low terrain” is triggered.

2.3.2. Cockpit Display of Traffic Information

The Cockpit Display of Traffic Information (CDTI) is an evolution of the TCAS and navigational displays for providing flight crew with greater situational awareness of surrounding traffic, potentially supporting future self-separation concepts. CDTI displays are designed to integrate and display traffic information from a range of different sources, such as Automatic Dependent Surveillance-Broadcast (ADS-B) and Traffic Information Service – Broadcast (TIS-B), and can also depict terrain or weather information. While TCAS displays provide the relative position, altitude and climb/descent information of proximate traffic, as well as the associated TA and RA, CDTI displays are expected to provide additional information such as aircraft callsign and type, range from ownship, closure rate, ownship/traffic trajectories as well as other forms of spatio-temporal information. As presented in Fig. 12, CDTI information can be displayed using two views – a plan-view Traffic Situation Display (TSD) and a side-view Vertical Situation Display (VSD) – improving flight crew awareness of proximate traffic and facilitating the execution of more complex lateral/vertical avoidance manoeuvers.

2.3.3. Multi-Functional Displays

Multi-Functional Displays (MFD) feature multiple pages, with each page typically serving a specific function. MFD allow pages to be switched either automatically or manually and for information to be layered on a single page, thus allowing the presentation of data from many sources. Emerging MFD in the business jet market also provide multi-touch capabilities (such as the Garmin G3X Touch and the Astronautics NEXIS Flight-Intelligence System) and can also serve as

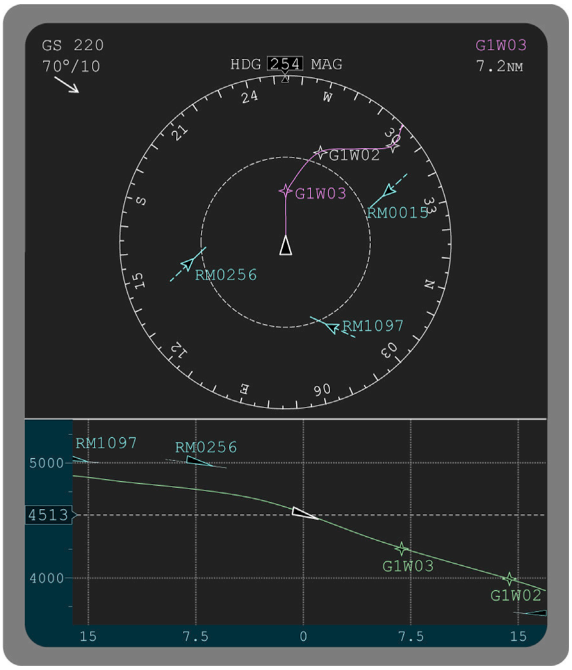

Fig. 12. A CDTI display containing both plan and vertical traffic displays.

Combined Vision Systems (CVS) by overlaying Enhanced Vision Systems (EVS) images onto synthetically generated terrain [28]. The FAA has provided guidelines for evaluating the human factors associated with MFD [29], which include the presentation and organization of information and controls to prevent clutter or mode confusion. The HFE considerations for designing MFD are discussed in greater detail in Section 3 but briefly include [29–31]:

- Accessibility and sensitivity of control and input elements (e.g., push buttons and touch screens);
- Colour and symbology usage;
- Organization of information elements (e.g., menus, windows, overlays);
- Clutter management;
- Sharing and switching between different functions.

2.4. Third generation flight decks

Third generation flight decks (Fig. 13) are likely to see a consolidation of second generation displays and interfaces. Advances in display technology will pave the way for larger MFD, providing fully integrated and interchangeable displays. Synthetic Vision Systems (SVS) are already in use in some business jets such as the Bombardier Challenger 650 and are likely to be integrated into the displays of third generation civil flight decks. EVS such as Heads-Up Displays (HUD) are being offered on some civil aircraft such as the Boeing 787 and the Airbus A320. Both SVS and EVS provide increased safety for flight in low visibility conditions such as darkness, smoke, fog or rain. SVS and EVS concepts are currently being evaluated by NASA [32,33] for future operations.

2.4.1. Synthetic/Enhanced/Combined Vision Systems

The intended function of Synthetic/Enhanced/Combined Vision Systems (SVS/EVS/CVS) is to provide a supplemental view of the external scene to provide the flight crew with an awareness of terrain, obstacles and relevant cultural features (which may include the runway and airport environment) [35,36].

- SVS provides a computer-generated image of the external scene using navigation data (attitude, altitude, position) and an internal reference database of terrain, obstacles and other relevant features. Advanced guidance information such as pathways-in-the-sky (Fig. 14) can be displayed on such systems and are an ongoing area of research. The quality of SVS images depends on the accuracy and precision of navigation data as well as the validity of the database.
- EVS uses imaging sensors (such as forward looking infrared, millimetre wave radar and/or low light level image intensifying) to provide the flight crew with a sensor-derived or enhanced image of the external scene. As such, the quality of EVS images very much depends on the type of sensors used.
- CVS combines information from synthetic and enhanced vision systems in a single integrated display.

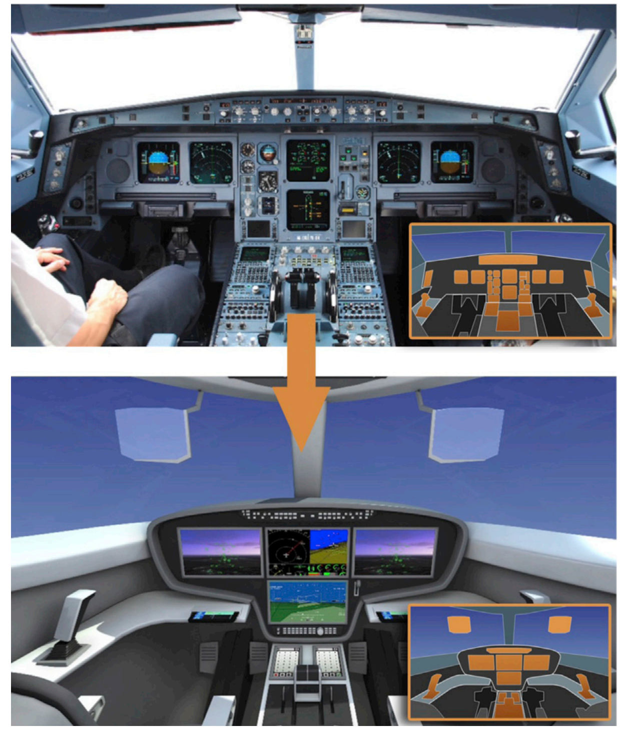

Fig. 13. Evolution of current second generation flight decks: conceptual image from ALICIA (All Condition Operations and Innovative Cockpit Infrastructure), research and development project co-funded by European Commission under the Seventh Framework Programme [34], courtesy of Airbus and Deep Blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

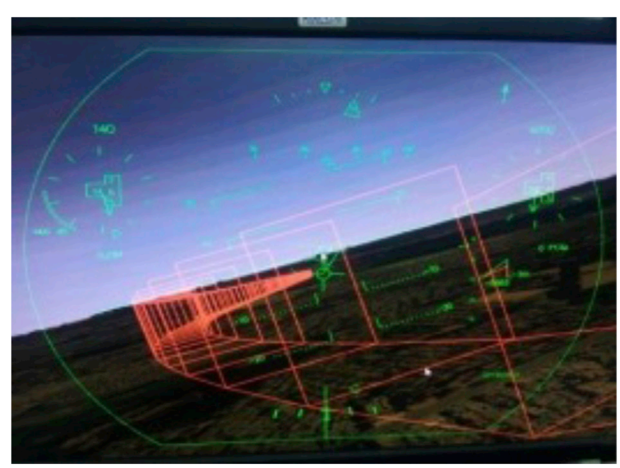

Fig. 14. An EVS concept using the pathway-in-the-sky representation to provide approach guidance, image used with permission of the author [37].

SVS/EVS/CVS have the capability to enhance the flight crew's situation awareness during normal and abnormal operations, contributing to a number of safety benefits [38,39]. These safety benefits include:

- Enhanced vertical/lateral path awareness;
- Enhanced terrain and traffic awareness;
- Improved recognition of, as well as recovery from unusual attitudes, aircraft upsets or missed approaches (e.g., recovery path is depicted for additional clarity);
- Reduced runway incursions;
- Supported transition from instrument to visual flight;
- Improved compliance with ATC clearances;
- Reduced possibility of spatial disorientation.

SVS/EVS/CVS provide the potential to support low-visibility or closely-spaced operations. A number of potential operational benefits were identified and include [38,39]:

- Intuitive depiction of information (e.g., ATC clearances, airspace, traffic and weather hazards, flight path guidance, RNP compliance, etc.);
- Support for enhanced surface operations (e.g., rollout, turn off and hold short, taxi, etc.);
- Support for enhanced departure and arrival operations (e.g., noise abatement operations, independent operations on parallel runways, reduced inter-arrival separation, reduced minimums, CAT III approaches, non-ILS approaches, etc.);
- Support for operations in low-visibility conditions;
- Support for 4D trajectory planning, navigation and monitoring.
- Possible reductions in training requirements.

The human factors considerations associated with these vision systems include [38,40–43]:

- Image quality (e.g., field-of-view, display size, clutter, symbology, brightness, contrast, data inaccuracy, noise, lag, jitter, etc.);
- Information integration (e.g., information presentation, information organization, systems and display integration, operator-related cognitive tunnelling, complacency, workload demand, skill retention, etc.);
- Operational concepts (e.g., display transitions, crew interaction, procedural changes, failure modes, depiction of essential information, crew trust, resource management, etc.).

2.4.2. Airborne Collision Avoidance System X

The next generation of collision avoidance systems are being developed to support future operational concepts. Airborne Collision Avoidance System (ACAS) X [44,45] is a proposed concept that has already undergone a number of flight tests [46]. The decision logic of ACAS X is based on a probabilistic approach, different from the rule-based logic of legacy TCAS systems. The approach allows for uncertainties in aircraft state [47], as well as pilot response [48] to be taken into account in the collision avoidance decision logic, offering greater operational flexibility and pilot acceptance in addition to enhanced safety. For example, ACAS X decision logics can be tailored to meet specific performance requirements for different classes (e.g., manned and unmanned) of aircraft, for different (e.g., reduced separation) procedures, or optimised to reduce the reversal or attitude crossing alert rates [49]. ACAS X is expected to reduce overall pilot workload, accommodate new surveillance inputs in addition to the transponders currently used in TCAS, improve operational efficiency, minimize interruptions to normal air traffic flow, as well as reduce costs associated with system implementation and upgrades. There are four variants of ACAS X: ACAS Xa (active), the general purpose ACAS X that will replace TCAS II; ACAS Xo (operation), designed for particular operations where ACAS Xa is unsuitable; ACAS Xp (passive), intended for low-performance general aircraft lacking certified collision avoidance protection; ACAS Xu (unmanned), designed for both RPAS and rotorcraft platforms.

2.4.3. Single cockpit displays

Research in Europe includes the 7th Framework Programme (FP7) One Display for a Cockpit Interactive Solution (ODICIS) project, which presented the concept of a projection-based single cockpit display for enhancing system architecture flexibility, customizability of displays and continuity of information [50]. All Condition Operations and Innovate Cockpit Infrastructure (ALICIA) was another FP7 project examining cockpit solutions in degraded flight conditions, such as the conceptual cockpit depicted in Fig. 13. ALICIA explored multi-modal cockpit displays such as tactile cueing, 3-dimensional audio, touch screen and SVS/EVS technologies [51,52].

2.4.4. Speech recognition

Speech recognition is an emerging concept that is being considered for implementation in third generation flight decks. Speech recognition technology can be used to augment current input methods, has significant synergies with other multi-modal input methods and can increase overall flight deck efficiency. Potential applications of speech technology include [53,54]:

- Voice-based FMS inputs;
- Voice-based tuning of radio frequencies;
- Calling up and interacting with voice-based checklists;
- Supporting cross-check and read-back during ATC-based communications;
- Synthesis of multi-modal interactions (e.g., touch screen, gesture recognition, eye tracking) to support context-aware inputs;
- Using voice authentication to augment cyber-security;
- Reduction of cultural bias or language misunderstanding through language-neutral cockpits;
- Emotion, stress and workload identification.

The three main types of speech recognition systems are speaker dependent, speaker independent and speaker adaptive [55]. Speaker dependent systems offer high accuracies as they are designed to be used by a single user. Speaker dependent systems need to be trained to the user's speech patterns, typically requiring many hours of speech. Speaker independent systems are designed to recognize general speech by any users and do not require any training of the system. However, speaker independent systems generally offer lower accuracies (or have more limited vocabularies) than speaker dependent systems. Speaker adaptive systems are a hybrid of the dependent and independent systems. Speaker adaptive systems begin as a speaker dependent system and adapt to the speaker incrementally over time, thereby reducing the need for initial training while allowing for improved performance over time.

However, a number of challenges remain before speech recognition technology can be successfully implemented on-board civil aircraft. These challenges include:

- Accidental/inadvertent triggering of the system leading to unintended inputs;
- Accuracy of the speech recognition system, which is affected by a number of factors, including aircraft background noise, user differences (e.g., tone, pitch, accents) as well as the type of system used;
- Changes in a user's voice under different operational (e.g., high/low workload) conditions, which might affect system accuracy;
- Reductions in system vocabulary, which might improve system accuracy at the cost of limiting the number of possible applications of the system;
- Training time required for speaker-adaptive systems to adapt to the user;
- User acceptance – some pilots prefer a sterile cockpit without small talk.

2.4.5. Enhanced audio

Multi-modal concepts are exploring applications of enhancing current audio technologies to improve the effectiveness of visual displays and to increase the situational awareness of human operators. In current flight decks, audio is used to provide secondary warnings, or in critical cases, to issue instructions for evasive action (as in the case of TCAS and GPWS advisories). Enhanced auditory displays can potentially reduce operator head down time on visual displays, while providing an additional channel to convey information to operators. Research in enhanced audio are focused on a number of key areas [56–58]:

– 3D audio for conveying spatial information (e.g., traffic proximity and location);
– Spatial separation of different auditory sources (i.e., the cocktail party effect) to facilitate user localisation of different types of cues;
– Sonification to indicate changes in data;
– Synthetic speech for voice narration of data link messages.

Enhanced audio concepts have also been explored in military [59,60] and RPAS applications [61–63], primarily for representing spatial information, augmenting situational awareness and improve overall operator performance.

2.5. Military cockpits

Similar to civil aircraft, military jet fighters can be classified into different generations according to their capabilities as well as the avionics technologies incorporated into each generation of aircraft. The Australian Air Power Development Centre identifies five generations of fighter aircraft, which are briefly summarized in Fig. 15 [64]. In generations one to three, the displays used on-board military cockpits were predominantly electro-mechanical, while from generation four onwards, military cockpits began to feature more advanced electro-optical displays. It is observed that advances in military aviation technology are generally ten to fifteen years ahead of their civil counterparts. Some examples include:

– The first fighter jets were introduced about a decade before the start of the civil jet age in 1952.
– Glass displays were used in third and fourth generation military cockpits in the 1970s, approximately a decade before the technology became available on civil flight decks of the 1980s.
– Fly-by-wire was first implemented in fourth generation fighter aircraft such as the F-16 (introduced to service in 1978) before being adopted in civil aircraft such as the Airbus A320 (introduced to service in 1988).

While first and second generations of fighter jets were designed to maximise aircraft performance (e.g., speed, range, payload capacity, manoeuvrability, etc.), the third generation of fighter aircraft had enhanced capabilities which were brought about by advances in mission and avionics systems (e.g., stealth, surveillance, weapons, etc.). These third generation fighters incorporated precision-guided munitions systems, which supported the transition to engagements beyond the visual range and led to the development of increasingly advanced systems for detection, acquisition, engagement and evasion of enemy aircraft. The transition to the fourth generation of fighters saw further advances in mission systems, allowing swing and multi-role fighters capable of operating in air-to-air or air-to-ground roles, or performing airborne reconnaissance, surveillance and support. Currently, fifth generation fighters are being developed to support network-centric warfare. Fifth generation fighter aircraft are characterised by their inherent capability to network with other aircraft and manage large amounts of data by intelligent data fusion algorithms, thereby enhancing the fighter pilot's situational awareness and tactical decision-making in increasingly complex scenarios.

2.5.1. First to third generation cockpits

Similar to flight decks of the electro-mechanical era, first to third generation cockpits featured dedicated analogue displays and instrumentation. Guided missiles were used on second and third generation fighters with the support of radar and infrared technologies. Late-second generation and third generation cockpits also saw the use of the electro-optical radar scope. Third generation fighters such as the F-4, as shown in Fig. 16, featured more advanced radar systems such as the Doppler radars, which supported "look-down, shoot-down" capabilities. The F-4 was manned by two crew members, with the pilot sitting in the front seat and the Radar Intercept Officer (RIO) managing the advanced radar system in the back.

2.5.2. Fourth generation cockpits

Fourth generation aircraft such as the F-15A (shown in Fig. 17) saw the introduction of advanced flight control systems. Fighters such as the F-16 and Mirage 2000 were designed with increased responsiveness and

Fig. 16. F-4 Phantom II, a third generation fighter.

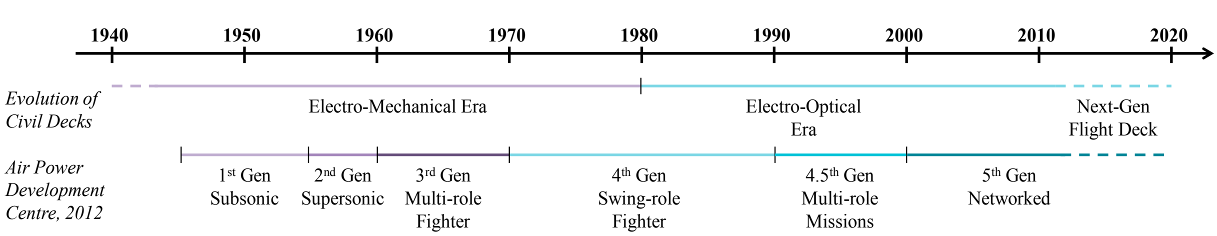

Fig. 15. Evolution of military fighter aircraft.

Fig. 17. F-15A Eagle, a fourth generation fighter, image courtesy of the National Museum of the U.S. Air Force.

manoeuvrability but were inherently unstable. Fly-by-wire systems were designed to compensate for this lack of stability by providing artificial stability. The head-down analogue instruments used in first to third generation fighters were gradually replaced with electro-optical displays in fourth generation cockpits. MFD-style displays, which were used by second generation civil flight decks of the 1990s, were already found in F-16 cockpits since the late 1970s. Similar to civil flight decks, MFD on fighter cockpits consolidated the displays of numerous standalone instruments into single glass displays, allowing fighter pilots and Weapon Systems Officers (WSO) to switch between different display configurations and functions. MFD supported the transition of fighter aircraft with dedicated roles, to multi-role and swing-role fighters. Typical MFD pages include:

- Horizontal Situation Display (HSD);
- Fire Control Radar (FCR);
- Stores Management System (SMS);
- Terrain Following Radar (TFR);
- Forward Looking Infrared (FLIR);
- Targeting Pod (TGP);
- Flight Control System (FLCS);
- Data Terminal Entry (DTE);
- Weapon Systems (WPN).

In addition to the head down MFD, fourth generation cockpits also feature HUD that are now beginning to appear in modern flight decks. The HUD is considered to be the aircraft's PFD and displays primary flight data. Additionally, fighter HUD typically include G readouts as well as weapon targeting information. The HUD allows fighter pilots to maintain situational awareness by providing pilots with crucial flight and combat information that they would otherwise have to obtain by shifting their gaze down toward the heads down displays. Another feature introduced in fourth generation fighters is the Hands on Throttle-and-Stick (HOTAS) controls. Buttons and switches are located on the HOTAS, allowing pilots to perform some tasks without taking their hands off the controls. Common switches on the side-stick include the trigger, weapon release switch and trim hat, as well as switches for managing the active displays, targets, countermeasures, sensors and autopilot. The throttle contains switches for managing communications, weapons and sensors. Some civil aircraft manufacturers (such as Airbus, Bombardier and Embrarer) favour the use of the side-stick over the yoke. The use of sidesticks in civil airliners frees up the space in front of the pilot, improving display visibility and allows for other for other uses in the area (such as incorporating alternative control devices like keyboards, trackballs, etc.). The Gulfstream G500 is the first civil aircraft to use an active inceptor system to provide pilots with tactile feedback.

2.5.3. Four-and-a-half generation cockpits

Reduced aircraft development due to forced reductions in military spending led to a half generation increment from fourth generation fighter jets. Four-and-a-half generation fighters such as the Eurofighter Typhoon (Fig. 18) included avionic improvements such as the Active Electronic Scanned Array (AESA) radar, integrated Infrared Search and Track (IRST) systems and high capacity data-link, allowing for network centric warfare. Four-and-a-half generation cockpits also feature alternative input technologies such as Direct Voice Input (DVI) and touchscreen displays.

2.5.4. Fifth generation cockpits

Fifth generation fighters are designed around the concept of network centric warfare, with the ability to exchange and store information between other battlespace elements. Such aircraft are characterised by advanced avionics systems capable of multi-sensor data fusion, which integrate data from multispectral and/or networked sensors to provide fighter pilots with a consolidated view of the battlespace. Helmet Mounted Displays (HMD) have been used since fourth generation fighters and are an ongoing area of development in fifth generation jets. Standard HMD provide a holographic display of aircraft data and target information within the helmet's visor. Images from on-board sensors such as the Forward Looking Infrared (FLIR) and Night Vision Imaging Systems (NVIS) can be fused to maintain pilot situational awareness in degraded visual conditions. HMD cueing systems allow pilots to designate and acquire targets as well as aim sensors and weapons via head motion. Eye tracking technology is not featured on current HMD but offer the potential for even more accurate HMD cueing.

Fifth generation fighters such as the F-35 (shown in Fig. 19) have completely replaced the HUD with HMD as the primary flight display. The F-35's HMD uses a distributed aperture system to provide a 360-degree view of the aircraft's surroundings, supporting even greater situational awareness. The F-35 also features a panoramic touchscreen MFD, similar to the type of displays that will be featured in next generation of civil flight decks. Fifth generation fighters are also typically single-seated, with the role of the Weapon Systems Officer (WSO) in the back seat being replaced by a combination of other networked battlespace support elements as well as by higher levels of on-board automation.

2.6. Single-pilot operations

SPO flight decks are currently used in the military, General Aviation (GA) and business jet domain, but given developments in flight deck autonomy and HMI^2 evolutions, SPO is expected to become a viable concept of operations for future commercial airliners. SPO flight decks contain HMI^2 elements of second and third generation two-pilot civil

Fig. 18. Eurofighter Typhoon, a four-and-a-half generation fighter.

Fig. 19. F-35 Lightning II, a fifth generation fighter.

flight decks – business jets such as the Embraer Phenom 300 (Fig. 20) are certified for SPO and feature streamlined interfaces containing wide-screen and high resolution MFD. The MFD functionalities can contain SVS, touchscreen and satellite weather capabilities that are typical of third generation civil flight decks.

Most notably, NASA conducted a series of SPO-related studies exploring a new concept of operations, whereby single-pilots would be supported by a number of ground crew members [66]. The ground crew would provide dispatch information and communication support in nominal operations. In off-nominal operations (such as single-pilot incapacitation), the ground crew would serve as remote pilots executing an emergency landing. The SPO ground station would resemble a remote pilot station, incorporating some ATM elements (such as weather and traffic monitoring functionalities) to support the ground crew member's role as dispatcher. The extension of SPO to commercial aviation has also been investigated in a number of studies [67–70]. These studies have suggested pilot monitoring functions to be implemented on-board SPO flight decks in order to detect periods of high pilot workload or pilot incapacitation. Sufficiently intelligent on-board systems would be able to provide adaptive and context-aware support in the case of excessive pilot workload, or even coordinate an emergency landing in the event of pilot incapacitation. These and similar considerations underpin the design of cognitive monitoring systems such as the ones described in sections 4–6.

Fig. 20. Embraer EMB-505 Phenom 300 flight deck, [65].

2.7. Rotorcraft cockpits

Leishman [71] provides a concise history of rotorcraft flight, beginning from the 1700s up to the 21st century. The early 1940s marks the introduction of modern helicopters, followed by the maturation of rotorcraft technologies in the next two decades. As with most developments in aerospace, military applications were the primary driver for these developments. In terms of cockpit environment, the historical evolution of the rotorcraft cockpit follows a similar trend as that of fixed wing aircraft, transitioning from analogue instrumentation to glass displays as well as featuring increasing levels of digitalisation and systems integration. However, different operational needs served by fixed wing aircraft and rotorcraft have led to a number of notable divergences in their respective system and cockpit evolutions.

Rotorcraft cockpit instrumentation are largely similar to those found on fixed wing aircraft. The information required for basic flight includes: attitude, altitude, airspeed, engine and rotor RPM, turn-and-slip, vertical speed, manifold pressure and magnetic heading. To support radio-based navigation, a radio control panel and CDI/RMI are also used. Modern glass cockpits feature PFD, ND and CAS displays, which are similar to fixed wing flight decks. Flight controls are more challenging as compared to fixed wing piloting. The rotorcraft pilot typically operates three controls: the collective lever, cyclic stick and anti-torque pedals. The collective lever is operated by the pilot's left hand and controls the vertical movement of the rotorcraft by adjusting collective pitch of the main rotor. The cyclic stick is operated by the pilot's right hand. The combined longitudinal and lateral inputs to the cyclic stick determines the orientation of the rotor disk. Motion of the cyclic along the longitudinal axis (fore and aft) controls rotorcraft pitch attitude, while motion along the lateral axis (left and right) controls rotorcraft roll attitude. The anti-torque pedals are operated by the pilot's feet and control the rotorcraft's yaw by adjusting the pitch angle of the tail rotor blades. As the three controls are coupled, pilots have to control all three simultaneously, which is somewhat different from the decoupled vertical and lateral controls used on fixed wing aircraft. Hovering is particularly challenging, as pilots are required to continuously make small corrections, accounting for the presence of external disturbances, in order to keep the rotorcraft stable.

2.7.1. Cockpit digitalisation

Rotorcraft avionics and cockpit digitalisation has traditionally lagged behind their fixed wing counterparts, due to a number of factors including the rugged operational environment, a lack of necessity for more advanced avionics, low demand, high relative cost, increased system complexity as well as space and weight considerations. In particular, owing to operations in degraded visual environments and turbulent flight conditions, the avionics systems used on-board helicopters require both higher levels of software certification as well as more robust, vibration-tolerant Line Replaceable Units (LRU), effectively hindering the introduction of modern cockpit technology. Glass cockpits first appeared around the mid-1980s on military rotorcraft, such as the Kiowa OH-58D reconnaissance helicopter (Fig. 21). This was approximately a decade after the adoption of glass displays in fighter jets, and around the same time that glass cockpits first appeared on civil fixed wing aircraft. The piloting stations of modern helicopter cockpits typically feature two MFD for horizontal or vertical situation information, along with a MCDU to allow the pilot access to the FMS for flight or mission planning (Fig. 22). Further avionics integration has supported the inclusion of more advanced functionalities in rotorcraft MFD, introducing additional modes supporting the display of additional mission or flight information, which might include video surveillance, target tracking and indication, as well as controls for facilitating communications between air and ground elements.

In terms of flight handling, the automated flight control systems used on-board helicopters were fairly advanced for their time. The Stability Augmentation Systems (SAS), force trim, as well as flight path

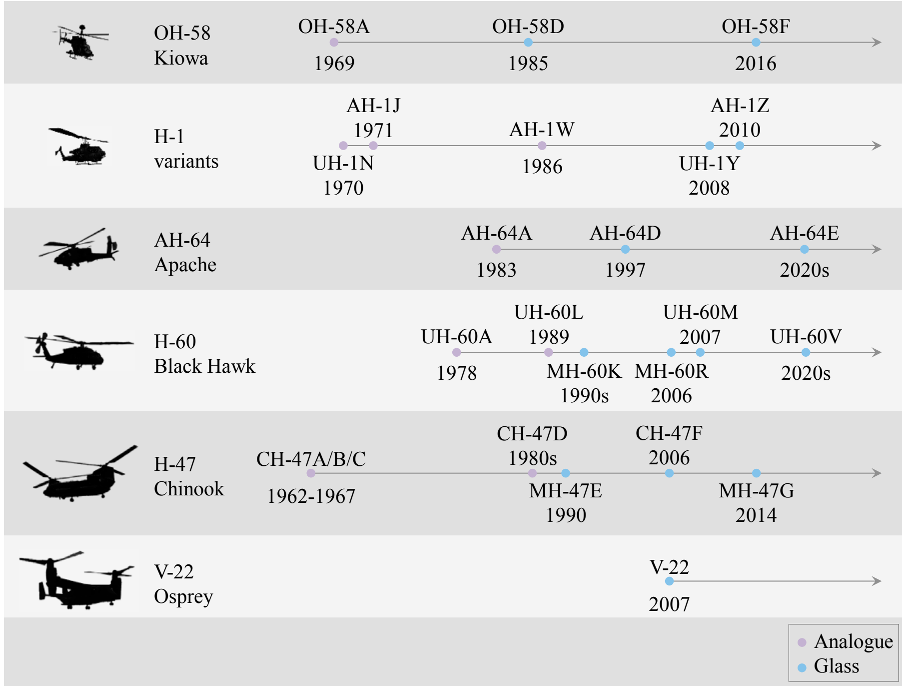

Fig. 21. Historical evolution of some military rotorcraft, with dates indicating when the different variants were first introduced (or are expected to be introduced) into service.

Fig. 22. Cockpits of the UH-1B (left) and UH-1Y (right, courtesy of Northrop Grumman Corporation).

stabilisation and autopilot systems were developed during the early-1960s to the late-1970s. However, possibly owing to increased costs and decreased demand, full cockpit digitalisation was somewhat slower (Table 2). The first fully Fly-By-Wire (FBW) transport helicopter was the NH90 [72], which went into production in the mid-2000s, at around the same time that FBW appeared for business jets like the Falcon 7X. In contrast, fixed wing aircraft with full FBW have appeared a number of decades prior to this, with the F-16 and A320 being the first military and civil aircraft to be equipped with fully digital FBW systems.

Table 2
Early aircraft to be equipped with fully FBW systems.

Type	Aircraft	Year of Introduction
Fighter jets	F-16	1978
	Su-27	1985
Civil fixed-wing aircraft	Concorde (hybrid analogue-FBW)	1976
	A320	1988
Business jets	Falcon 7X	2005
Rotorcraft	NH90	2006
	UH-60MU	2011

Rotorcraft human factors research is primarily concerned with introducing higher levels of safety through increased tactical situational awareness. A study by the NLR identified 145 technologies for mitigating helicopter accidents, with the top 10 technologies being [73]:

– Digital range image algorithms for visual guidance in low-level flight;
– EGPWS/TAWS;
– Passive tower-based Obstacle Collision Avoidance Systems (OCAS) comprising ground-based installations near power lines that provide warnings to helicopters flying in its vicinity [74];

– New terrain following guidance algorithms for rotorcraft displays (including SVS and EVS concepts);
– LIDAR-based obstacle and terrain avoidance systems [75];
– Predictive ground collision avoidance using digital terrain referenced navigation (i.e., based on the helicopter flight path);
– Full Authority Digital Engine Control (FADEC);
– Engine backup systems;
– Practical regime prediction approach for Health Usage Monitoring System (HUMS) applications;
– Helicopter pilot assistant systems featuring flight planning and 4D-trajectory optimisation [76].

2.7.2. *Degraded visual environments*

Operations in Degraded Visual Environments (DVE) are a significant contributing factor to rotary-wing accidents and also lead to reduced operational effectiveness in missions involving search and rescue, flight to remote locations and landing on undeveloped sites. DVE operations encompass a range of conditions, including:

– Inadvertent entry into Instrument Meteorological Conditions (IIMC), which refers to a situation where a pilot originally planning to fly under Visual Flight Rules (VFR) is prevented from doing so due to deteriorating visibility due to weather (e.g., heavy rain, cloud, fog, darkness, etc.). IIMC may lead to spatial disorientation and a loss of visual contact with the ground.
– Whiteout and brownout, which are usually associated with military operations and refer to the loss of visibility close to the ground when the rotor wash blows up either snow or dust. The sudden loss of visual cues might cause the loss of situational awareness, leading to a misjudgement of the appropriate landing manoeuvre.
– Flat light conditions, which typically occur over uniform landscapes such as calm water, desert or snowy terrain and are caused by the diffusion of light by overhead clouds, creating a shadowless surface environment. Flat light makes it difficult for pilots to perceive depth, distance, altitude or motion and can give the impression of ascending or descending when actually flying level.

Traditionally, Night Vision Imaging Systems (NVIS) have been extensively employed in rotorcraft operations allowing for operations in low-light environments [77]. However, a number of programs have recently emerged that are targeting EVS/SVS/CVS solutions (e.g., Airbus's Sferion system [78,79], BAE System's BLAST technology [80], Defence Research and Canada's DVEST program [81], NATO [82]) for mitigating/avoiding accidents in DVE conditions. The systems comprise four main components:

– Sensors such as Millimetre Wave (MMW) radar, LIDAR, thermal and low-light cameras for detecting and recognising surface features and texture, slope and obstacles;
– Software which process the sensed data into a readily interpretable picture. These can include classification algorithms which allow the sensed objects to be visualised as conformal symbols (i.e., symbols which appear to overlie the objects they represent);
– Displays, including helmet mounted, heads up and heads-down displays, which depict the information using relevant 2D/3D symbology;
– Automatic flight control systems with advanced flight control laws utilising sensor data.

2.7.3. *Terrain/traffic awareness*

Helicopter TAWS (HTAWS) and TCAS systems are similar to the GPWS and TCAS systems installed on fixed wing aircraft, providing relevant cautions, warnings and advisories. However, due to helicopter flight specificities (which are in many ways similar to those of RPA platforms), the terrain, obstacle and traffic warning systems used by rotorcraft typically introduce some modifications to the alerting logics, also relying to a greater extent on an extensive terrain/obstacle database and exploiting on-board sensor systems. The flight specificities can include:

– Operating envelopes which are different to commercial fixed-wing aircraft, but comparable with those of RPA and light general aviation aircraft;
– Increased vertical manoeuvrability, thereby requiring 'look-down' capabilities in addition to the 'look-ahead' modes employed on existing systems;
– Use of additional sensors for surveillance purposes (e.g., MMW radar, LIDAR, FLIR, etc.);
– Operations involving low level navigation and terrain following;
– Operations in environments with a variety of natural and/or man-made obstacles;
– Operations in areas with high traffic densities, which might saturate the capacity of cooperative (e.g., transponder-based) sensors;
– Operations involving mobile or transient obstacles (such as, in the case of offshore operations, large ships, construction barges or installations).

HTAWS devices integrate terrain and obstacle databases with position information from GNSS and other sensors to generate display information, aural and visual alerts. The HTAWS equipment may be a stand-alone system, or may be interfaced with the weather radar, navigation displays, or other display systems. An example of an obstacle warning system is the Lidar Obstacle and Warning System (LOWAS) [75] as depicted in Fig. 23, which can be used for sense-and-avoid applications by both rotorcraft and small-to-medium sized RPA platforms. According to RTCA DO-309 [83], HTAWS is expected to provide cautions and warnings for a number of conditions [84]:

– Excessive descent rate;
– Excessive terrain closure rate;
– Excessive altitude loss after take-off or go-around;
– Unsafe terrain clearance while not in landing configuration;
– Excessive downward deviation below the instrument glide path;
– Checks on pressure altitude, excessive banking and pitch angles;
– Vortex ring state, which is a stall condition occuring when the rotorcraft is descending in a manner that causes it to get caught up in the downwash of its main rotor.

A recent report on the use of HTAWS proposed a number of modifications to current EGPWS systems to make them more suitable for offshore environments [85]:

– EGPWS Modes 1 and 4 envelopes to be modified such that alerts are triggered at higher altitudes;
– EGPWS Mode 3 envelope to monitor for loss of airspeed rather than loss of altitude after take-off;
– A new envelope to be introduced which monitors airspeed vs. torque. At low speeds (usually < 80 kts), due to the increased effects of induced drag, the required torque typically increases with decreasing airspeed.

2.7.4. *Collision avoidance*

While collision avoidance systems have been a requirement for fixed wing aircraft since the 1980s, there is currently no mandate for the installation of such systems on rotorcraft. However, TCAS is still typically included as optional equipment on medium and heavy commercial helicopters and certified based on the TCAS II standard. A number of considerations regarding the installation of such TCAS systems have been cited in past studies [86–88]:

– TCAS algorithms are not well-suited for the lower operating airspeeds (<100 kts) and rate-of-climb of rotorcraft compared to fixed wing

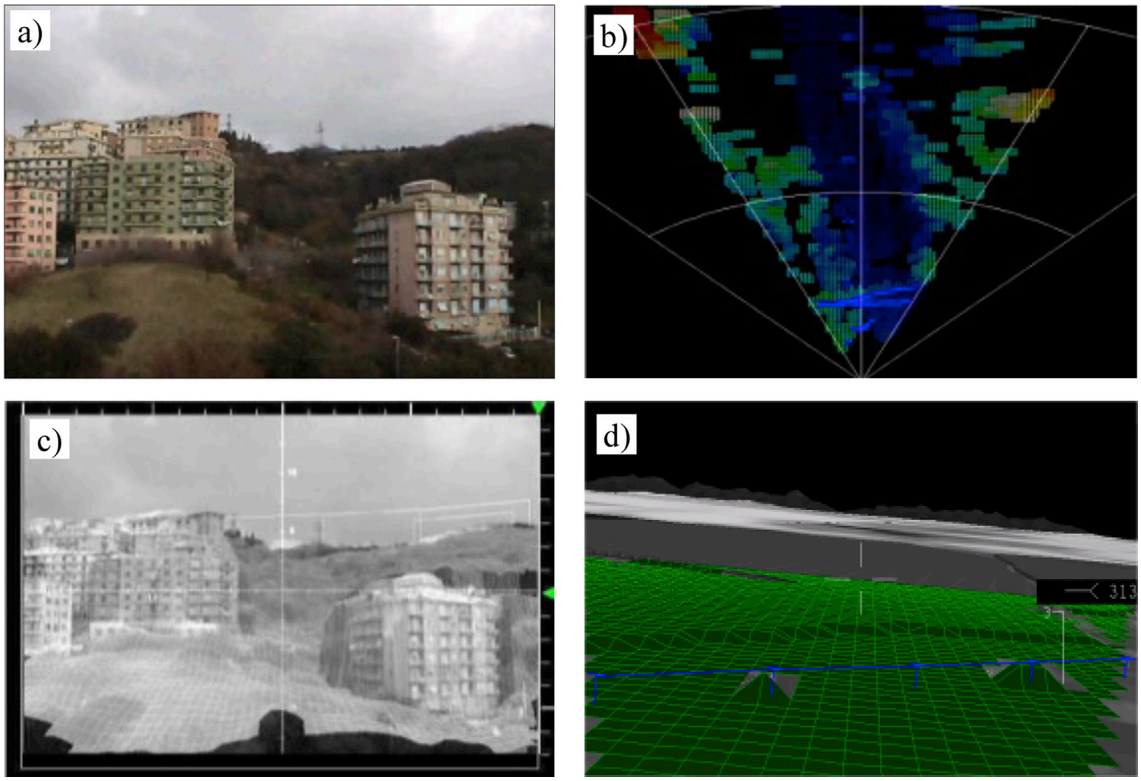

Fig. 23. HMI formats for the Lidar Obstacle Warning and Avoidance System; a) visible image, b) Planar display with detected obstacles along with ground profile represented as blue lines; c) enhanced format combining Lidar and FLIR imagery; d) Synthetic display format with wire obstacles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

commercial aircraft, instead being more similar to those of light general aircraft or RPA;
- the lower airspeed of rotorcraft allows a substantially smaller volume of protection as compared to fixed wing aircraft, and also implies that most conflicts will result from overtaking manoeuvres by high speed aircraft, approaching from the critical quadrant (left/rear), thereby requiring a protection volume optimised for such conflicts;
- rotorcraft typically operate at low altitudes where the vertical RAs provided by TCAS might not be as effective as a horizontal RA;
- rotorcraft might operate in high traffic density areas, which might degrade the reliability of TCAS -based systems (TCAS II provides reliable surveillance for traffic densities of up to 0.3 aircraft per NM^2);
- TCAS antennae performance can be susceptible to interference from the rotorcraft's main and tail rotors;
- TCAS antennae are vertically polarised, which means that there are blind spots situated directly above and below the antennae. This presents an issue for rotorcraft, which are able to manoeuver into these regions, thereby requiring more accurate coverage of these areas;
- the use of additional on-board sensors (e.g., LIDAR, MMW radar, visual camera) for navigation and tracking can enhance the performance of collision avoidance systems.

2.7.5. *Flight and mission management*

Following the introduction of glass displays, further avionics integration in the 1990s supported the development of Mission Management Systems (MMS) for special operation helicopters such as the MH-47E and MH-60K [89], with similar systems emerging for civil rotorcraft applications in the following decade. Similar to the FMS of fixed wing aircraft, rotorcraft pilots interact with the MMS through the CDU. Rotorcraft FMS/MMS are however designed for more tactical applications, providing a number of unique functionalities in addition to the flight planning, navigation and guidance functions offered on fixed-wing FMS, which can include:

- Multi-sensor navigation (GPS, INS/GPS, VOR/DME/TACAN, Doppler, SBAS, FLIR, Radar, etc.);
- Centralised management of navigation and communication radios, and integration with tactical communications system;
- Up/down link of tactical flight plans with external sources;
- Automated flight pattern generation for search and rescue, surveillance and surveying applications, which can include the following patterns:
    - Rising ladder, race track, expanding square, creeping line, parallel track, track crawl, sector search, orbit and border patrol [90,91];
- Additional flight modes including terrain following and transition to hover;
- Centralised control of tactical sensors (e.g., FLIR, weather radar, SAR, visual camera) and their associated video feeds;
- Target acquisition, tracking and prediction;
- Integration with existing Health and Usage Monitoring Systems (HUMS);
- Night vision compatible displays.

Additionally, the use of ground-based mission planning systems, similar to those used by RPAS pilots, provide pre-flight planning, additional decision support and post-flight debriefing functionalities.

2.7.6. *Manned/unmanned teaming*

An emerging research focus area is Manned/Unmanned Teaming (MUMT) between unmanned or remotely piloted platforms and manned aircraft. Instead of being controlled from a ground station, these autonomous platforms would be controlled directly from the cockpit of a manned platform via tactical data links. In particular, manned rotorcraft offer a number of opportunities due to the operational synergies between the two platforms. Most of the research and development efforts are directed at military applications, ranging from Intelligence, Surveillance and Reconnaissance (ISR) to cooperative targeting and remote strike. A recent review provided the major testing and demonstration programs in this area [92]. The different programs are presented in Fig. 24 and were successful in demonstrating a number of technological concepts for supporting higher levels of RPAS interoperability, in accordance with the levels as described in the NATO Standard Agreement (STANAG) 4586 [93]:

– Level 1 interoperability: Indirect receipt/transmission of RPA-related payload (sensor) data;
– Level 2 interoperability: Direct receipt of Intelligence, Surveillance and Reconnaissance (ISR) data, where "direct" covers reception of the RPA payload data by the remote control system when it has direct communication with the RPA;
– Level 3 interoperability: Control and monitoring of the RPA payload in addition to direct receipt of ISR and other data;
– Level 4 interoperability: Control and monitoring of the RPA (both flight and payload), less launch and recovery;
– Level 5 interoperability: Control and monitoring of the RPA, plus launch and recovery.

Most of the programs assessed technologies supporting Level 3 and 4 RPA interoperability, which require human operators to assume some form of control of the RPA platforms while on-board the rotorcraft. The key enabling technologies supporting such operations include:

– Tactical data links allowing for different degrees of communication between manned and unmanned platforms;
– Software architectures supporting interoperability between heterogeneous platforms or coalition groups;
– On-board functionalities including data fusion, sense-and-avoid, as well as autonomous tactical decision making, planning and replanning;
– HMI allowing for more efficient command and control;

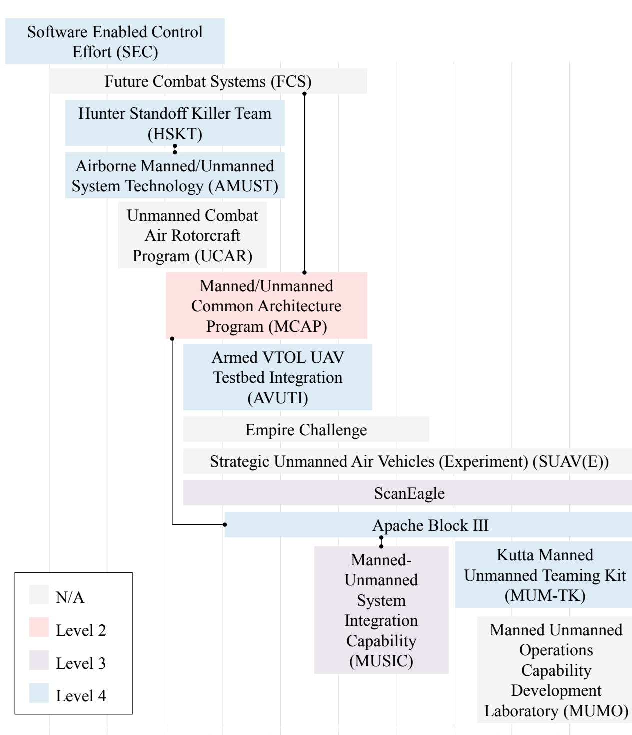

Fig. 24. Key programs investigating MUMT technologies and concepts, based on the review from Ref. [92].

– Models of crew behaviour, workload and situation awareness associated with manned-unmanned operations.

2.8. RPAS ground segment

In general, RPAS possess increased automation and autonomy, which compensate for the drawbacks associated with RPAS operators being physically removed from the flight deck. RPAS are designed with higher levels of autonomy and decision authority (e.g., in the Guidance, Navigation and Control (GNC) loop [94]) relative to their manned counterparts. The forms of RPA control and coordination can range from remote control in the Visual Line of Sight (VLOS), to managing and coordinating multiple platforms via Beyond Line of Sight (BLOS) data links. There are different sets of challenges associated with the design of RPAS HMI[2], especially for more complex operations requiring human operators to work collaboratively with other human and autonomous agents. Some HFE considerations include [95–98]:

– Lack of physical sensory (vestibular, haptic, auditory) cues;
– Data link latency and performance;
– Detection and recovery from abnormal situations;
– 'Out-of-the-loop' effects and loss of situational awareness resulting from long periods of low activity;
– Transfer of RPA platform control between different pilots/stations;
– Coordination of multiple RPA platforms;
– Team dynamics in multi-operator control, particularly for teams in different geographical locations;
– Information integrity for establishing trusted autonomy;
– Human machine collaboration.

The Ground Control (GC) segment contains the elements that allow remote crew members to control and coordinate the actions of one or multiple RPA platforms. RPAS GC segments range from small handheld units to large multi-operator centres. Three levels of increasing size (unit, station, centre) are provided to illustrate the different scales of operations.

A GC Unit (GCU) is manned by a single remote pilot and is designed to be highly portable, containing all the necessary functionalities and HMI[2] for the remote pilot to carry out his/her mission. As illustrated in Fig. 25, GCU are typically laptops or handheld units designed to provide human operators with tactical control of RPA platforms within the Visual Line of Sight (VLOS).

A GC Station (GCS) is typically a deployable structure (but can be either mobile or fixed) comprising multiple integrated GCU (i.e., multiple displays, controls and computer processors). An example of a GCS is the Heterogeneous Airborne Reconnaissance Team (HART) GCS (Fig. 26),

Fig. 25. Handheld control unit.

Fig. 26. The Heterogeneous Airborne Reconnaissance Team (HART) system, courtesy of Northrop Grumman Corporation.

which supports ground forces with near real-time intelligence, surveillance and reconnaissance information from multiple manned and unmanned platforms. The HART GCS communicates with a command and control centre, which coordinates, prioritises and allocates re-tasking requests from multiple GCS. While a single remote pilot can potentially operate a GCS, the GCS would typically comprise multiple human operators, with each fulfilling a specific role. Peschel [100] has identified three generic roles – mission management and planning, platform control, as well as data exploitation, communications, or sensor operation. Similar to units, stations are typically associated with the control of a single RPA platform, but the design of GCS is also evolving to support the coordination of multiple platforms by multiple operators [101]. Due to the number of human operators available, GCS typically allow for more complex missions to be carried out compared to GCU. Additionally, while GCU are associated with control and coordinating RPA platforms via VLOS, GCS can also be used for Beyond VLOS (BVLOS) control and coordination.

A GC Centre (GCC), such as NASA's Global Hawk Operations Centre (Fig. 27), is a fixed structure containing a large number of computers, displays and controls. Centres integrate elements of GCU and GCS within a centralised facility, allowing a large number of human operators to carry out complex missions requiring the coordination of multiple RPA platforms. GCC are associated with the need for processing significant amounts of data in real-time, high level strategic mission planning, as well as coordinating efforts across multiple entities (such as ATM as well as other GC centres, stations and units).

The GC display interfaces are comparable to the MFD of civil flight decks. Depending on the mission and operational requirements, a number of reconfigurable and customisable displays are used to support human operators in performing the "aviate, navigate, communicate and manage" tasks traditionally undertaken by pilots of civil flight decks. Typical interfaces include the following elements:

– Primary flight information, similar to PFD elements;
– Navigation and traffic information, similar to ND elements;
– Waypoint planning and management, similar to FMS/MCDU elements;
– System status information, similar to EICAS/ECAM elements;
– Sensor feed and payload control;
– Mission-related information (e.g., mission objectives, progress and status);
– Text or voice-based communication with other human operators.

Fig. 27. NASA Global Hawk Operations Centre, image courtesy of NASA.

While RPAS crew members share a number of tasks in common with conventional flight crew members, there is a greater emphasis on the management aspect of RPAS operations, due in part to the higher levels of autonomy afforded by unmanned or remotely piloted systems. Table 3 provides a comparison of RPAS crew tasks identified by Nehme [103], Ashdown [104], Peschel [100] and Ramos [105]. The four sources include some elements of aviate, navigate and communicate tasks but focus primarily on the management aspect. Manage tasks are divided into three categories – the management of systems, data and the mission. Some aspects of systems and mission management are similar to civil operations (requiring similar displays as EICAS/ECAM and MCDU) but also encompass other elements such as payload and sensor planning and operation. Data management is a task unique to RPAS operations and depends largely on the mission requirements. Although some aspects of data management are also required on civil flight decks, it is currently not considered one of the primary tasks of flight crew. The key GC HMI elements are discussed in the following sections.

2.8.1. Reconfigurable MFD

The RPAS HMI design is predominantly based on the MFD concept of modern flight decks. Elements of modern PFD, ND, FMS and ECAM/EICAS are featured in the GC displays. Additional features are included to support data-link monitoring, mission planning and sensor management. Depending on the mission profile and scale of operations, GC HMI can comprise single displays containing reconfigurable windows, or fixed displays dedicated to specific functions, or a combination of the two. Fig. 28 illustrates a representative GC display consisting of sensor image, navigation display, sensor control, system settings and status, navigation waypoint management and primary flight display.

2.8.2. Sense-and-Avoid

Sense-and-Avoid (SAA) is a key requirement for RPAS to operate alongside manned aircraft in unsegregated airspace. A number of concepts (such as JADEM [106], MuSICA [107] and ACAS Xu [108]) have emerged in the literature as extensions of existing ACAS. From a HFE perspective, the HMI design needs to assist the flight crew in detecting possible traffic conflicts as well as to provide appropriate decision support for the avoidance of these conflicts. The HMI used for RPAS SAA are similar to the CDTI concepts used on-board civil flight decks.

The Vigilant Spirit Control Station (VSCS) [109] simulation environment was used to explore possible SAA display concepts, such as the Omni Band depicted in Fig. 29. In the figure, the host platform is represented by a hollow cyan arrow and the intruder platform is represented by a solid yellow arrow. A colour-banded ring around the host platform is used to represent various flyable headings, represented as yellow, green or red bands. The red band indicates no-fly headings, which if flown, would result in a possible loss of well-clear with the intruder platform. The yellow bands comprise dashed and solid portions, which represent different thresholds on the minimum separation distance. The green portion of the Omni Band indicates the safe headings, which if flown, would either prevent or resolve a loss of well-clear.

Fig. 30 depicts another possible SAA HMI concept based on conflict probes [111]. The conflict probes are depicted as yellow and red contours

Table 3
RPAS "Aviate, Navigate, Communicate and Manage" tasks.

Tasks	Nehme, 2007 [103]	Ashdown, 2010 [104]	Peschel, 2015 [100]	Ramos, 2016 [105]
Aviate and navigate	– Optimal position supervision	Vehicle operation –	Tele-operation of vehicle Navigation	Aircraft command and control
Communicate	Negotiating with and notifying relevant stakeholders	Communications	Communications with other teams	Voice communications Dissemination of payload products
Manage – systems	Monitoring RPA health and status Monitoring network communications Monitoring payload status	Vehicle systems management Payload systems management	Monitor technical condition of vehicle Payload delivery Sensor operation	Aircraft systems monitoring Data link command and control Payload command and control
Manage - data	Analysing sensor data Monitoring for sensor activity Positive target identification Tracking target	Payload data management Data processing Target detection	Visual inspection and tactical direction	Exploitation of payload products
Manage – mission	Resource allocation and scheduling Path planning supervision	Asset tasking Scheduling Route planning Sensor coverage planning	Strategy, planning and coordination	Mission planning and replanning

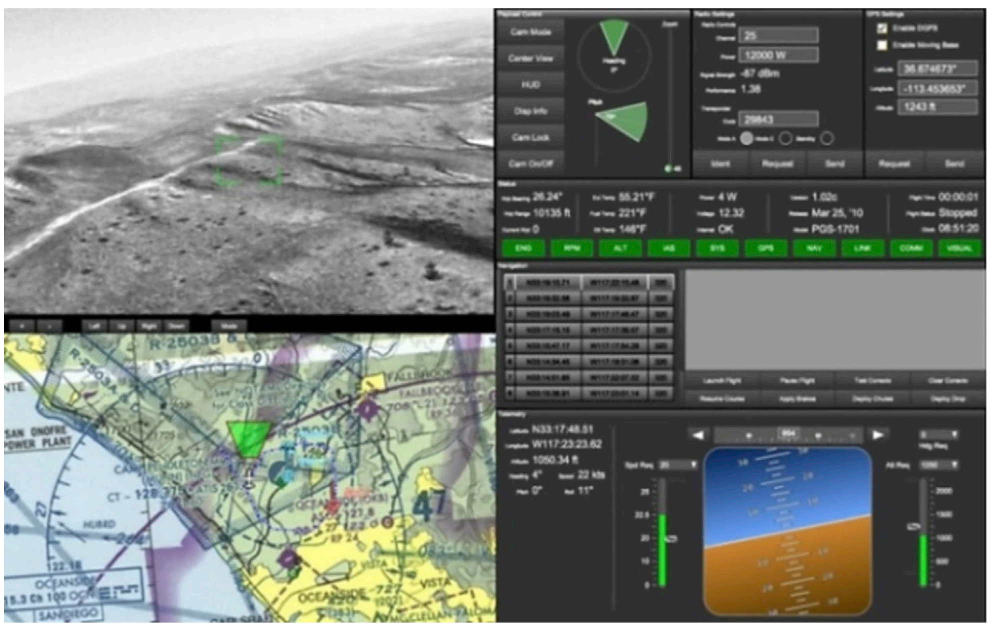

Fig. 28. Representative GC display with reconfigurable MFD, image courtesy of Presagis (http://www.presagis.com/solutions/RPAS_ground_control_station/).

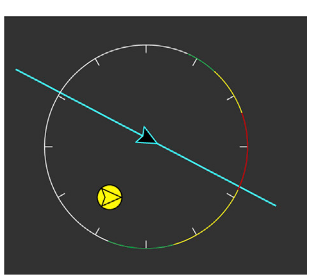

Fig. 29. Omni Band display concept, adapted from Ref. [110].

in both the TSD and VSD, representing potential areas where a future loss of separation might occur. The size, shape and position of the probe contours vary with the intruder's distance, the rate of closure (dependent on the relative speed between the host and intruder aircraft), as well as the time to the closest point of approach. The probe contours indicate either violation (yellow) or collision (red) hazard criteria. Solid contours indicate regions lying on the host platform's current flight path, while transparent probes indicate regions which do not. Similar to the Omni Band concept, information is presented on the CDTI-type display; colour banding (red and yellow) is used to indicate no-fly headings and altitudes. General Atomics Aeronautical Systems, with support from Delft University have been utilising the conflict probe display as part of ongoing research and development activities with NASA and the FAA, including recent flight test campaigns on NASA's Ikhana RPAS platform [112].

2.8.3. Mission planning and management

GC functionalities are also required to support pre-flight mission planning and management. Some functions include:

– Designating primary and secondary mission objectives;
– Flight planning and trajectory optimisation based on mission objectives, using inputs from airspace and terrain databases, as well as weather and traffic forecast information;
– Risk analysis of any potential damage to personnel and property as well as potential loss of satellite navigation or communication links;
– Generation of contingency plans;

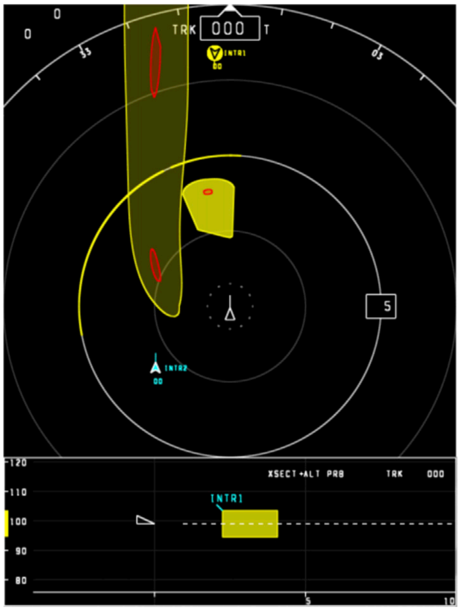

Fig. 30. Conflict probe display concept, used with permission from the authors [113].

– Database of local airspace and regulations;
– Requesting and obtaining operational approvals, permissions and clearances from relevant parties;
– Performing pre-flight rehearsal and simulations.

Fig. 31 shows an example of a mission safety assessment and contingency support tool. The tool allows both RPAS and ATM operators to evaluate the safety of a flight plan based on population, weather, airspace and traffic inputs. Decision support tools are included to help users identify possible contingency options and routes.

Fig. 32 shows an example of mission planning software for photogrammetry-specific missions. A terrain database is used to support route and payload (camera) planning. No-fly zones can also be designated as part of the mission planning process. Pre-flight rehearsals can be performed through software simulations.

2.8.4. Multi-platform coordination

The coordination and control of multiple RPA platforms is an ongoing area of research. The main HMI[2] challenges revolve around appropriate presentation of information to human operators, as well as the delegation of tasks and responsibilities between the human operator and various automated/autonomous functions. The different types of multi-platform coordination include, but are not limited to:

– Swarming, where multiple autonomous platforms are capable of self-organizing and are typically commanded as a number of homogeneous entities;
– Single-operator, multi-platform management of a number of heterogeneous platforms, with platforms typically having different capabilities, performance limits as well as overlapping/interdependent goals, and are separately managed;
– Multi-operator, multi-platform management, requiring humans to collaborate and coordinate their tasks and actions, possibly over large geographic distances.

Table 4 further elaborates on these operational concepts. Moving across the columns of the table from the left to the right, it can be observed that there are increasing interactions between different entities (either mechanical or human), which reflects a correspondingly increasing level of complexity. The top and bottom rows illustrate different operational and HMI concepts, with multi-platform operations implicitly requiring higher levels of platform automation. Compared to single platform operations, which uses interfaces that are designed from the pilot's perspective, the interfaces designed for multi-platform operations can draw inspiration from elements of ATC, ATM or UAS Traffic Management (UTM) displays to assist remote operators in supervising and managing multiple RPA platforms [116]. A number of HMI concepts for multi-platform operations are briefly presented in the following paragraphs.

The HMI illustrated in Fig. 33 allows RPA crew members to toggle between different views. The views include a third-person auto-stereoscopic display for mission management, or a first person mode for piloting/payload operation. Sidebars and tabs allow relevant flight and mission parameters to be displayed, while minimizing clutter when the information is not required.

The VSCS HMI in Fig. 34 contains a vehicle alert and summary tool in left sidebar, which allows operators to monitor the parameters of a number of RPA platforms and to assume control of the selected RPA. The right and bottom sidebars provide additional features for commanding and managing the tasks and objectives of each platform. These dedicated sidebars are used to avoid pop-ups and overlays that could obscure important information, as compared to "heads-up" concepts (e.g., Figs. 33 and 36) that seek to avoid moving the operator's gaze away from the area of interest.

The HMI in Fig. 35 contains different windows (called vantages) supporting multi RPA control. The task and status vantage summarizes important aircraft status and task information. The workload management vantage provides a summarized timeline display of upcoming tasks. An expanded timeline vantage provides additional detail on aircraft sortie events. The quick views vantage offers a filtered view of upcoming tasks according to the task type.

Glyphs have also been proposed for enhancing operator situational awareness through representing information in a more compact manner. Glyphs are avatar-like icons, with dynamically-changing visual attributes to provide operators with platform or mission-specific information. For example, the glyph depicted in Fig. 36 contains six attributes: mission type, platform automation mode, mission status, fuel status, payload information and call sign. As glyphs depict information in a simplified graphical manner, the need for explicit textual information is reduced, therefore reducing unnecessary clutter. When depicted on a tactical display, glyphs can be co-located with the platform position, reducing the need for operators to scan between different displays in order to obtain necessary information. Additionally, dynamic changes in the visual attributes of glyphs provide salient cues of system state changes and allow adaptive alerting functions to be integrated within the glyph portrayal.

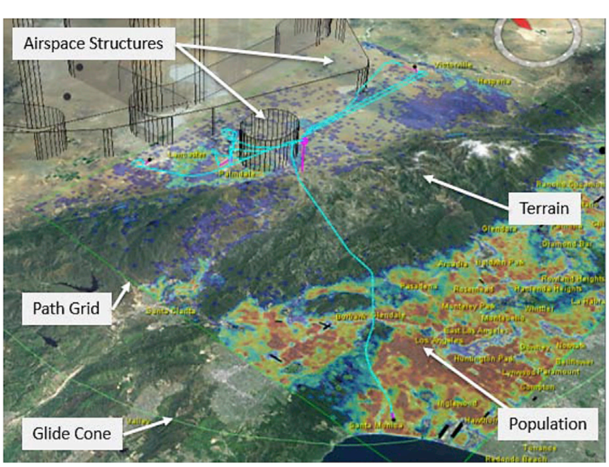

Fig. 31. Contingency route generation using the Aviate flight planning toolbox. © 2016 IEEE. Reprinted, with permission, from Ref. [114].

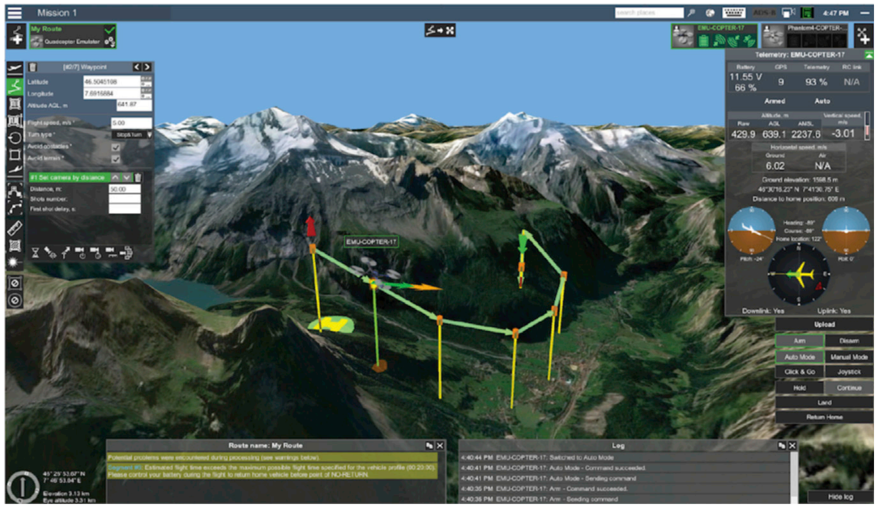

Fig. 32. RPA mission planning software – UgCS, developed by SPH Engineering (www.ugcs.com) [115].

Table 4
Different concept of operations in RPAS operations and their associated HMI^2 concepts.

	Single Remote Operator	Multiple Remote Operators
Single Platform Ops	Concept of operations (1) – Manual piloting of low complexity platforms (e.g., micro and very small RPA) possessing low automation. Concept of operations (2) – Management of highly complex platforms (e.g., MALE, HALE) possessing high automation. HMI^2 concepts (1) – Manual piloting interfaces can range from handheld units to larger workstations; – Parallels can be drawn with single-pilot general aviation flight decks. HMI^2 concepts (2) – Multifunctional displays are used to monitor different subsystems; – Some degree of adaptiveness as operators can switch between different windows; – Separate windows are typically used for mission planning, navigation, flight and electrical/ engine systems; – Parallels can be drawn with single-pilot military cockpits.	Concept of operations – Control of highly complex RPA possessing low automation; – Each operator assumes a different functional roles (ref Table 3). HMI^2 concepts – Currently, each human operator fulfils a specific functional role; – HMI are tailored to specific roles; – Parallels can be drawn with multi-crew flight decks.
Multiple Platform Ops	Concept of operations (1) – Swarming, where multiple platforms are commanded as homogeneous entities (either as a single entity or as multiple homogeneous entities). – The behaviour of the swarm can be controlled in a number of different ways [118]: • by selecting specific swarm characteristics, tactics or algorithms (e.g., through playbooks); • by directly controlling swarm leaders when more precision is required. Concept of operations (2) – Management of multiple platforms, where each platform is treated as an individual entity; – Platforms could be either homogeneous or heterogeneous; – Parallels can be drawn with air traffic control stations. HMI^2 concepts (1 and 2) – Offline mission planning, modelling and simulation; – Online mission status monitoring, task management and tactical re-planning; – Enhanced or synthetic vision, conformal overlays and multi-platform data fusion; – Ability to monitor, query and assume control of different platforms; – Compact, glyph portrayal of information [96]; – Intuitive presentation of information, including adaptive decision support and automated decluttering; – Multimodal controls, possibly including tactile, speech, gaze and haptic elements; – Operator performance monitoring and modelling.	Concept of operations – Coordination of RPA possessing high complexity and autonomy/ automation; – Tasks can be dynamically reallocated between different operators; – Introduces elements of network-centric operations; – Information management and collaborative decision making. HMI^2 concepts – Greater focus on information management; – Can feature separate workstations whose authority is decomposed into either: • Functional roles (paralleling satellite constellation control centres); • Geographic sectors or platform clusters (paralleling air traffic flow management centres).

3. Human Factors Engineering considerations

The human factors of systems design span a broad range of design elements. One area the human factors practitioner is concerned with is the design of human-machine interfaces (i.e., the medium where information is exchanged between the human user and the system) and interactions (i.e., the manner in which information is exchanged) occurring at the interface. The design of human-machine interfaces tends to be associated with physical characteristics of the display, the content, format, timing and duration of information presented to the user (visual, auditory, haptic or otherwise), as well as the modality of user inputs to the system. The design of human-machine interactions is associated with

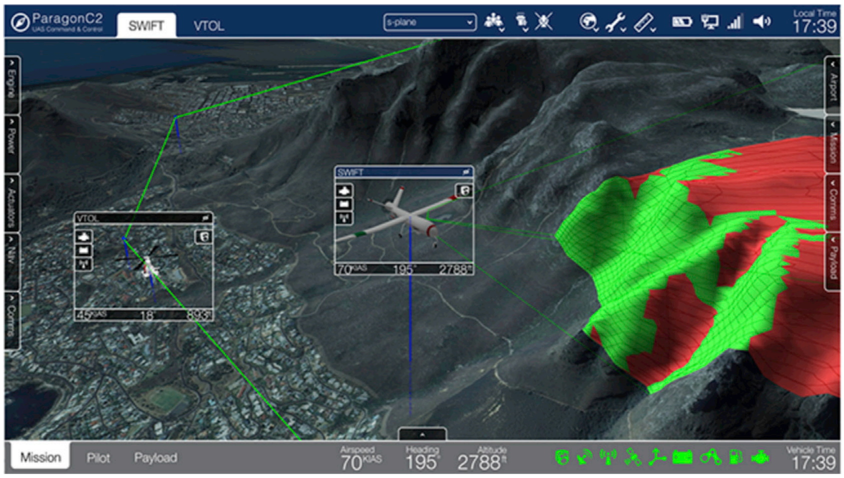

Fig. 33. An example of a third-person display for multi-platform management. Image by S-PLANE Automation: www.s-plane.com.

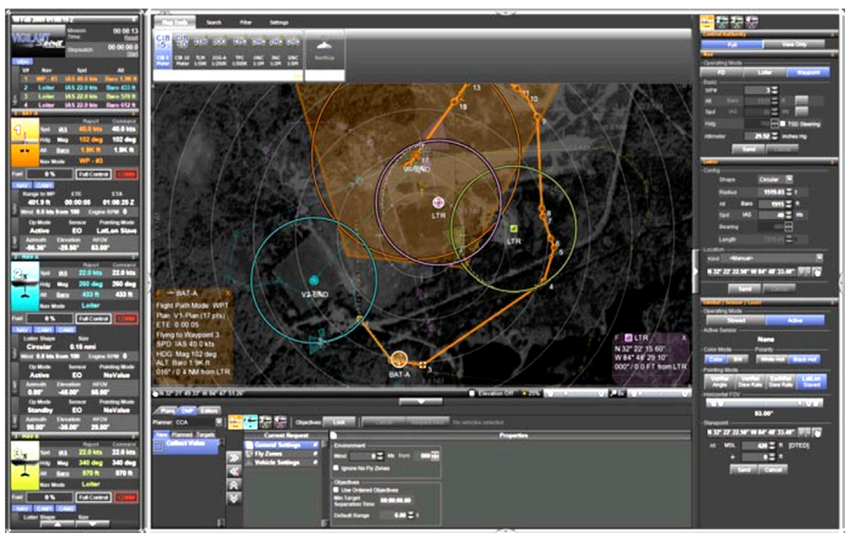

Fig. 34. Illustration from Vigilant Spirit Control Station, from Ref. [117] (image used with permission from Springer).

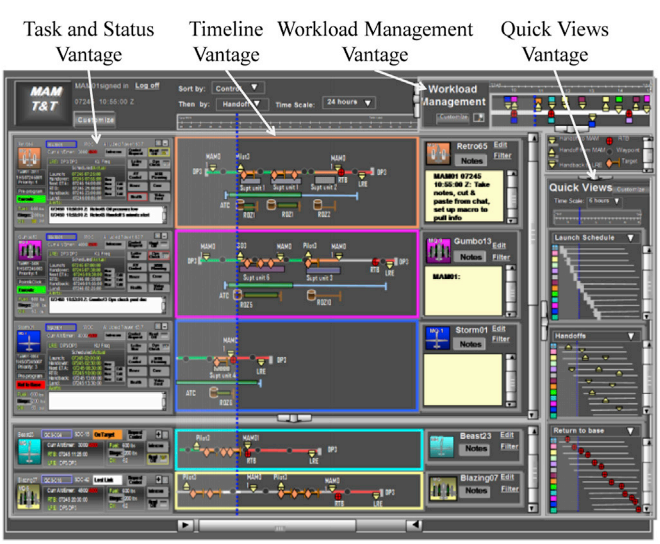

Fig. 35. Multi Aircraft Manager Tasking and Timeline Display, image used with permission of the author [119].

the dynamic behaviour of the system, such as the work/information flow, as well as interface adaptations to user input or external conditions. Well-designed HMI^2 supports appropriate user trust in operations involving higher levels of system autonomy, thereby increasing overall performance in terms of efficiency and safety. The following sections present an overview of the HFE design elements typically considered in avionics systems design; the reader is referred to [120–122] for more comprehensive guidelines.

3.1. Physical characteristics

Physical characteristics encompass many HFE considerations, including the operating environment, the design of the pilot's workstation as well as the hardware used for the actual interfaces. The workstation design considers the layout and placement of consoles and work surfaces such that the operator can perform his/her task effectively and comfortably. Design elements include consideration of pilot anthropometry (space clearances, physical reach and line of sight); environmental stressors (ambient temperature, humidity, lighting, air quality, noise, vibration and motion) as well as safety (risk of accident and threat to pilot). Physical characteristics of the interface are used to describe the

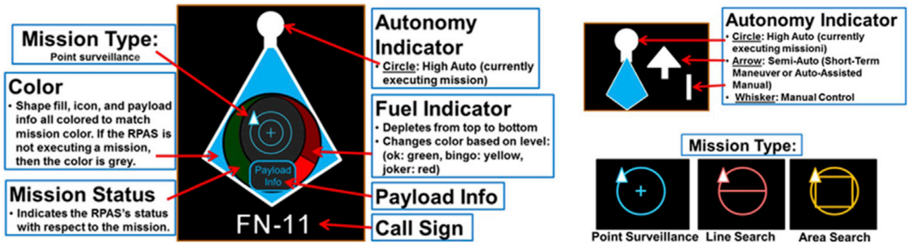

Fig. 36. Glyph portrayal of RPA information, from Ref. [96]. Copyright © 2017 by John Wiley Sons, Inc. Reprinted with permission from John Wiley & Sons, Inc.

quality of visual, auditory or haptic feedback presented to the pilot. The readability of information is affected by display considerations such as its size, resolution, luminance, glare, dimming, contrast, chromaticity, responsiveness and refresh rate. Auditory displays can be used to direct the pilot's attention to events requiring an immediate response. Auditory displays can refer to either message annunciations or auditory signals. Auditory signals are characterised by their frequency (pitch), intensity (loudness), duration and spatial location.

3.2. Display elements: colour

The use of colour directs pilot attention to useful pieces of information, aiding visual search in complex and dense displays. Colour can be used to draw pilot attention, convey meaning (through colour-coding), or to associate between spatially-separated information elements. Whenever possible, colour-coding should be consistent and standardized across all displays. The established convention reserves red, amber and yellow for flight crew alerting, while green is used to indicate normal or safe operating conditions. Use of red, amber and yellow for functions other than flight crew alerting must be limited to prevent users from becoming desensitized to the meaning of the colours, ultimately resulting in slower response times or confusion when alerts are presented. Blue should be avoided due to its low luminance and its similarity to yellow. Colour-coding is usually accompanied by another distinctive coding parameter (e.g., size, shape, location, etc.) as a form of redundancy. This is important because approximately 1 in 12 males and 1 in 200 females have some form of colour blindness. In addition, colour discrimination may be poor due to other operational considerations such as ambient light, solar glare, light filtration, etc. It is not recommended to colour code objects with different shades of the same colour. Additionally, overuse of colour should be avoided to reduce visual clutter, enhance display legibility and reduce impact on user memory. It is considered good practice to use at most six colours for colour-coding. Colours should be distinguishable from each other across the range of operating conditions (e.g., avoid the use of green on white, yellow on green, or blue/red on black). Bright or saturated colours can be used to draw attention to the display but can cause eye strain and interfere with the readability of other flight deck instrumentation (e.g., avoid the use of saturated red and blue).

3.3. Display elements: symbology

Similar to the use of colour, symbol design should enforce consistency, distinctiveness and saliency. The use of different symbols for the same purpose (or the same symbol for different purposes) might lead to confusion or misinterpretation. To maintain consistency, it is recommended for designers to make use of existing symbol sets. Symbol modifiers (such as colours, fill and borders) can be used to convey multiple levels of information but should also be consistent to guidelines and across the design. The design of symbols and their level of detail in displays affect their distinctiveness and saliency. The level of detail in symbols is influenced by the display characteristics, which can include display resolution, contrast, brightness, colour and rendering techniques. Designers may need to specify a minimum size for symbols to ensure that the symbol's key features are preserved on electronic displays. Symbols with high levels of detail run the risk of losing distinctiveness when symbol modifiers are introduced. FAA conducted a study on the use of symbology for navigation aids, airports, lines and linear patterns across nine avionics display manufacturers and four chart providers [123]. The study also investigated the use of symbol modifiers to convey different levels of information (e.g., fly-over vs. fly-by, compulsory vs. on-request). Subjects experienced more difficulty identifying symbols with more detail (e.g., NDB, VORTAC, Waypoint) than symbols with less (e.g., DME, VOR, Fix) [124].

3.4. Display elements: organization of information

Multiple sources of information, such as traffic, weather, terrain, navigation aids or flight procedures can be shown on integrated displays but require adequate organization to prevent clutter and confusion. Information can be organized by importance (e.g., the colour coding and symbology used to depict traffic information on a ND), function, logical flow, sequence of use, or any combination of the four. Display elements include windows, pages, menus and pop-ups. Windows are well-defined areas within a display dedicated to specific functions or applications. Multiple windows should be avoided for displays with small screen size, low screen resolution or slow processing speed. Each window can contain one or multiple pages, sometimes referred to as display formats, with each page displaying the relevant function or task-related information (e.g., the EICAS display contains dedicated pages showing information on the engine, electrical, hydraulic, flight control and environmental control systems). Menus allow the flight crew to switch between different pages, activate system functions or toggle the visibility of display elements. Menu layouts may be characterised by the number of levels (depth) and the number of choices at each level (breadth). Complex menu layouts can hinder the flight crew in accessing desired information. Generally, menus should not require flight crews to traverse more than three levels. Frequently performed tasks should require no more than two levels of transitions [120]. Pop-ups are alerts triggered by conditions and are meant to attract the flight crew's attention. Pop-up information can appear as overlays or separate windows. Three main techniques for organizing information are by overlaying (e.g., weather, navigation, airport and traffic information on a ND), time-sharing (e.g., switching between system information and flight planning pages) and concurrent display (e.g., a ND containing both horizontal and vertical situation indicators).

3.5. Alerting

The term 'alerting' is used in a generic sense to cover all types of alerts, ranging from general annunciations of mode changes or operating status, to off-nominal indications that require immediate pilot action. The implementation of alerting functions within a flight deck is guided by the following considerations [125]:

– The reason for implementing an alert;
– The level of alert required for a given condition
– The characteristics of each specific alert;

– Integration of multiple alerts.

Alerts serve the purpose of directing the attention of the flight crew to particular events as well as providing relevant information to support the flight crew's situational awareness of the event. An alerting function comprises the presentation of the alert, the sensed condition triggering the alert, as well as the information processing leading to the presentation of the alert. These three components should all be designed to support the purpose of the alerting function. Alerts are categorized into warnings, cautions or advisories, according the urgency of awareness and response required from the pilot (Table 5).

Alerting systems can present a combination of visual, audial, or haptic information to the operator. Warnings and cautions usually include a combination of visual and audial elements. A consistent alerting philosophy should be present in the design of all alerts – consistency should be enforced for the prioritisation, inhibition and recall of alerts as well as the alert presentation format. Alerts should also be designed to avoid false and nuisance alerts while providing reliable and accurate alerts to the flight crew. Alerts should be managed with a prioritisation scheme. The prioritisation scheme should take into account the urgency of flight crew awareness and response as well as the alert modality. The prioritisation scheme should show that any delayed and inhibited alerts do not adversely impact safety. If multiple alerts are presented at the same time, they should be clearly distinguishable and understandable to the flight crew, as well as presented in a hierarchy to show the common root fault.

3.6. User controls and inputs

User controls comprises the set of inputs, devices and surfaces that provide the user with control of the system; these might include buttons, knobs, levers and switches, as well as keyboards, mouse, joystick, touchpad, or voice activated systems. The key considerations in the design of a control interface include the design of control's physical characteristics (shape, dimensions, surface texture, range of motion, colour); placement (location, orientation, arrangement, accessibility, visibility); function (purpose, mode of actuation, effect on the rest of the system); and user interaction (feedback, control options, method of operation). In particular, touchscreen technologies are emerging as alternative input channels for the HMI of GA and business aircraft. Novel human-machine interactions such as touch gestures, multi-touch, stylus input, gaze input and voice input have the potential to supplement current forms of input with more natural and intuitive methods. The drawbacks associated with these input modalities should also be noted, such as decreased input precision and speeds, inadvertent activation, as well as physical fatigue or accessibility issues associated with current touch interfaces [126].

4. Adaptive HMI^2 concepts

Adaptive HMI^2 are able to assess the context and needs of the user based on passive or implicit inputs, dynamically reconfiguring itself to provide the required support. This is distinguished from adaptable HMI^2, where the authority for reconfiguration and task delegation is held by the human user [127]. While current HMI^2 do afford some level of adaptability, the increasing complexity of future operations, both civil and military, will require future systems to have more advanced adaptive functions. This is supported by Billings [128] and Parasuraman [129], who both argue that while higher levels of automation are required to support future operations, the nature of automation needs to be user-centric and adaptive to the needs of the human user. This section provides a general review of some of the adaptive system concepts that have been proposed in the literature. Most of these concepts are based on the idea of associate systems, which are analogous to virtual assistants providing human-like assistance to the flight crew.

Table 5
Alert categories, from Ref. [120].

Category	Awareness	Response
Warning	Immediately required	Immediately required
Caution	Immediately required	Subsequently required
Advisory	Required	Not mandatory

4.1. Super Cockpit

Furness proposed a concept in the 1980s termed the Super Cockpit [130]. The Super Cockpit augments information management in the cockpit through advanced sensing and forms of augmented reality. The pilot's state is monitored using hand, eye and head tracking systems, which is sent to a knowledge-based inference engine to assess pilot intent. The inference engine is used by an intelligent associate system to adapt the presentation of information to the pilot through visual, audio and tactile feedback, as well as to dynamically reconfigure various control modes (e.g., head-aimed control, voice-actuated control, touch-based control, virtual hand control). The cockpit interfaces are based on the concept of a virtual world, which provide an immersive 3-dimensional environment to fully utilise the multimodal senses of the pilot. For example, 3D audio signals provide directional cues for incoming threats, while a 3D visual scene allows information from the data bus (e.g., sensors, threat warning system, terrain map, weapon delivery, etc.) to be presented in a format relevant to the location of the information source.

4.2. Pilot's Associate

The Pilot's Associate (PA) program was initiated by DARPA in the 1980s and 90s [131,132]. The PA program investigated the use of associate systems for supporting information management in fighter pilot cockpits. The PA system uses cooperating, knowledge-based subsystems to filter data, help with time-critical decisions and assist different aircraft subsystems. The PA comprises two assessor subsystems (situation assessment and system status assessors) and two planning subsystems (tactics and mission planners) as well as a Pilot/Vehicle Interface, which manages the flow of information between the pilot and the PA. The situation assessment subsystem manages information from aircraft sensors and external sources to keep track of air and ground objects, assessing different attributes such as the lethality, intent, priority and impact as well as the uncertainty associated with each attribute of the different targets. The system status subsystem manages aircraft systems to detect and diagnose faults, provide corrective measures and evaluate the mission and tactical plans relative to aircraft performance limitations. The tactics planner assesses targets/threats for evasion/attack and coordinates with the situation assessment subsystem to monitor high-interest threats. The tactics planner suggests tactics to the pilot, adapting specific tactics parameters based on the dynamic situation. The mission planner functions as a route optimiser for generating mission routes based on different parameters such as the threat environment, tactical needs as well as aircraft performance. The PA was showcased in a number of demonstrations [133] and was the basis of the US Air Force's Rotorcraft Pilot's Associate [134] program. Additionally, there has been recent interest in applying lessons learnt from the PA to the design of a RPA Pilot's Associate [135].

4.3. Pilot/Vehicle Interface

The Pilot/Vehicle Interface (PVI) [136] was developed in the mid-1990s and was integrated into the Synthesized Immersion Research Environment (SIRE) at the US Air Force Armstrong Laboratory. The PVI interfaces with a situation assessor and workload estimator to reconfigure and adapt the pilot display. The situation assessor receives aircraft system and external environment inputs from the avionics system while the workload estimator provides an aggregate indicator of the pilot state based on inputs from the situation assessor as well as the pilot's physiological state. The indicator is then fed to an expert system utilising knowledge bases of human performance and display configuration to adapt the PVI to given situations.

4.4. Cockpit Assistant System

The Cockpit Assistant System (CASSY) was developed in the mid-1990s as an assistant and alerting system for IFR pilots [137]. CASSY monitors aircraft systems, aircrew behaviour, manages the flight plan and issues warnings during abnormal situations. CASSY comprises a number of modules that interface with the crew, aircraft systems and air traffic control. These modules include the dialogue manager, automatic flight planner, piloting expert, pilot intent and error recognition as well as monitoring and execution aid modules. The dialogue manager interfaces between CASSY and the aircrew, selecting appropriate advisories and conveying it to the crew via speech and/or graphic display, as well as picking up inputs from the crew and directing them to other modules within CASSY. The automatic flight planner is responsible for generating the flight plan, assessing the situation for possible conflicts and conducting replanning as required. The piloting expert is responsible for modelling pilot behaviour. Modelling was done with petri nets and comprises a situation assessment component (i.e., recognition of flight segment and the progress of plan execution) as well as an action management component (i.e., modelling of pilot primary flight guidance; operation of flaps, landing gear and speed brakes; radio navigation; and communication with air traffic control). The pilot intent and error recognition module compares the expected pilot behaviour with the actual pilot behaviour. In case of a deviation in behaviour, the module infers if the pilot behaviour is erroneous or intentional and issues advisories if the behaviour is erroneous while making necessary flight plan modifications if the behaviour is intentional. The monitoring sub-modules are responsible for monitoring flight progress, system status as well as the surrounding traffic and weather conditions. The execution aids provide a variety of optional service functions that are controlled by the crew via speech. CASSY was first evaluated in a simulated environment with scenarios involving flight planning and re-routing [138]. CASSY was also later evaluated in flight tests for IFR operations between a number of regional German airports [138]. A military version of CASSY, the Crew Assistant Military Aircraft (CAMA), was later developed by the German Department of Defence [139].

4.5. Cognitive Cockpit

The United Kingdom (UK)-based Defence Evaluation and Research Agency (DERA) initiated the Cognitive Cockpit (CogPit) [140] project in the late-1990s. The CogPit project exploited lessons learnt from the PA programme (Section 4.2) to develop adaptive automation based on interacting knowledge-based systems. The CogPit is based on four modules: a Cognition Monitor (CogMon), a Situation Assessment Support System (SASS), a Tasking Interface Manager (TIM) and the cockpit that interprets and executes display modifications (CogPit). The CogMon monitors the pilot's physiology and behaviour to provide an estimation of pilot state (e.g., G-induced loss of consciousness, spatial disorientation or loss of situational awareness). The SASS assesses the aircraft and external situation to provide rule-based-decision aiding information. The CogMon and SASS interact with the TIM, which is responsible for tracking, prioritising and planning tasks. The TIM coordinates with the CogMon and SASS to trigger changes within CogPit, such as replanning or updating the mission, deciding automation levels and automating tasks.

4.6. Augmented Cognition

As an evolution of the PA (Section 4.2), DARPA initiated the Augmented Cognition (AugCog) program in the 2000s, which focused on incorporating neurophysiological assessment techniques in the design of associate systems (a comparison between the PA and AugCog projects is presented in Ref. [141]). The program was conducted in two-phases and involved stakeholders from industry, universities and government. Phase I of the program [142] explored the use of different sensors as cognitive gauges while phase II of the program [143] proposed and validated a number of systems for land, sea and air military applications. Cognitive processing bottlenecks were established to provide performance goals for evaluating the success of each system.

4.7. Cognitive Avionics Toolset

The Cognitive Avionics Toolset (CATS) [144] was developed by the Operator Performance Laboratory (OPL) at the University of Iowa with support by NASA Langley and Rockwell Collins. CATS employs a multi-sensory data fusion approach in assessing the operator's cognitive load. The toolset also allows researchers to organize and process incoming data from multiple sensors. The system framework includes sensor and filters to extract features from and array of sensors including: ECG, respiration, skin resistance, blood oxygenation, eye tracking, face temperature, EEG, as well as control inputs and environmental parameters. A neural network then uses the features as inputs to provide a classification of operator load. CATS also comes with a graphical user interface for monitoring, querying, analysing and processing sensor data. Recent work by the OPL has included the integration and validation of CATS into a Cognitive Pilot Helmet for real time measurement of pilot workload in training [145] and operational scenarios [146]. CATS has also been used to study the effects of fatigue on pilot engagement [147] and to evaluate simulator fidelity [148]. The research from CATS has also supported the development of a committee machine-based classifier for operator cognitive state [149,150].

4.8. Alerting and Reasoning Management System

The Alerting and Reasoning Management System (ALARMS) [151] was the product of a collaboration between Aptima Inc, Science Applications International Corporation (SAIC) and NASA. ALARMS uses a pilot performance model to select appropriate levels of automation and hazard alerts. Workload is modelled as a linearly weighted sum of three factors: mental effort, task demands and ongoing task performance. The factors are estimated from a number of measures, including physiological, subjective, task and performance measures. The modelled workload is then used to predict the expected performance quality and duration using a Time-Dependent Markov Decision Process (TMDP).

4.9. Intelligent Adaptive Interface

Defence Research and Development Canada developed an Intelligent Adaptive Interface (IAI) framework to support the command and control of multiple RPAS [152]. The IAI uses an agent-based architecture composed of four components: a situation assessment and support system, an operator state assessment system, an adaptation engine and an operator machine interface [153]. The situation assessment and support system uses a knowledge base to monitor the mission, aircraft systems and the environment while the operator state assessment system monitors the operator's psychological, physiological and/or behavioural state. Both these systems interface with the adaptation engine, which relies on a knowledge base to compare the situation assessment and operator state inputs and adapt the operator machine interface. The IAI agents were evaluated with human-in-the-loop experiments involving multi-RPAS command and control [154]. The IAI was also integrated into a RPAS GCS simulation tool to explore the effects of multi-modal display on supervisory control [153]. Planned verification activities also involved the control of multiple micro aerial vehicles in an urban environment [155].

4.10. All Condition Operations and Innovative Cockpit Infrastructure

The All Condition Operations and Innovative Cockpit Infrastructure

(ALICIA) project was funded by the European Union (EU) 7th Framework Programme (FP7) [52], aimed at developing new and scalable cockpit architectures, which can extend flight operations in a wider range of degraded conditions such as weather disturbances [156] or ground perturbations. The project addressed HMI solutions in four main areas: navigation, surveillance, cockpit display and multi-modal input/output technologies. Evaluated concepts included head mounted/head up displays, touch/cursor/keyboard interfaces [34,51,157,158], voice inputs, 3D auditory displays as well as passive/active sensors.

4.11. Advanced Cockpit for Reduction of Stress and Workload

The Advanced Cockpit for Reduction of Stress and Workload (ACROSS) [159] was another project funded by the EU under FP7. The goals of ACROSS were to develop cockpit solutions for reducing peak workload during off-nominal scenarios, as well as for facilitating reduced crew and single pilot operations. The development of systems primarily addressed the six functional areas of aviate, navigate, communicate and manage systems, crew monitoring and crew incapacitation [160]. One of the challenges the project addressed was the integration of different cockpit technologies using an integrated human factors approach [161,162]. A virtual-reality flight simulator was used to evaluate different operational scenarios and HMI concepts [163,164]. The workload reduction solutions proposed in ACROSS included: crew monitoring systems incorporating functional Near Infrared Spectroscopy (fNIRS) imaging, heads up displays, radio management panels, weather awareness systems, as well as soft interface control panels.

4.12. Cognitive Man-Machine Interface

The Cognitive Man-Machine Interface (CAMMI) was a project based in Europe, which aimed at developing systems for adapting to the cognitive state of human operators. CAMMI comprises two interacting modules: a cognitive state assessment module for estimating the operator's cognitive workload, as well as a mitigation manager for adapting the HMI based on the measured workload and the context of the actual activity. As part of the CAMMI project, a Knowledge-Based System (KBS) was developed to support RPAS pilots in controlling RPAS swarms [165]. The cognitive monitor that was developed employs fuzzy logics to classify operator workload, using measures of heart rate, respiratory frequency, electro-dermal activity (EDA) and body temperature. The mitigation manager implemented four different strategies (modification of interaction, task management, automation assistance and offloading tasks to automation) for assisting the human pilot in the swarm management task.

4.13. Cognitive Pilot Aircraft Interface

The Cognitive Pilot Aircraft Interface (CPAI) [166] is a system concept supporting the transition from two-pilot to single-pilot operations [167,168]. CPAI comprises three modules providing sensing, estimation and reconfiguration functionalities. The sensing module acquires psycho-physiological data from the pilot, as well as environmental and operational data from the aircraft. The estimation module uses suitable human cognition and task models to predict the pilot's cognitive states. The reconfiguration module adapts the level of automation, display formats or alerts such that the HMI[2] complements the pilot's cognitive states. The proposed CPAI system is integrated within a Next-Generation FMS (NG-FMS) to support the retrieval of data from a number of NG-FMS subsystems, provide adaptive interface management as well as support the detection of pilot incapacitation and transition to autonomous flight. Numerical simulations were used to evaluate the CPAI operation in worst-case conditions and verify the implemented models. Ongoing research is addressing the application of CPAI functionalities to RPAS single and multi-platform operations [169,170].

5. Driving adaptations with human performance

There exist four broad techniques for assessing human performance: subjective assessments, task-based metrics, analytical models and psycho-physiological measures:

- Subjective assessments require the subject to assess his/her own performance through questionnaire-based feedback such as rating scales or structured interviews.
- Task-based metrics measure the subject's performance using parameters related to either primary or secondary task performance. The primary task refers to the main task, while the secondary task refers to an additional loading task performed on top of the primary task.
- Analytical techniques predict or diagnose specific aspects of human performance (typically related to flight handling qualities, human reliability as well as human cognition) using models developed from a combination of theoretical/expert knowledge, as well as empirical data.
- Psycho-physiological measures typically employ sensors for collecting the subject's physiological data, which are then translated into measures of performance using established psycho-physiological and analytical models.

These performance assessment techniques have been traditionally used to assess and evaluate the human factors considerations in new operational concepts, as well as to evaluate the design of systems and the suitability of their associated HMI[2]. The interactions between the four techniques are illustrated in Fig. 37. Analytical models are usually employed in modelling and simulation efforts, typically used in the early stages of an engineering design process to allow refinement of the initial design before actual human-in-the-loop (HITL) studies. During actual HITL studies, task-based and psycho-physiological measures are respectively collected from the evaluated system and the human user. Finally, subjective assessments are collected from the human user at the end of the HITL study through surveys, questionnaires or interviews. Task-based, psycho-physiological and subjective measures are used to evaluate human performance in the engineering design as well as to improve the analytical model, thereby completing the design loop. Some prominent reviews on the use of human performance assessment techniques and metrics can be found in Refs. [171–175].

As evidenced by the adaptive HMI[2] concepts presented in Section 4, ongoing research has been addressing the challenges of incorporating these techniques within systems possessing higher levels of intelligence and autonomy. Systems augmented with the capability to assess human performance can enhance human-machine teaming through performance-driven HMI[2] adaptation. Some emerging concepts include autonomous adaptive agents with human-like behaviour [176,177], as well as HMI[2] driven by operator workload or engagement [178–180]. While early concepts explored the feasibility of using task-based metrics to drive adaptation, there has been increasing focus on incorporating analytical and psycho-physiological measures. Such measures provide greater inference capabilities for intelligent systems and support

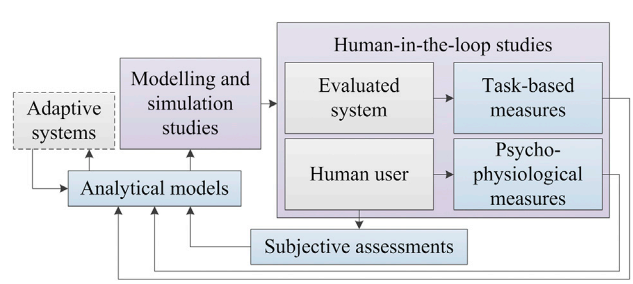

Fig. 37. Interactions between the different human performance assessment techniques.

interactions tailored to individual users. This section provides an overview of the different techniques, identifying salient aspects and focusing on emerging methods on modelling human cognition (such as cognitive architectures and psycho-physiological measures).

5.1. Subjective techniques

Subjective measures have been developed and used in human factors evaluations over the past half-century. Some subjective techniques include:

- Flight handling qualities: Cooper-Harper [181], Bedford [182] and Modified Cooper-Harper [183] scales;
- Workload: NASA Task Load Index (TLX) [184], Subjective Workload Assessment Technique (SWAT) [185], Subjective Workload Dominance (SWORD) [186], Rating Scale Mental Effort (RSME) [187], Workload Profile (WP) [188];
- Situational awareness: Situational Awareness Rating Technique (SART) [189], Situational Awareness SWORD (*SA-SWORD)* [190], Situational Awareness Rating Scales (*SARS*) [191];
- Usability: Software Usability Measurement Inventory (SUMI) [192], System Usability Scale (SUS) [193];
- Trust: Checklist for Trust between People and Automation [194], Trust Factor Survey [195], Human Robot Interaction (HRI) Trust Scale [196].

While subjective measures are easy to apply and are a widely accepted measure, they also have a number of disadvantages:

- Ratings are typically collected at the end of a task, and are thus insensitive to the dynamics of human performance during the task;
- Subjective ratings can be quite intrusive if collected during the task, since it requires users to pause their current task and/or divert their attention towards providing appropriate feedback.
- Since the ratings are based on subjective opinion, they might neither be a reflection of actual human performance, nor the constructs they intend to measure (e.g., workload measures may measure the perceived task difficulty rather than actual workload).

5.2. Task-based measures

Similar to subjective measures, task-based measures has also been the predominant means of assessing human performance in the past half-century (as compared to the newly emerging techniques of analytical models and psycho-physiological measures). Task-based measures can be categorized as either primary or secondary measures.

Primary task-based measures provide a direct assessment of human performance on the particular task. Within task-based measures, Gawron [197] identifies accuracy and time-related metrics. Accuracy measures include absolute error, root-mean-square error, error rate, percent error, deviations, false alarm rate, number correct, percent correct and correct to error ratio. Time measures include detection time, movement time, reaction time, search time, time to complete, glance duration and reading speed. Additional primary measures include behavioural measures captured from activity logging, such as mouse and keystroke dynamics [198]. The actual implementation of these measures depends on the specificities of the system, operational scenario and cognitive resource to be evaluated.

For example, the Situation Awareness Global Assessment Technique (SAGAT) [199] was developed by Endsley and has been used to evaluate the situational awareness of pilots [200,201] and ATM operators [202]. The three levels of situational awareness assessed are based on Endsley's model of situational awareness and comprise the perception of data (level 1), comprehension of meaning (level 2) and projection of the near future (level 3). Using SAGAT, a simulation is paused at randomly selected times to allow subject to respond to SAGAT queries regarding the current situation, providing snapshots of the subject's situational awareness.

Researchers have noted the artificiality of pausing a task in order to measure situation awareness, given that it disrupts normal behaviour and removes access to the information required to build and maintain the very awareness whose measurement is sought. This has been addressed using the Situation Present Assessment Method (SPAM), which Durso and his colleagues have used to measure situation awareness in air traffic control tasks [203,204].

While primary task-based measures are directly related to the task, secondary tasks are applied on top of a primary task as a measure of the operator's remaining mental or perceptual capacity. Depending on the scenario, the operator might be asked to maintain consistent performance on either the primary or secondary task, with his/her performance on the other task serving as a measure of human performance [205]. Secondary tasks can be selected based on the cognitive resource to be evaluated and can include [205]:

- Memory tasks (e.g., n-back, spatial association, etc.);
- Signal detection tasks;
- Mental arithmetic;
- Time estimation task;
- Number of concurrent tasks (e.g., NASA Multi Attribute Task Battery [206]);
- Tracking task (e.g., Jex tracking task [207]).

A distinction is made between standard secondary measures, which have been validated and operationally realistic secondary measures, which provide greater realism at the potential expense of internal validity. In selecting secondary measures, the researcher must consider trade-offs of these two types of measures (i.e., sacrificing realism for validity or vice versa).

5.3. Analytical techniques

Analytical techniques rely on models based on a combination of theoretical and expert knowledge, usually validated with empirical data, to predict operator performance. An overview of three classes of analytical techniques, namely, pilot control models, task analysis techniques and cognitive architectures, is provided in the following subsections.

5.3.1. Pilot control models

Pilot models are control theory-based models, typically used to analyse flight-handling qualities. Models can vary in complexity to account for pilot responses to different modes of control (e.g., proportional, integral, damped, etc.). Additionally, models can incorporate different aspects of pilot physiology (e.g., the nervous, neuromuscular, vestibular or visual systems) to estimate pilot delay or response times. The prominent models include:

- Crossover Model [208];
- Precision Model [208];
- Hess Structural Model [209];
- Hosman Model [210];
- Optimal Control Model [211].

New pilot models have been developed in more contemporary research to evaluate the effects of haptic and visual feedback on pilot control [212,213], multi-axis control tasks [214] and to detect and alleviate aircraft/rotorcraft pilot couplings [215]. Comprehensive reviews of control theory-based models can be found in Lone [216], Pavel [217] and Gennaretti [218].

5.3.2. Task analysis

Task analysis techniques are a set of techniques for analysing complex tasks. Task analysis techniques usually start with a decomposition of the main task into smaller subtasks. Depending on the focus of the analysis, different techniques are used in decomposing the main task and analysing the subtasks. Task analyses are used for identifying safety-critical tasks, possible sources of error and failure, as well as the cognitive demands of human-computer interactions associated with particular tasks. The key techniques include:

– Hierarchal Task Analysis [219];
– Critical Task Analysis [220];
– Cognitive Task Analysis [221–225];
– Cognitive Work Analysis [226–228].

Notable methodologies employing task analysis techniques in aviation include:

– Human Factors Analysis and Classification System (HFACS) [229], which is used to diagnose causes of human error, primarily in aircraft accident and incident investigation. HFACS has been used in commercial aviation [230], general aviation [231–234], military (DOD-HFACS [235] and Systematic Error and Risk Analysis – SERA [236]), maritime [237,238] and rail [239] accident and incident investigation.
– Human Error Template (HET) [240], which is intended to be used for the certification of flight deck interfaces. HET has been applied in a number of studies [241,242] to demonstrate its validity as a tool for flight deck design evaluation.

Task analyses have been widely applied in aviation human factors studies. Some applications include of task analysis include the analysis of interfaces and operational procedures associated with commercial aviation [243], single-pilot operations [244,245], RPAS design [246–249] and ATC/ATM [250–252].

5.3.3. Cognitive architectures

Cognitive architectures are computational models of human cognition and behaviour. Cognitive architectures typically incorporate analytical relationships from cognitive science to describe how human agents acquire, organize, retrieve and apply knowledge based on interactions with other human or autonomous agents, as well as the external environment. Cognitive architectures have applications in many fields of research (a broad overview of 195 cognitive architectures is found in Ref. [253]) but the more prominent ones (ACT-R, SOAR, ICARUS and PRODIGY) are reviewed in greater detail in Ref. [254]. The cognitive architectures that have been applied to aviation, reviewed in Refs. [255] and [175], include:

– Adaptive Control of Thought-Rational (ACT-R) [256];
– Air-Man-machine Integration Design and Analysis System (Air-MIDAS) [257];
– Attention-Situational Awareness (A-SA) [258];
– Cognitive Architecture for Safety Critical Task Simulation (CASCaS) [259,260];
– Distributed Operator Model Architecture (D-OMAR) [261].

Other notable cognitive architectures applied to aviation include:

– Architecture for Procedure Execution (APEX) [262];
– CogTool [263], an implementation of ACT-R;
– Improved Performance Research Integration Tool (IMPRINT) [264];
– State, Operator and Result (SOAR) [265];
– Trust-based situation awareness models such as the one proposed in Ref. [266].

Another cognitive architecture, though not yet applied to aviation, is the Adaptive, Reflective Cognition in an Attention-Driven Integrated Architecture (ARCADIA) [267]. ARCADIA is a computational model explicitly driven by visual attention, which is an important concept in aviation. ARCADIA is being used to investigate change-blindness [268,269] as well as attentive processes in multiple object tracking [270]. The designers of ARCADIA also plan to extend the architecture to model elements of auditory attention and memory.

Table 6 summarizes the cognitive architectures and their application to research in the aviation domain. Most cognitive architectures focus on assessing three main cognitive constructs workload, attention/situational awareness and task performance. A number of architectures (ACT-R, APEX, D-OMAR, SOAR) have been used in modelling more complex behaviour in agent-based simulations, such as decision making and emergent behaviour of interactions.

5.4. Psycho-physiological measures

Psycho-physiological measures have been used to assess human performance in aviation since the 1960s but are still considered an emerging field of research. An early report [307] noted the advantages of psycho-physiological measures:

– Does not require active input from human operators;
– Provides passive and continuous streams of data;
– Different measures provide a multi-dimensional view of human performance;
– Provides generalizable models that can be used across a broad range of tasks.

There are however a number of existing challenges that need to be overcome before psycho-physiological measures can become an established measure of human performance:

– Current sensors that need to be worn by operators can be intrusive and hinder operational effectiveness;
– Psycho-physiological models need to separate the different dimensions of human performance with appropriately-defined constructs (e.g., workload, trust, fatigue, situational awareness, etc.);
– The presence of sensor noise and artefacts which require the development of additional filtering algorithms;
– Extensive validation is required for these psycho-physiological models;
– Statistical validation techniques lack sensitivity to variances between individual operators;
– In order to improve the accuracy of a system, additional data is required to calibrate the system from an established baseline;
– Issues with user privacy and operator acceptance.

The key psycho-physiological measures can be categorized into three areas [308]: the central nervous system comprising brain activity; the cardio-respiratory system comprising heart and respiratory activity; and peripheral systems comprising eye, muscular and hormonal activity.

5.4.1. Central nervous system

The increasing commercial availability of mobile/wearable brain sensing devices (Fig. 38) has opened up many avenues for neuroergonomic research. Mehta [309] provides a review of nine neuroergonomic techniques for the evaluation of cognitive and physical states. Out of the nine, four were identified as the most promising due to their high portability, relatively low cost and low intrusiveness: Event-Related Potentials (ERP), Electroencephalography (EEG) spectral analysis, functional Near-Infrared Spectroscopy (fNIRS) and Transcranial Doppler Sonography (TCDS). An additional fifth technique discussed in this section is the Steady State Visual Evoked Potential (SSVEP) [310,311].

These five techniques can be divided into two categories according to the type of brain activity measured. The first category measures the brain's electrical activity (ERP [313], SSVEP [310], EEG [314]), while the

Table 6
Summary of cognitive architectures and their applications in the aviation domain.

	Workload	Attention/Situational awareness	Task performance	Decision making	Emergent behaviour
ACT-R [256]	ATM human-machine interactions [271]	Approach and landing scenarios [272,273] Taxi Operations [274]	Approach and landing scenarios [272,275] FMS training [276] ATM human-machine interactions [271]	Taxi Operations [274, 277]	–
Air-MIDAS [257]	NextGen operations and displays [278] ATM free flight concept [279] Big Airspace operational concept [280]	NextGen operations and displays [278] HUD evaluation [281] SVS evaluation [282]	NextGen operations and displays [278] ATM free flight concept [279] ATM human-machine interactions [283] Big Airspace operational concept [280]	–	–
APEX [262]	ATC handoff tasks [284]	–	Runway sequencing [262] ATC handoff tasks [285]	Runway sequencing [262]	–
A-SA [258]	–	Approach/landing scenario [258].	Taxi errors [258]	–	–
CASCaS [259, 260]	Advanced flight interfaces [286,287]	Advanced flight interfaces [286,288,289]	Advanced flight interfaces [286, 290]	–	–
CogTool [263]	–	–	Pilot-to-ATC communications [291]	–	–
D-OMAR [261]	–	Approach and landing scenarios [292]	Taxi Operations [293]	RPAS operations [294]	–
IMPRINT [264]	RPAS operations [295,296]	–	–	–	–
SOAR [265]	En-route air traffic controller behaviour [297]	Military simulations [298]	En-route air traffic controller behaviour [297] Target identification [299]	Naval command and control [300]	Flight deck interactions [301] RPAS operations [176,302] Military simulations [177, 298,303–306]

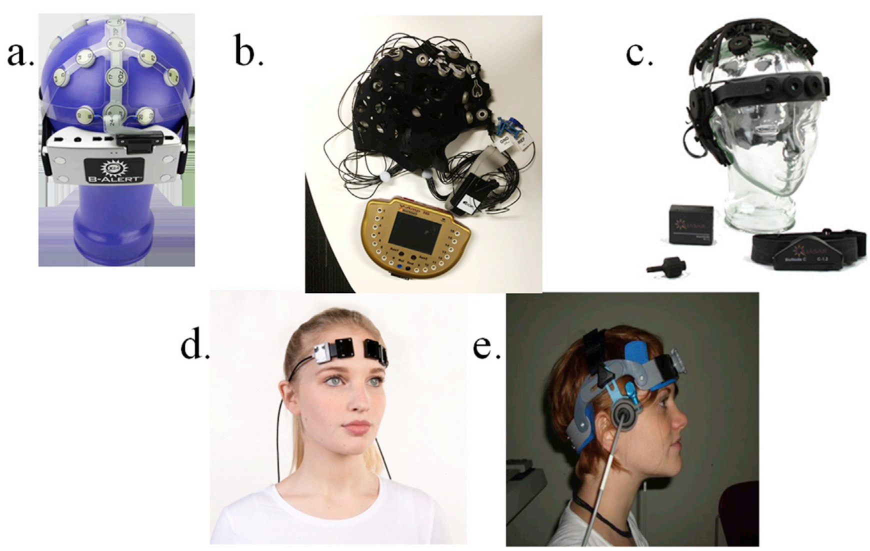

Fig. 38. EEG systems: (a) B-Alert X24 EEG System, Advanced Brain Monitoring, Inc, Carlsbad, California, USA; (b) *Brain Products* ActiCap Xpress; (c) DSI 10/20, Quantum Applied Science and Research (QUASAR) Inc., San Diego, California, USA. fNIRS system: (d) PortaLite, Artinis Medical Systems, Elst, The Netherlands. TCDS system: (e) *Welder* TCD headband (Image credit: David A. Washburn, Georgia State University) [312].

second category measures the brain's hemodynamic activity (fNIRS [315], TCDS [316]). The use of techniques in the first category (electrical response) is characterised by:

- High temporal resolution and sensitivity (limited by the sampling rate of the equipment used), in the order of milliseconds [317,318];
- Limited spatial sensitivity, in the order of centimetres to tens of centimetres, depending on the number of electrodes used [317,319];
- Poor sensitivity for deep brain structures – more invasive techniques are needed to obtain these interactions [317];
- Sensitive to movement (e.g., eye, head, body, etc.) artefacts, requiring noise filtering algorithms.

The use of techniques in the second category (hemodynamic response) is characterised by:

- Limited temporal resolution (limited by the sampling rate of the equipment used), in the order of tens to hundreds of milliseconds [320,321];

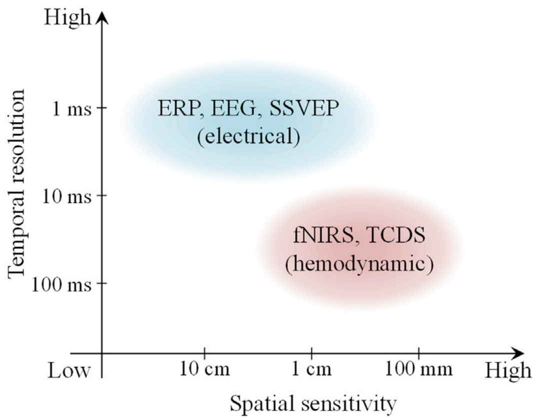

Fig. 39. Comparison of the two categories of brain activity measurement techniques.

– Limited temporal sensitivity (limited by the hemodynamic response of the brain), in the order of seconds to tens of seconds [322,323]; −High spatial sensitivity for fNIRS, in the order of sub-centimetres [321];
– Low spatial resolution for TCDS, as it is only able to probe specific arteries of the brain [320,322].

Fig. 39 provides a comparison illustrating the temporal resolution and spatial sensitivity of the two categories of measurement techniques.

Table 7 summarizes past human factors studies employing brain-related measures. The studies are arranged row-wise according to the technique used, with the columns indicating the cognitive constructs correlated to human performance. A significant number of studies have focused on evaluating mental workload or attention/engagement/vigilance. ERP measures were used in the 1980s while EEG spectral analysis techniques started emerging from the 1990s. fNIRS has gained significant attention since the 2010s, while SSVEP and TCDS are still relatively new neuroergonomic techniques. Different EEG data analysis techniques are listed in the table. Early techniques segregated EEG data into frequency (or spectral) bands commonly associated with different brain functions. The spectral bands were used to identify and evaluate changes in different cognitive constructs. The spectral ratio refers to the relative strengths between the different spectral bands, and was mainly used as an indicator of engagement or workload. Classification techniques like regression, neural networks, discriminant analysis or multivariate analysis were later used as a means of identifying patterns from the large volumes of EEG data generated.

One of the challenges with physiological measures is determining ground truth, particularly when classifying human cognitive states with supervised learning algorithms. One approach is to use objective measures of task difficulty as a basis of ground truth to approximate human cognitive states. However, these objective measures do not map directly or linearly to the brain state of mental workload as demonstrated by individual differences across the same level of task difficulty. Alternatively, thresholds are specified allowing incoming data to be classified as high and low. However, a classifier that can only predict if mental load is high or low does not give enough input to the system because there is no objective task reference. Non-linear hierarchal modelling may be used to produce individualized stress-strain curves for better system adaptation.

5.4.2. Cardio-respiratory system

Measures from the cardio-respiratory system mainly comprise heart and respiratory activities. Cardio-respiratory measurement techniques are less intrusive than the techniques used to measure brain activity. Heart activity is typically measured with an electrocardiogram (ECG), while respiratory activity is measured with strain gauges. Advances in remote imaging systems provide the potential for cardiorespiratory activity to be monitored remotely [389–391]. Due to the relative ease of data collection and processing, cardio-respiratory measures have been used in early aviation studies (since the 1960s) to assess fatigue [392], stress [393] and performance [394]. A number of studies have suggested that heart and respiratory rate variability are good indicators of the operator's cognitive [395,396], physical [397] and emotional [398,399] states. Further research is required to develop measures capable of discriminating between these states [400]. Additionally, the slower response of the cardio-respiratory system as compared to the central nervous system (the temporal resolution of variability measures are in the range of several seconds to around 10 s [401,402]) implies that cardiorespiratory measures might not be sensitive to the more rapid changes in human performance.

Table 8 provides a summary of the different cardiorespiratory measures of used to assess human cognitive performance, as well as their expected response to increases in task load. Arrows indicate either an increase (↑) or decrease (↓) in the measure, while dashes (−) indicate an uncertain effect. The table indicates that there is a large emphasis on respiratory volume measures as well as heart and respiratory variability measures. In particular, variability measures require relatively more sophisticated analysis using statistical, geometric or spectral means [397,403,404].

5.4.3. Peripheral systems

Measures of activity in the peripheral systems include head movement, eye movement and pupillometry, facial and voice expressions, muscular activity as well as hormonal changes.

Advanced HMD on fifth generation military cockpits (Section 2.5) allow the use of accurate head tracking data. While head movement data can be exploited to enhance the accuracy and range of eye tracking

Table 7
Summary of relevant studies in aviation, using brain activity as indicators of human performance.

	Mental Workload	Attention/Engagement/Vigilance/ Situation Awareness	Fatigue	Working memory	Learning	Control strategies
ERP	P300 [324–327] N400 [324] Power ERP [328]	N100 [329,330] P300 [331] Power ERP [328]	P300 [324]	P300 [332]	–	–
EEG	Spectral bands [333–339] Spectral ratio [340–342] Regression [343] Neural networks [344–352] Discriminant analysis [178,347, 350,351,353–357] Multivariate analysis [358–360] Bayesian modelling [342]	Spectral bands [336,341,361,362] Spectral ratio [180,363,364] Discriminant analysis [356,365] Committee machines [147,366,367]	Discriminant analysis [356] Multivariate analysis [359]	–	Spectral bands [361, 368] Discriminant analysis [353]	Discriminant analysis [369]
fNIRS	[370–377]	[375,378–380]	–	[381,382]	[383–386]	–
fTCDS	–	[387,388]	–	–	–	–
SSVEP	–	[310,311]	–	[311]	–	–

Table 8
Cardio-respiratory measures for assessing human cognitive performance and expected response to increased task load.

Category	Heart measures [395,405]	Respiratory measures [396]
Time	Mean of inter-beat (NN) intervals (↓)	Inspiratory time (↓) Expiratory time (−)
Rate	Mean heart rate (↑)	Respiratory rate (RR) (↑) Mean inspiratory flow rate (↑) Sigh rate (↑)
Volume	–	Tidal volume (TV) (−) Minute ventilation (MV) (↑) Expiratory volume (↑) O_2 consumption (↑) CO_2 production (↑)
Variability	Standard deviation of NN intervals (↓) Root mean square of differences between successive NN intervals (↑) Low frequency component of Heart Rate Variability (HRV) (↑) High frequency component of HRV (↓) HRV triangular index (↓) Minor and major axes of the Poincaré plot (↓)	RR variance (↓) RR coefficient of variation (−) RR autocorrelation (↓) TV coefficient of variation (↑) TV autocorrelation (−) MV coefficient of variation (−) MV autocorrelation (−)
Count/ ratio	Number/proportion of successive NN interval pairs that differ by more than 50 ms (↓) Ratio of low frequency to high frequency components of the HRV (↑)	Inspiratory/expiratory ratio (−) Inspiratory duty cycle (↑) Respiratory exchange ratio (−)

systems, it can also be used on its own to drive HMI adaptations. Head position, head orientation and head movement velocity have been used as indicators of attention and efficiency. A number of studies by the US Air Force Research Laboratory (AFRL) on multi-modal adaptive interfaces used head motion patterns as a measure of performance for pilots performing a visual search [406,407]. Pilots supported with cueing (visual, auditory, visual and auditory) exhibited brief ballistic head motions directed towards the target of interest, while pilots in non-cueing conditions exhibited a series of non-terminating searches in the field of regard.

Eye activity has emerged as a popular measure for assessing human cognitive performance (Fig. 40) (i.e., eye movement and pupillometry). Gaze-control technology was reviewed by in a recent FAA report [408]. The report found that gaze-control technologies were sufficiently mature to be incorporated into flight deck HMI[2]. A number of applications were

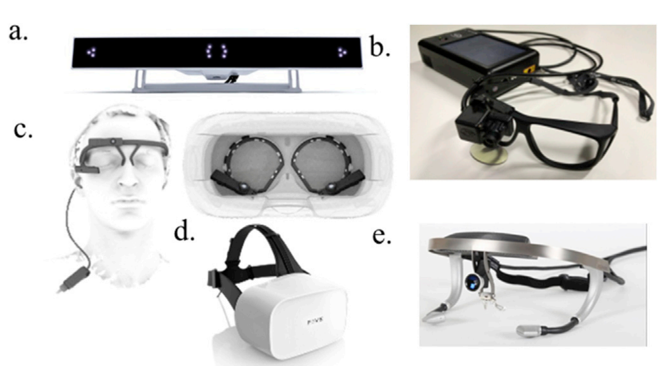

Fig. 40. Eye tracking technologies. (a) GP3 HD, Gazepoint, (b) MobileEye XG, Applied Science Laboratories [423]; (c) Pupil Eye Camera and HTC Vive Binocular Add-on, Pupil Labs, Berlin, Germany [424] (d) FOVE 0 Eye Tracking VR Headset, FOVE, San Mateo, California, USA; (e) Dikablis Eye Tracking in HMD, Ergoneers GmbH, Geretsried, Germany.

identified, ranging from eye-based input, to activity recognition, to post-flight diagnostics. However, a number of research challenges were identified, including the chance of inadvertent function activation, the accuracy and repeatability of eye measures, as well as pilot expertise affecting eye activity. Peysakhovich suggested that the integration of eye-tracking technology could be phased out over four stages with increasing on-board autonomy, namely pilot training, on-board gaze recording, gaze-based flight deck adaptation and finally gaze-based aircraft adaptation [409]. Table 9 provides a summary of the parameters used to assess eye activity, based on a review of the literature [410–415]. Specific metrics such as dispersion [416], the explore/exploit ratio [417], gaze entropy [410], Nearest Neighbour Index [418] and Index of Cognitive Activity [419] are also included in the table with reference to their respective sources. Another significant review was performed by Glaholt [413], which included 78 aviation-based empirical studies. Merchant and Schnell [420] identify a number (27) of eye tracking equipment and vendors. Table 10 presents an updated list featuring some additional vendors and systems. The table describes the tracking accuracy (pupil, gaze, head or pupil diameter), the sampling frequency of the eye and field (for head-mounted systems) cameras, the head-box region (for remote systems), monocular/binocular eye tracking capabilities, data processing latency as well as software compatibility. Important properties for eye tracking systems include sampling frequency, accuracy, precision and latency [421]. Systems with higher sampling frequencies are able to detect more rapid eye movements (e.g., saccades and micro-saccades). In reading, saccades occur with a latency of around 30 ms–40 ms, so systems with sampling frequencies of 50 Hz–60 Hz will only register the motion with one to two samples, while systems with sampling frequencies below 30 Hz are unable to reliably detect these movements [421]. Micro-saccades have the same dynamic

Table 9
Parameters and metrics for describing eye activity [410–414].

Parameter	Description	Derived metrics
Fixation	The state of a gaze that is focused (fixated) on an object.	Fixation (duration, frequency, count) Time to first fixation
Saccade	Small, rapid, involuntary eye movements between fixations, usually lasting 20–200 ms.	Saccadic length/ amplitude, frequency Saccade velocity (mean/ peak) Fixation/saccade time ratio
Dwell	Eye movements comprising a series of fixation-saccade-fixation movements, usually with reference to (or within) a given area of interest.	Dwell count, percentage Average dwell time Dispersion [416]
Transition	The change of dwell from one area of interest to another, and is usually represented in the form of a matrix.	One-/two-way transition Transition frequency
Scan path	The series of eye movements in accomplishing a specified task. A scan path can include elements of fixations, saccades, dwells and transitions.	Hysteresis (changes to scan path over different cycles) Direction Efficiency (path length, path duration) Explore/Exploit ratio [417] Gaze entropy [410] Nearest Neighbour Index [418]
Pupillometry	Measures of pupil size and reactivity.	Percent change in pupil diameter Index of Cognitive Activity [419] Pupillary Diameter, Variability and Harmonic Ratios [179]
Blink	Measures of partial or full eye closure.	Blink Percentage closure [425–428]

Table 10
List of eye-tracking systems and their relevant specifications.

S/N	Device name	Configuration	Tracking accuracy	Eye camera	Field camera	Head box	Mono/bino	System latency	Software
1	*ASL* Mobile Eye XG[c]	Head-mounted	Pupil: 0.5°–1.0°	30Hz	640 × 480 @30fps	-n/a-	Mono	No information on latency	MobileEye XG software
2	*Ergoneers* Dikablis Essential	Head-mounted	Pupil: 0.1°; Gaze: 0.3°–0.5°	384 × 288 @50Hz	768 × 576	-n/a-	Mono	No information on latency	D-Lab
3	*Ergoneers* Dikablis Professional[c]	Head-mounted	Pupil: 0.05°; Gaze: 0.1°–0.3°	648 × 448 @60Hz	1920 × 1080	-n/a-	Bino	No information on latency	
4	*Ergoneers* Dikablis HMD	Helmet-mounted display	No information on accuracy	400 × 400 @30Hz	-n/a-	-n/a-	Bino	No information on latency	
5	*Ergoneers* Dikablis HDK	Helmet-mounted display	No information on accuracy	648 × 448 @60Hz	1920 × 1080 @30fps	-n/a-	Mono/bino	No information on latency	
6	*FOVE* FOVE 0	Integrated VR eye-tracker	Pupil: <1°	120Hz	VR display: 2560 × 1440 @70fps	-n/a-	Bino	No information on latency	FOVE SDK Unity Plugin
7	*Gazepoint* GP3 HD	Remote camera	Gaze: 0.5°–1.0°	60Hz 150Hz	-n/a-	35 cm × 22 cm (with a range of 30 cm)	Bino	No information on latency	API/SDK
8	*ISCAN* ETL-200	Remote camera	No information on accuracy	120Hz 240Hz	-n/a-	No information on head box	Mono	No information on latency	DQW Raw Data Acquisition and Analysis Software
9	*Pertech* EyeTechSensor	Head-mounted	No information on accuracy	25Hz 200Hz	-n/a-	-n/a-	Mono	No information on latency	EyeTechPilot, EyeTechLab
10	*Pupil Labs* Pupil	Head-mounted	Gaze: 0.60°±0.08°	640 × 480 @30Hz, 640 × 480 @120Hz	1910 × 1080@30fps; 1920 × 1080 @30fps; 1280 × 720 @60fps; 640 × 480 @120fps;	-n/a-	Mono/bino	3 ms	Pupil Service (open source)
11	*Pupil Labs* VR/AR add-on	Helmet-mounted display	Gaze: 1.0° ± 0.08°	640 × 480 @120Hz	-n/a-	-n/a-	Mono/bino	3–4 ms	
12	*Seeing Machines* faceLAB	Remote camera	Gaze: 0.5°–1.0°; Head: 1 mm (translation), 1° (rotation)	60Hz	-n/a-	35 cm × 23 cm x 60 cm	Bino	No information on latency	EyeWorks
13	*Seeing Machines* FOVIO	Remote camera	Gaze: 0.78°±0.59°	60Hz	-n/a-	31 cm × 40 cm @65 cm (with a range of 40 cm–80 cm)	Bino	No information on latency	
14	*Seeing Machines* SceneCamera (forward looking field camera)	Accessory	-n/a-	-n/a-	640 × 480 @30fps	-n/a-	-n/a-	-n/a-	
15	*SmartEye* Pro[a,b]	Remote camera	Gaze: 0.5° Head: 0.5° (rotation)	60Hz, 120Hz	-n/a-	40 cm × 40 cm x 50 cm (2 camera set-up)	Bino	No information on latency	Single/Panaroma Scene Camera;
16	*SmartEye* Aurora[a,b]	Remote camera	Gaze: 0.3° Head: 0.3° (rotation)	60Hz, 120Hz, 250Hz	-n/a-	50 cm × 40 cm (with a range of 50 cm–80 cm)	Bino	No information on latency	API; Third-party integration
17	*SMI* REDn Scientific[a]	Remote camera	Gaze: 0.4°	0.05° resolution @30Hz, 60Hz	-n/a-	50 cm × 30 cm @65 cm (with a range of 40 cm–100 cm)	Mono/bino	25 ms	SMI Experiment Suite; SMI SDK; Third-party integration;
18	*SMI* RED250mobile[a]	Remote camera	Gaze: 0.4°	0.03° resolution @60Hz, 120Hz, 250Hz	-n/a-	32 cm × 21 cm @60 cm (with a range of 50 cm–80 cm)	Mono/bino	8 ms	EyeWorks
19	*SMI* RED500[a]	Remote camera	Gaze: 0.4°	0.03° resolution @500Hz	-n/a-	40 cm × 20 cm @70 cm (with a range of 60 cm–80 cm)	Bino	<4 ms	
20	*SMI* HMD[a]	Helmet-mounted display	Gaze: 0.2°–1.0°	60Hz, 250Hz	-n/a-	-n/a-	Bino	No information on latency	
21	*SMI* Eye Tracking Glasses 2[a,c]	Head-mounted	Gaze: 0.5°	60Hz, 120Hz	1280 × 960 @24fps; 960 × 720 @30fps	-n/a-	Bino	No information on latency	
22	*SR Research* EyeLink II[a]	Head-mounted	Gaze: <0.5°	0.01° resolution @500Hz; 0.025° resolution @250Hz	250Hz	-n/a-	Mono/bino	3.0 ms ± 1.11 ms	Eyelink Data Viewer; Third-party integration; EyeWorks

(*continued on next page*)

Table 10 (*continued*)

S/N	Device name	Configuration	Tracking accuracy	Eye camera	Field camera	Head box	Mono/bino	System latency	Software
23	*SR Research* EyeLink Portable Duo[a,b]	Remote camera	Gaze: 0.25°–0.5°; Pupil diameter: 0.1%	0.01° resolution @500Hz	-n/a-	22 cm × 22 cm @ 52 cm (with a range of 42 cm–62 cm)	Mono/bino	3.49 ms ± 0.70 ms	
24	*SR Research* EyeLink 1000 Plus[a]	Remote camera	Gaze: 0.25°–0.5°	0.05° resolution @500Hz	-n/a-	40 cm × 40 cm @ 70 cm (with a range of 40 cm–150 cm)	Mono/bino	3.0 ms ± 0.6 ms	
25	*Tobii Pro* Glasses 2[a,b]	Head-mounted	No information on accuracy	50Hz, 100Hz	1920 × 1080 @25fps	-n/a-	Bino	No information on latency	Tobii Pro Lab; Tobii Pro Studio; Tobii Pro Glasses 2 API; Tobii Pro SDK; Tobii Toolbox for MATLAB; Third-party integration; D-Lab; EyeWorks
26	*Tobii Pro* Spectrum[a,b]	Remote camera	Gaze: 0.4°±0.1°	600Hz	-n/a-	29 cm × 23 cm @65 cm (with a range of 55 cm–75 cm)	Bino	<5 ms	
27	*Tobii Pro* X3-120[a,b]	Remote camera	Gaze: 0.4°±0.24°	120Hz	-n/a-	50 cm × 40 cm @80 cm (with a range of 50 cm–90 cm)	Mono/bino	<11 ms	
28	*Tobii Pro* X2-60[a,b]	Remote camera	Gaze: 0.4°–1.2°	60Hz	-n/a-	50 cm × 36 cm @70 cm (with a range of 40 cm–90 cm)	Mono/bino	>35 ms	
29	*Tobii Pro* X2-30[a,b]	Remote camera	Gaze: 0.4°–1.0°	30Hz	-n/a-	50 cm × 36 cm @70 cm (with a range of 40 cm–90 cm)	Mono/bino	50 ms–70 ms	
30	*Tobii Pro* TX300[a,b]	Remote camera	Gaze: 0.5°–1.1°	300Hz	640 × 480 @30fps	37 cm × 17 cm @65 cm (with a range of 50 cm–80 cm)	Mono/bino	<10 ms	
31	*Tobii Pro* T60XL[a,b]	Remote camera	Gaze: 0.5°; Head: 0.2°	60Hz	640 × 480 @30fps	41 cm × 21 cm @65 cm (with a range of 50 cm–80 cm)	Mono/bino	<33 ms	

[a]Detailed specifications can be found on the website.
[b]In addition to gaze direction, the system also measures pupil diameter.
[c]Wireless mode also available.

characteristics of saccades but at a factor of 50 times smaller [422]. However, the durations of micro-saccades are only somewhat smaller than saccades. In practice, sampling frequencies of no lower than 200 Hz are used in micro-saccade research [421].

Another emerging area of research is emotion recognition using voice patterns. El Ayadi [429] provides a review of the features and classification schemes used in voice emotion recognition systems. Features are categorized as continuous features (e.g., pitch, frequency, energy and timing), qualitative features (e.g., features derived from continuous features such as tense, lax, harsh, breathy, jitter and shimmer), spectral features (i.e., the spectral energy distribution across the speech range of frequency) and Teager Energy Operator (TEO)-based features (the TEO is a non-linear operator describing the energy of a signal). Classification schemes include Hidden Markov Models (HMM), Gaussian Mixture Models (GMM), neural networks, Support Vector Machines (SVM) and multiple classifier systems. Systems are capable of classifying emotions such as anger, joy, sadness and fear [430], and can potentially be extended to measure stress and cognitive load. The Speech Under Simulated Stress (SUAS) database [431] contains speech data produced under a number of conditions (single tracking task, dual tracking task, amusement rides, helicopter piloting tasks) to assist the development of algorithms for detecting stress and emotion.

5.5. *Adaptation strategies*

A useful framework for designing adaptive HMI^2 can be used to categorize the adaptations based on their purpose and immediacy [432]. The framework comprises combinations of semantic and syntactic, as well as immediate and future adaptation strategies as presented in Table 11. Semantic adaptations affect the system's function, behaviour and goals, and can be thought of as modifying the system interactions. Syntactic adaptations affect the presentation of information through the user interface without modifying the system behaviour. These two adaptations can be implemented as either immediate or future changes to the HMI^2. Immediate adaptations affect the interface or interaction elements that are currently active, while future adaptations affect future interfaces and interactions by modifying the logics that are implemented in the adaptation engine. While current HMI^2 utilise adaptation strategies that are immediate (i.e., hard-coded into the system), research has progressively shifted towards HMI^2 implementing future adaptation strategies. Such strategies are supported by systems that observe human users, reason about the users' reactions to presented stimuli, and adapt the internal adaptation logics to complement the user's preferences. Adaptive HMI^2 show great potential to build user trust and enhance human-machine teaming, but will require sufficient assurance to ensure that all safety requirements are fulfilled.

6. Systems design for adaptive HMI^2

As presented in Section 2, the HMI^2 of current avionics do possess some degree of adaptiveness. Systems such as ACAS, EGPWS, FMS and ECAM/EICAS are capable of adapting the HMI^2 according to feedback from the environment (such as traffic, weather or terrain) and flight parameters (such as flight phase and on-board system status). However, the evolution of avionic systems for manned and unmanned/remotely piloted aircraft will introduce systems with higher levels of autonomy and intelligence. By teaming with systems possessing sufficient intelligence, the performance of human operators can be significantly improved, leading to higher levels of operational safety, efficiency and effectiveness. The capability of systems to appropriately assess, infer and react to improve human and overall system performance will be a key factor in mediating the required human-machine interactions, thereby providing trusted autonomy. Such concepts can be integrated into the HMI^2 of next generation cockpits and ground control systems. For example, the introduction of new interaction modalities, such as speech input as well as gesture or gaze-aware technology, can be exploited to

Table 11
HMI^2 adaptation strategies, adapted from Ref. [432].

	Immediate	Future
Semantic	Immediate changes to the system's function, behaviour or goals. (e.g., changes to the automation level, task scheduling, tracked target, etc.)	Future changes to the system's function, behaviour or goals. (e.g., recalibration of autonomy or performance thresholds, modification of task allocation strategy, etc.)
Syntactic	Immediate changes to the user interface. (e.g., decluttering, text highlighting, colour coding, triggering of alerts and warnings, etc.)	Future changes to the user interface. (e.g., rearrangements in the alert and warning hierarchy, personalised presentation of information, etc.)

provide passive inputs (e.g., psycho-physiological and cognitive states) alongside the active inputs (e.g., commands or direct inputs).

6.1. System elements

The review of adaptive HMI^2 concepts presented in Section 4 allows some general observations on the characteristics of adaptive HMI^2 systems. Fig. 41 illustrates the general layout of an adaptive HMI^2 system. The system comprises three basic, interacting modules. The human performance module assesses the human operator and, using specific human performance models, provides estimates of human performance and/or cognitive states. The task management module monitors the external environment and on-board system parameters, prioritising and tracking the progress of current tasks, as well as planning and scheduling future tasks. The adaptation engine receives inputs from the human performance and task management modules and reconfigures the HMI^2 according to a set of decision logics.

Table 12
The level of automation taxonomy (LOAT), from Ref. [457].

Information Acquisition	Information Analysis	Decision and Action Selection	Action Implementation
A0) Manual Info Acquisition	B0) Working Memory Based Info Analysis	C0) Human Decision Making	D0) Manual Action and Control
A1) Artefact-Supported Info Acquisition	B1) Artefact-Supported Info Analysis	C1) Artefact-Supported Decision Making	D1) Artefact-Supported Action Implementation
A2) Low-Level Automation Support of Info Acquisition	B2) Low-Level Automation Support of Info Analysis	C2) Automated Decision Support	D2) Step-by-Step Action Support
A3) Medium-Level Automation Support of Info Acquisition	B3) Medium-Level Automation Support of Info Analysis	C3) Rigid Automated Decision Support	D3) Low-Level Support of Action Sequence Execution
A4) High-Level Automation Support of Info Acquisition	B4) High-Level Automation Support of Info Analysis	C4) Low-Level Automatic Decision Making	D4) High-Level Support of Action Sequence Execution
A5) Full Automation Support of Info Acquisition	B5) Full Automation Support of Info Analysis	C5) High-Level Automatic Decision Making	D5) Low-Level Automation of Action Sequence Execution
		C6) Full Automatic Decision Making	D6) Medium-Level Automation of Action Sequence Execution
			D7) High-Level Automation of Action Sequence Execution
			D8) Full Automation of Action Sequence Execution

6.1.1. Human performance module

The human performance module translates observables of the human operator into cognitive constructs and performance estimates. These observables can include subjective ratings, task-based inputs, or psycho-physiological measures. The two predominant approaches for translating these observables into practical outputs are the classification-based approach and the model-based approach.

Classification-based approaches use statistical or probabilistic methods to identify patterns in empirical data. The classification-based approach has been used to assess cognitive workload or engagement from psycho-physiological data. The classifier infers human performance or cognitive states based on extracted features from raw data (Fig. 42). Typically, prior to online use, the accuracy of a classifier system can be improved with additional calibration from its initial baseline settings. The calibration phase can be performed either in an online or offline context and trains the classifier on a dataset specific to the user. Classification techniques include regression [433], support vector machines [434,435], fuzzy systems [436,437], discriminant analysis [438,439], neural networks [440–442], Bayesian networks [342,443,444], extreme learning machines [440] or committee machines [445]. The algorithmic nature of classification-based methods makes them well-suited for a system implementation. The use of dimensionality reduction techniques allows classification approaches to accommodate an arbitrary number of input observables and output states, providing greater flexibility if the model's complexity needs to be scaled up. The system is able to adapt and learn from empirical data through automatic tuning of classification parameters, allowing changes within individuals (e.g., learning or ageing effects) or differences between individuals (e.g., in personality or abilities) to be captured. However, most classification-based systems function as black boxes, providing output that is difficult to interpret and diagnose. The use of statistical or probabilistic methods lacks theoretical support from underlying cognitive principles. Additionally, classification-based systems require initial calibration on existing empirical data, making it difficult to set-up without prior data.

Model-based approaches place greater emphasis on modelling the processes underlying human performance than on identifying patterns from collected data. Specific aspects of human cognition such as long-term memory, working memory and perception are modelled. Model-based approaches have been used to assess cognitive workload, attention and awareness, but are also useful in evaluating higher-level processes such as planning, decision making or agent-interactions. Cognitive architectures (Section 5.3) such as ACT-R, MIDAS and SOAR (Fig. 43) are feasible candidates for a system implementation as a human performance module – past research has already explored the use of cognitive architectures in the design of autonomous systems [176,302].

Cognitive architectures incorporate psycho-physiological models (e.g., MIDAS includes models of eye activity to assess attention [278]), but use of psycho-physiological models are limited by the lack of an underpinning theoretical understanding behind certain psycho-physiological observables (e.g., brain and cardio-respiratory models are not used). Therefore, implementation of these psycho-physiological models requires further developments in cognitive

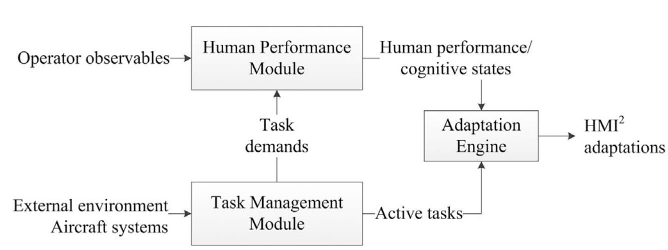

Fig. 41. General layout of adaptive HMI^2 systems.

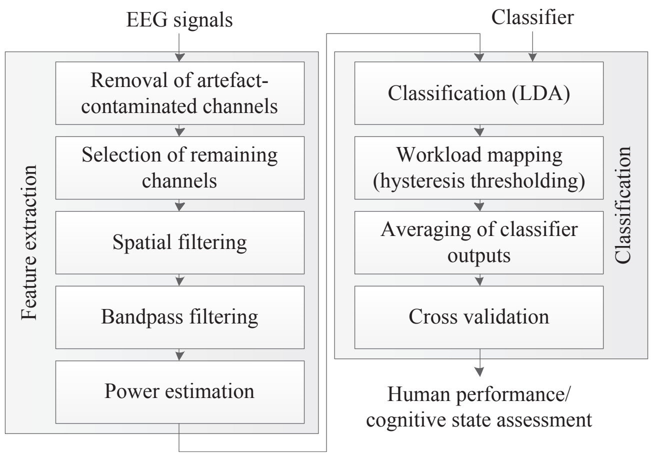

Fig. 42. A classification-based approach for EEG-based workload prediction, adapted from Ref. [439].

research to bridge the gap between what is observed (i.e., low-level psycho-psychological processes) and what can be inferred (i.e., high-level cognition and decision-making).

6.1.2. *Task management module*

The task management module interfaces with different aircraft systems (such as the FMS, EICAS/ECAM, ACAS or GPWS) to monitor the status of pilot tasks relating to the flight planning, aircraft systems monitoring, traffic, terrain and weather surveillance as well as pilot-ATC communications. Fig. 44 illustrates the general layout of a task management module. The task management module includes the tasks performed by both human and system elements. Tasks are represented hierarchically and can be complemented with cognitive architectures or semantic world models. A task-monitoring sub-module checks incoming data to monitor the progress of current tasks. The task-monitoring sub-module interfaces with the task-planning and task-generation sub-modules to modify and prioritise tasks in the task list. The task-planning sub-module is responsible for making high-level decisions about how tasks should be generated, prioritised, scheduled, sequenced or merged. The task-generation sub-module generates tasks based on the parameters provided by the task planner and adds these tasks to the task list.

The task list interfaces with the adaptation engine to provide updates on the active tasks. Additionally, a task demand estimator uses task models to assess the objective task demand. The estimated task demand is then passed to the human performance assessment module to assess the operator's cognitive state and performance.

6.1.3. *Adaptation engine*

There is limited research thus far with respect to the development of a HMI^2 adaptation framework. Most HMI^2 adaptations occur within a specific experimental scenario, interface or application and do not generalize well to other applications. HMI^2 adaptations require both the interfaces (displays and information symbology, as well as aural and haptic feedback) and interactions (commonly defined by an automation scale) to be adapted. Most frameworks make reference to a Level of Automation (LOA) scale (Table 12) when defining adaptations. Adaptations are driven by a decision table that trigger changes in the HMI^2 when certain conditions are met. The dimension of decision tables scales with the number of parameters and can quickly become very complex when a large number of parameters are used to define HMI^2 adaptation.

State diagrams offer an intuitive way of representing the behaviour of adaptive systems. A state diagram shows the set of possible states that can

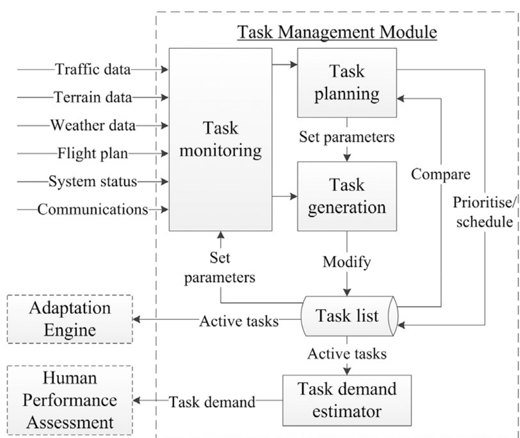

Fig. 44. Typical process flow of a task management module.

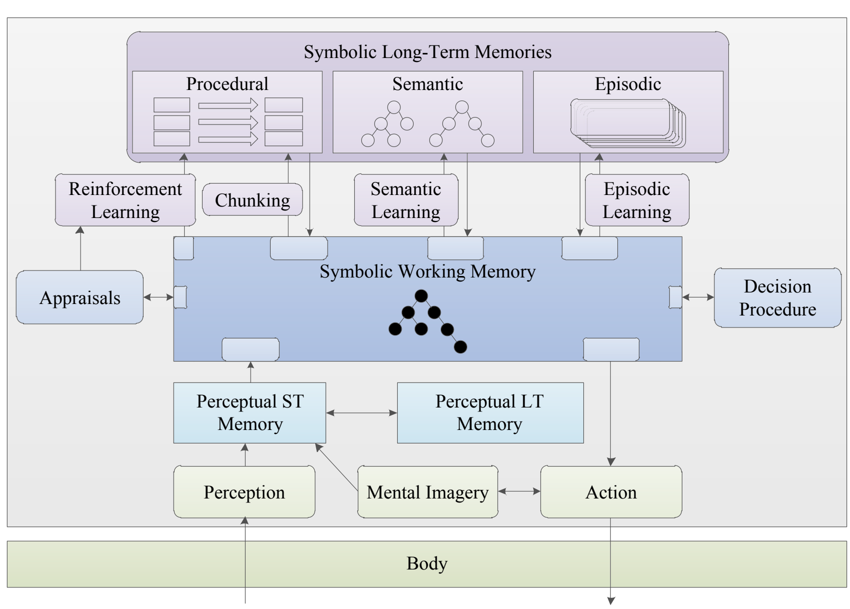

Fig. 43. Block diagram of SOAR 9, adapted from Ref. [446].

be occupied by the system. Transitions between states can occur when certain conditions are met and guard conditions can be imposed to prevent transitions under specific conditions. Individual state diagrams, each modelling the behaviour of machines and humans, can be combined to obtain a composite model of the human-machine behaviour (Fig. 45). The composite model can then be used to identify any illegal or erroneous states. Formal methods are a promising technique for evaluating the human-machine interactions represented by state diagrams, with research currently focusing on pilot interactions with automated flight control systems [447,448].

State diagrams can also be nested within different layers of abstraction, supporting the design of complex behaviour for autonomous systems. The Layered Pattern Recognizable Interfaces for State Machines (L-PRISM) [449] concept proposes to use finite state machines to depict the behaviour of multiple autonomous RPA platforms. The concept proposed in L-PRISM can be extended to a framework for describing the adaptations in HMI^2 and their associated transitions.

6.2. Assurance considerations

Assurance of adaptive systems can be provided using two techniques: via design time assurance, where the system is verified and validate through offline analysis and testing to a level required for certification of the system; and via runtime assurance, where the system is monitored during live operation to determine if the adaptive system is operating correctly.

6.2.1. Design time assurance

In design time assurance, requirements for system safety assurance are based on the concept that correct behaviour of a system can be specified, predicted and verified prior to operation. The verification of adaptive systems poses significant challenges to conventional verification processes because such systems adapt their behaviour in response to feedback from the environment and can be less predictable than traditional avionics systems. Thus far, research in the verification of adaptive systems by the FAA has focused on the application of adaptive systems to flight control, using control theory to characterise different types of adaptive systems and identify possible verification techniques that can satisfy DO-178C certification objectives [450]. The lessons learnt can be extended to more complex adaptive systems such as the adaptive-cognitive HMI^2 concepts introduced in this paper.

In particular, formal methods are a way of verifying the behaviour of adaptive systems early in the software development lifecycle. Formal methods can be used to validate the consistency and completeness of the

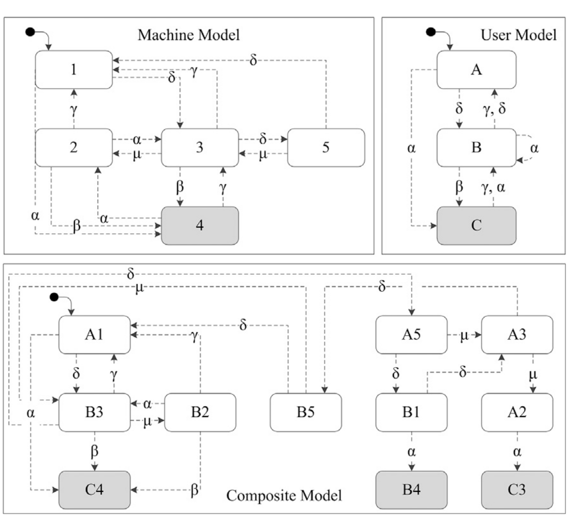

Fig. 45. State diagram representation of human-machine behaviour, adapted from Ref. [448].

model specification as well as the software behaviour. Formal methods have been used to evaluate RPAS SAA algorithms [451] and can be extended to evaluate multi-agent interactions in RPAS [452] as well as the HMI^2 of adaptive systems [453]. Formal methods are based on a two-step process comprising [454,455]:

- Specification, where the system and its desired properties (such as its functional behaviour, timing behaviour, performance characteristics or internal structure) are described with a mathematically-defined syntax and semantics;
- Verification, where the formal analysis techniques are used to provide assurance of that the properties satisfy the verification objectives. Three categories of approaches are commonly used: theorem proving, model checking and abstract interpretation.

The model checking ability of formal methods lends itself well to the verification of model-based representations provided by a state diagram representation. Recent research has explored the use of a formal, model-based approach to analyse human-automation interactions with autopilot [448] and autoland [456] systems. The approach presented serves as a potential starting point for the development of more complex adaptive HMI^2 systems and the verification of the behaviour of such systems.

6.2.2. Runtime assurance

Runtime assurance is provided by a runtime-protected system (Fig. 46). The runtime-protected system comprises the following elements:

- An advanced system, which may contain adaptive, learning or non-deterministic algorithms that cannot be certified at design time;
- A reversionary system, which acts as a fail-safe system lacking the advanced functionalities of the advanced system, but able to perform basic functions to ensure safe operations;
- A runtime assurance monitor and switch mechanism, which monitors the system to determine if the system is approaching unsafe operating conditions, upon which control is switched from the advanced system to the reversionary system;
- An input allocator, which parses the inputs to the runtime assurance protected system to their appropriate destinations.

The approach provides additional assurance for adaptive HMI^2 systems. Adaptive HMI^2 systems that cannot be certified to the required level can run alongside reversionary systems in runtime-protected systems to provide trusted behaviour. Runtime assurance protected systems have been investigated in RPAS applications [458,459]. In particular, Integrated Configurable Algorithms for Reliable Operations of Unmanned Systems (ICAROUS) [460] is a software architecture that has been formally verified and operate alongside other unverified, mission specific software components.

7. HMI^2 in the CNS + A context

The evolution of avionics within the CNS/ATM paradigm of operations will be driven by the need to support higher precision and accuracy in flight operations, more coordination and interaction between air and ground platforms, more extensive synthesis of information, as well as strategic 4-dimensional flight planning and management [461,462]. The emerging CNS + A concepts will be a major driver of HMI^2 evolutions, therefore this section briefly outlines some of the key aspects that will have the greatest impacts on HMI^2 design.

7.1. Four-Dimensional Trajectory-Based Operations

Four-Dimensional (4D) Trajectory-Based Operations (TBO) is one of the four Performance Improvement Areas in ICAO's Aviation System

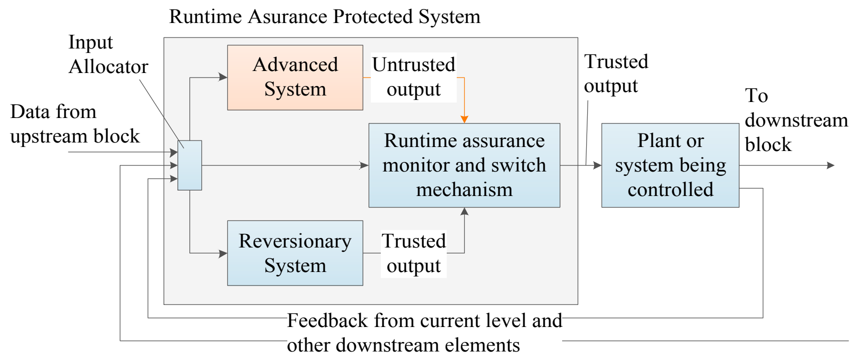

Fig. 46. Runtime assurance protected system, adapted from Ref. [458].

Block Upgrade (ASBU) framework [463]. TBO aims to enhance operational efficiency and consistency by implementing real-time exchange and management of 4D trajectories (3D position plus time) between aircraft and ground-based systems [464]. To yield increased route flexibility and consequently airspace capacity, 4D trajectories are expected to be more complex than legacy flight plans. HMI^2 evolutions will therefore need to address the presentation and exchange of 4D trajectory information, as well as to facilitate effective monitoring, planning, negotiation and validation of 4D trajectories, in a collaborative framework.

7.2. Performance-Based Operations

The concept of Performance-Based Operations (PBO) aims to enhance operational safety and efficiency through the implementation of systems that monitor the performance of CNS systems. Different performance requirements are specified for different flight phases over different classes of airspace – aircraft with CNS capabilities that satisfy these performance requirements are permitted to operate in more flexible airspace (e.g., reduced separation minima, optimised 4D trajectories, curved approaches, continuous descent approach, etc.) [465]. HMI^2 evolutions will need to provide additional information on CNS performance as well as display appropriate advisories when the performance requirements are not met. Advanced forms of HMI^2 will include predictive performance monitoring elements, which anticipate the potential loss of performance, as well as corrective performance augmentation elements, which provide appropriate levels of decision support to circumvent or recover from a loss of performance [466,467]. Additionally, the use of HMI^2 that can dynamically estimate operator performance (e.g., reaction time) will provide greater flexibility in PBO (e.g., for Required Communication, Navigation [466,468] [469]and Surveillance [75, 470] – RCP, RNP and RSP – applications), greatly benefitting operations.

7.3. System Wide Information Management and Collaborative Decision Making

System Wide Information Management (SWIM) describes a concept for facilitating the global exchange and management of information. SWIM is supported by a common set of standards, infrastructure and governance, which facilitates interoperability at the signal-in-space, systems and HMI levels [471]. The use of SWIM-enabled applications will contribute to user situational awareness by increasing the availability and quality of information, thereby contributing to the Collaborative Decision Making (CDM) process with improved decision-making [465]. A common set of open standards will allow more flexible and cost-effective communications between different stakeholders in the SWIM network. HMI^2 evolutions will need to facilitate collaboration by allowing all stakeholders to share, view and retrieve information relevant to any particular operational context. Effective integration and display of information from multiple sources and systems will minimize operator workload while increasing operational efficiency. To facilitate the effective display of information, HMI^2 will need to be contextually aware, adapting to situations and circumstances by providing or requesting information to or from the human user. HMI^2 evolutions will also need to provide a common operating picture by ensuring the compatibility and interoperability of the approaches, methods and terminologies used by all stakeholders. Appropriate levels of decision support are required to provide human operators with the necessary level of situational awareness to maximise overall system performance.

7.4. Dynamic Airspace Management

Dynamic Airspace Management (DAM) aims to optimise the use and allocation of airspace by dynamically restructuring sector boundaries. Sector boundaries might be changed to accommodate shifting traffic demands, changing weather conditions, ATC availability, sharing of airspace resources by civil/military users or other dynamic factors [464, 465]. DAM supports PBO, allowing airspace to be dynamically reconfigurable according to different performance objectives varying in time and space. HMI^2 evolutions need to support pilots to transit seamlessly between dynamically managed sectors, as well as providing the necessary decision support to allow the planning, negotiation and validation of 4D trajectories within dynamically changing airspace. HMI^2 should provide intuitive interfaces that enhance the situational awareness of the flight crew, allowing them to anticipate possible changes in airspace configurations and supporting free-routing operations at different levels of complexity. HMI^2 evolutions should also provide a common operating picture to all stakeholders to facilitate the CDM process.

7.5. Separation Assurance and Collision Avoidance for manned and unmanned/remotely piloted aircraft

The integration of RPAS into non-segregated airspace requires seamless operations between manned and unmanned/remotely piloted aircraft. In particular, a significant consideration is the provision of Separation Assurance and Collision Avoidance (SA&CA) capabilities between manned and unmanned/remotely piloted aircraft [470]. HMI^2 evolutions will need to provide human operators with sufficient situational awareness to anticipate possible conflicts with both types of aircraft. HMI^2 need to accurately project traffic conditions ahead of time and convey such information to the human operator in an intuitive and timely manner. HMI^2 will also need to offer the necessary decision support tools for facilitating safe and effective (e.g., in terms of time and cost) de-confliction in the strategic, tactical or emergency timeframes. Trusted interactions are required to facilitate de-confliction between human and autonomous agents, while keeping the human within the decision-making process at all times.

8. Conclusions

This paper reviewed the developments in Human-Machine Interfaces and Interactions (HMI^2) for manned and unmanned aircraft in civil and military applications. The historical evolution of HMI^2 has been largely driven by advances in avionics computing and display systems, with many developments first occurring in military applications before being adopted in the civil aviation domain. Current defence trends point towards network-centric operations requiring higher degrees of interconnectivity and collaboration between airspace or battlespace elements. To assist human operators in increasingly complex tasks, HMI^2 of future avionics systems will incorporate adaptive features, which might include higher levels of autonomy to facilitate operations in off-nominal scenarios. The design of modern adaptive HMI^2 systems draws inspiration from military cockpit concepts conceived in the late 1980s and early 1990s. These early concepts envisaged associate systems as virtual copilots teaming up with human operators to provide context-aware assistance and support. The three main components of such associate systems fulfil the distinct functions of assessing the system/environmental states, assessing the operator's functional state as well as driving HMI^2 adaptation. In particular, the evaluation of operator states can be augmented using human performance metrics. Subjective and task-based human performance assessment techniques have been traditionally used in experimental settings to evaluate new operational procedures or to validate HMI^2 concepts. Emerging research in the area of analytical models and psycho-physiological observables can provide real-time measures of human performance, which show significant potential to drive HMI^2 adaptations. In particular, recent studies have shown that human cognitive states and human performance can be inferred via psycho-physiological measures. Further studies have demonstrated the feasibility of HMI^2 adaptations driven by measures of human cognitive states – termed Cognitive HMI^2 (CHMI^2). CHMI^2-enabled systems have the potential to enhance the intuitiveness of human-machine interfaces, provide more natural human-machine interactions, facilitate trust in autonomous systems and support tighter coupling between human-machine teams. In particular, the application of CHMI^2 in the CNS + A context provides many opportunities of enhancing operational safety, efficiency and effectiveness. However, significant research is still required before CHMI^2-enabled systems can be certified and operationally deployed.

9. Future research

Future research activities will concentrate on the following main areas:

1. Investigation of adaptive HMI^2 concepts in single pilot operations (with a focus on cognitive ergonomics), addressing the cases of pilot partial/total incapacitation and the consequent transition of the single-pilot aircraft to a Remotely Piloted Aircraft (RPA);
2. Investigation of adaptive HMI^2 concepts in manned and unmanned aircraft teaming, particularly exploring one-to-many scenarios in Remotely Piloted Aircraft Systems (RPAS) operations where a single RPAS crewmember controls or manages multiple RPA platforms (assisted by automation);
3. Assessment of adaptive HMI^2 to enhance operator trust as well as to support human-machine teaming at higher levels of system autonomy;
4. Exploration of improved interoperability amongst disparate connected systems – for example, it may prove advantageous for the adaptation displayed on a HMI in the flight deck to invoke a related adaptation on the HMI of an ATM system connected to the aircraft via datalink;
5. Exploration of Extended Visual Line of Sight (EVLOS) scenarios, where multiple RPAS crewmembers perform RPA handovers with the support of multiple visual observers;
6. Investigation of the potential for using appropriate human performance metrics to drive real-time HMI^2 adaptation;
7. Evaluation of different wearable and remote sensing technologies and their suitability in psycho-physiological assessment;
8. Investigation of online human performance assessment to support forensic applications (i.e., accident and incident investigation);
9. Investigation of potential synergies between classification-based and model-based approaches in evaluating human performance and cognition;
10. Investigation of formal, model-based approaches in analysing human-computer behaviour and verifying human-machine interactions;
11. Extraction of general lessons learned and application of these lessons to other areas in the aviation context (e.g., HMI^2 of Air Traffic Management, Air Traffic Flow Management and UAS Traffic Management systems) and in other transport/mission systems domains.

Acknowledgements

The authors wish to thank and acknowledge THALES ATM Australia, the Australian Defence Science and Technology (DST) Group and Northrop Grumman Corporation for separately supporting different aspects of this work under the collaborative research projects RE-02544-0200315666, RE-02826-0200316323 and RE-03163-0200317164 respectively.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.paerosci.2018.05.002.

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