How are Laser Attacks Encountered in Commercial Aviation? A Hazard Analysis Based on Systems Theory

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Laser attacks in commercial aviation have become headline news worldwide and the frequency of incidents has increased. A review of the research regarding lasers in commercial aviation shows the need for a systematic analysis. By applying a hazard analysis of system theory (both STAMP and STPA) to a practical example it is possible to identify possible countermeasures and their current state of elaboration. Furthermore, this research considered the concept of reduced-crew operations, and the possible effects of laser strikes. Whereas the pilot operational procedures are established, the legislation lags behind for some nation states. Detection and prevention of lasers operating in the same area as aircraft is critical reduction of attacks.

Keywords: laser illumination, aviation, STAMP, STPA, systems theory

# 1. Introduction

Over the last two decades, the increased number of laser attacks at aircraft has become a growing concern in civil aviation (Civil Air Navigation Services Organisation, 2014; Esler, 2016; Eurocontrol, 2016). The aviation community had already recognized lasers as a flight safety hazard around the turn of the millennium (Nakagawara & Montgomery, 2001; Rash & Manning, 2001; Stastny & Griffith, 2001). Fig. 1 shows the calculated ratio of reported laser attacks to annual flight movements for each country in the left chart. There had been an increasing trend of laser attacks in air traffic up to 2010. Since then, laser attacks have decreased slightly except in Australia and USA. Against this background, the total number of laser attacks has remained constant since 2015 as shown in the chart on the right side. Until the middle of the last decade, none of these laser incidents in aviation was linked to terrorism (Elias, 2005). No commercial airliner has been involved in a laser-related crash yet. Nonetheless, laser illuminations become more and more critical for flight safety because they can be used as weapon as well in terms of global trends in terrorism. Laser light aimed at an aircraft cockpit can illuminate the crew and distract the pilots during critical flight phases at low altitudes. This is especially the case for single-pilot aircraft, where a laser attack on approach can become extremely hazardous. In civil aviation, commercial aircraft are most likely to be illuminated by a laser beam from ground (Nakagawara, Montgomery, & Wood, 2010). More than 73% of reported incidents of a laser illumination stem from commercial carriers in US during 2004–2008. Most occurred under an altitude of 10,000 feet. Here, approach (45%) and final approach (24%) were affected most whereas departure (7.9%), enroute (7.8%) and descent (5.3%) were affected much less. During these low-level flight operations, the pilots’ ability to operate the aircraft is impaired, particularly for laser illuminations above 5 µW/cm² (Nakagawara, Montgomery, Dillard, McLin, & Connor, 2003). In addition, the flight operations in these phases are characterized by high workload which does not tolerate any limitations on eyesight (European Commission, 2015). During approach, the pilot and copilot have to complete many tasks with strict safety margins (Federal Aviation Administration, 2001). Here, any distraction by lasers or any other source is hazardous for safe flight operations. These exemplary US-American data on the frequency of laser incidents need be supplemented with international statistics because there are no complete datasets for international regions yet.

The following incident on a Boeing 737-8AS represents a typical example of a laser strike and its effects on flight operations. In this incident, the scheduled passenger flight from Lille (France) to Porto (Portugal) had proceeded uneventfully until the aircrew was conducting a final non-precision approach during twilight (Air Accident Investigation Unit Ireland [AAIU], 2016). The First Officer (FO) as Pilot Flying (PF) recognized a laser light from the city centre, which did not shine into the direction of the aircraft, before disappearing. He did not inform the captain because he assumed the beam had been switched off. Suddenly a laser light glared into the cockpit. The FO protected his eyes by putting the left hand up in front of his eyes. The Captain as Pilot Monitoring (PM) did not recognize the laser, looked up, and the laser hit her eyes. As a result, she suffered from flash-blindness and missed the “approaching descent” call. She simultaneously confirmed the Air Traffic Control’s (ATC’s) instruction to contact the tower frequency and informed approach control about the laser strike. The FO announced “approaching descent” himself and carried out corresponding actions. As the aircraft had been above the ideal flight profile (because of the missed approach descent call) it returned to its original descent path by increasing speed and rate of descent. In the meantime, the Captain’s (PM’s) flash-blindness was over, she was aware of the FO’s (PF’s) actions, and confirmed the “approaching descent” actions as completed. The FO (PF) requested the extension of landing gear and flaps to reduce the increased aircraft speed. The approach had become unstable due to an increased speed which is why the Captain (PM) requested a missed approach procedure. The FO (PF) executed the procedure and subsequently landed the aircraft safely. The Captain did not suffer any lasting injury. Incidents such as this example of a laser strike are extremely hazardous to flight operations because laser beams can cause harm to the pilots’ sight and affect their ability to operate the aircraft. Hence, the present work considers how these laser attacks on commercial aircraft may be counteracted.

A laser (*Light Amplification by Stimulated Emission of Radiation*) device produces “an intense, coherent, directional beam of optical radiation by stimulating emission of photons by electronic or molecular transition to lower energy levels“ (International Civil Aviation Organization [ICAO], 2017b, p. 5). The classes 1–4 of a laser specify the level of the laser radiation hazard in standardised viewing condition (International Electrotechnical Commission, 2014). The higher the class the more dangerous is the given laser beam of a device for the human eye. Visible lasers as of class 2 and above can cause a temporary visual incapacitation of a pilot. A pilot may be medically fit but is suddenly impaired in their visual ability by the glare of a laser. In this way, a negative physiological state of a pilot could arise (i.e., visual impairment) which might jeopardize flight safety (ICAO, 2012). Lasers can cause four different types of visual distraction and damage of the human eye through the cockpit windshield: distraction, glare, temporary flash-blindness and eye injuries (Murphy, 2009; Nakagawara, Montgomery, & Wood, 2007; Palakkamanil & Fielden, 2015; Wright & Scott, 2016). Firstly, a laser beam can distract the pilot during take-off and landing. It veils vision to a greater extent than light from non-laser sources. Secondly, glare as an intrusive light source can reduce visual activity and contrast sensitivity. In this way, an after-image can remain in the visual field for a few seconds after an exposure to a bright light. Thirdly, flash-blindness potentially knocks out a portion of the visual field as an effect of bright light. The effect persists for a while after the illumination stopped. Finally, a laser beam of all wavelengths can result in eye injuries. For example, a flash-blindness of a commercial pilot may lead to a retinal injury which is an irreversible lesion of a part of the eye and sight (Gosling, O'Hagan, & Quhill, 2016). Not all effects occur in every case and they can appear alone or in combination with another. Permanent eye injuries are thankfully very rare in commercial aviation (Nakagawara, Wood, & Montgomery, 2008).

The extent to which a laser hazard can subsequently affect the pilot’s eyesight is dependent on several factors. In general, the pilot’s awareness of outside laser activity is crucial for avoiding all harmful effects of a laser light on vision because they can shield their eyes or look away (Derenski, 2010; Murphy, 2009). If the pilot does not manage to shield his eyes from the laser beam, the following factors can influence the occurrence of visual effects and their appearance to varying degrees. Firstly, the colour of a laser beam directly relates to its wavelength and is less important for causing visual effects. Lasers of all colours, except invisible lasers, can induce glare (ICAO, 2003). During twilight, dawn and night-time, greenish-yellow lasers of 500–600 nm (88%) are hazardous for a possible illumination (Murphy, 2009). Blue and red lasers (ca. 5%) of equal power are less illuminating and less distracting (Nakagawara et al., 2010).

Secondly, the occurrences of laser attacks correlate with natural light (i.e., time of day), day of week, and month (Nakagawara, Montgomery, & Wood, 2011). They are more likely from late summer through early winter between 7 and 11 pm. During summer the total number of illuminations decline to a lower level because of the longer period of daylight. They are more frequent during weekends. In summary, these temporal factors affect the occurrence of laser attacks on an aircraft.

Thirdly, the distance of the laser’s source in combination with the power of the laser plays a significant role in determining the extent of its potential damaging effect on pilot’s vision. The power of a laser refers to rate with which its energy is emitted (ICAO, 2003). It is measured in watt (joule/second) indicating the amount of optical radiation received in a given period of time. Low powered lasers can damage the eyes from a distance of 200–500 feet (Murphy, 2009). They can cause visual distraction at 1,000–2,000 feet. The laser’s power also interacts with the colour of the light band. For example, an illumination of a 5 mW green laser can cause a distraction at 1,200–11,700 feet, a glare/disruption at 260–1,200 feet, a flash-blindness under 260 feet, and an eye damage under 52 feet. A 5mW green laser represents the maximum laser pointer limit in U.S. (Murphy, 2018). The hazard arising from a laser at different distances can be estimated by software, and will depend upon power, divergence and colour band (International Laser Display Association, 2017; Kentek, 2018; Murphy, 2018; Stewart, 2011).

Lastly, beam divergence, motion and speed of aircraft can also play a role in the effects of the laser attack on the pilot’s eyesight, but these factors have not been researched as much. For example, a low-divergent beam can be hazardous at greater distances than a high-divergent beam (Murphy, 2009). In other words, a laser beam of equal power is less hazardous to eyesight if its beam is wider. The hazard arising from different divergent laser beams can also be calculated. Operational factors like beam movement or its location relative to the airport are less well understood. A moving laser beam, as used for laser shows, is more likely to strike an aircraft than a static beam. In summary, there are many different factors contributing to the harmful effects of laser incidents on pilots. Effective countermeasures should aim to minimize the laser hazard for aircraft especially at low-altitude flight operations.

The present paper aims to analyse how laser attacks are handled in principle and practice in the field of commercial aviation. It contributes to closing the research–practice gap by applying a systems theory accident analysis technique to assess the current state of the countermeasures used against laser attacks (Underwood & Waterson, 2013). There is a lack of research investigating the issue of laser attacks holistically as well as the Human Factors and Ergonomics being involved in operations. Although laser illuminations on the flight deck have officially been recognized as a hazard to flight safety, the contributing areas of research are fragmented. Here, international regulations (ICAO, 2017b), national politics (Elias, 2005), less research units (Nakagawara, Wood, & Montgomery, 2006) and industry (Warwick, 2017) have contributed to assess the issue and minimize the hazard. Nonetheless, the only publication having dealt with substantive operational procedures for pilots is the SAE International (2009) which further details the suggestions outlined by ICAO (2007). No public information is available on how well these procedures are established in aerial practice. Therefore, we chose a systems theoretic perspective to analyse an exemplary incident of a laser attack on an aircraft including all involved fields into the hazard analysis. The analysis considers all current countermeasures to evaluate this special type of incident comprehensibly.

Subsequently we transferred the exemplary incident of a laser attack to Reduced-Crew Operations (RCO) and in order to understand its potential effects. RCO represents an alternative option to SPO for commercial airlines. Several research groups have already investigated the potential impact of RCO in commercial aviation (Harris, 2007; Lachter, Brandt, Battiste, Matessa, & Johnson, 2017; Stanton, Harris, & Starr, 2016). One of the main hurdles to this concept for flight operations is pilot incapacitation, including a laser attack (Johnson et al., 2012). If the single-pilot becomes incapacitated, control has to be handed over to automated or another human operator (on the ground). The extension and transfer of the scenario of a laser attack to RCO represents an in-flight incapacitation induced by a laser illumination. Hence, the analysis provides a first systematic picture on how this potential hurdle to commercial RCO can be encountered. In this way, we could model potential effects of a laser attack on the operations of a single-pilot aircraft.

# 2. Method

The System Theory Accident Modelling and Process (STAMP) provides a holistic view on how we can understand incidents and accidents. It serves as causal model for the corresponding proactive hazard analysis technique, the System-Theoretic Process Analysis (STPA; Leveson, 2011). The technique has its roots in Rasmussen’s system theory (Leveson, 2017). System theory argues that risk management is rather a control problem that must be modelled across the area of several disciplines and different levels of control (Rasmussen, 1997). Consequently STAMP understands a system as *“interrelated components that are kept in a state of dynamic equilibrium by feedback loops of information and control”* (Leveson, 2004, p. 250). The system dynamically adapts to the environment in order to reach its goal. Hence, the analysis technique includes all components being involved in accident causation across the entire sociotechnical system. We explain this definition of a sociotechnical system and how accident causation is understood by considering the contents of STAMP in detail.

STAMP consists of three primary components: safety constraints, hierarchical safety control structures containing control loops, and process models (Leveson, 2004). Safety constraints are the relationships between the system variables which are in other words statements about which types of system level behaviour and states are acceptable or unacceptable for safe operation. These can be a fail-safe design, standards in design, redundancy, maintenance processes, standard operating procedures, regulations, laws, insurance, and other social controls like social or organisational culture (Leveson, 2017). If the environmental conditions change the system still has to operate safely. Hence, safety is understood as control that results from appropriate constraints in place. In the system, a human and/or automated controller enforces these constraints through behaviours and interactions. A lack of appropriate safety constraints leads to incidents and accidents by an improper (or lack of) enforcement of them on the components’ behaviour. It can happen at each level of the hierarchical safety control structure. This structure represents the system as a hierarchy of control that is characterised by adaptive feedback loops and mechanisms. In general, a controller has goals which affect the system’s state. This controller uses a model of the system to ascertain the system’s state (Leveson, 2004). This model enforces safety constraints on the operating processes. For example, a human controller would hold a mental model of the system (Revell & Stanton, 2012, 2017) whereas an automated controller’s model would rather consist of a formal control logic. A human controller interacts with an automated controller in a feedback loop that can contain multiple automated and human controllers. In a feedback loop, actuators implement command signals as control actions from a controller whereas sensors give values obtained about a controlled process as feedback to the controller. The mechanisms of control for a complex socio-technical system are modelled in a hierarchical control structure. Such a structure can be created for system development and system operations (Leveson, 2017). Each controller both enforces constraints and is enforced by constraints. Consequently, controllers are all part of different feedback loops to enable safe system operation. The control structures change over time, which migrate a system towards higher or lower states of risk. Process models describe the operation between the controllers of each hierarchical level. They are part of previously described control loops. In this feedback loop a controller can carry out four types of Unsafe Control Actions (UCAs; Leveson, 2017, p. 588):

1. A control action is not provided;
2. An unsafe control action is executed;
3. A control action is executed too early or too late;
4. A control action is applied too short or too long.

These four types of UCAs explain how a lack of appropriate constraints can be made of. In this way, STPA explains the occurrence and causation of an incident/accident. It makes use of this model of causation by analysing the process models in detail.

STPA offers three main advantages compared to other hazard analysis techniques (Leveson, 2011). Firstly, traditional techniques tend to include just a selected series of events into hazard analysis. Accidents are viewed as a chain of component failure events. Hence, the selection of events and decision of where to start the analysis makes its results subjectively depending on the analyst(s). Failures are explained as a lack of reliability or redundancy of single components. Event tree analysis (Čepin, 2011), fault tree analysis (Geymar & Ebecken, 1995; Lee, Grosh, Tillman, & Lie, 1985) and the Failure Modes and Effects Analysis (FMEA; Aven, 2015) are examples for top-down reliability analysis methods. Here, the analyst selects at least one event at the top, i.e. the beginning in chronological order. The subsequent analysis is dependent on this start event by determining subsequent events under analysis. The Hazard and Operability (HAZOP) analysis (Dunjóa, Fthenakis, Vílcheza, & Arnaldosa, 2010) represent examples for a bottom-up reliability analysis technique. It looks at an existent or future system by breaking down the design into manageable section with clear boundaries. Then, the given design is compared with the ideal normal operations to detect deviations from the norm. The selection of the parts of the system under analysis is done subjectively as well. Systematic Human Error Reliability and Prediction Approach (SHERPA) is generally considered on the better preforming human error identification techniques (Stanton & Baber, 2002; Stanton et al., 2009; Stanton & Stevenage, 1998). Juxtaposed to the aforementioned technical reliability methods, SHERPA focuses on the human tasks and how they could go wrong. In contrast to all these technical and human reliability techniques, STPA captures the entire accident process by including new causal factors the mentioned traditional techniques cannot assess in their entirety. It includes the whole scenario and the sociotechnical system on all levels. There is no need of selecting a starting event. Secondly, STPA can be used for the design of a future complex sociotechnical system in early conceptual design phases. It supports designing safer systems throughout the whole system life cycle (Leveson, 2017). The application of STPA only requires a design concept of the given system under analysis. Therefore, STPA is the method of choice if we investigate incidents and accidents in commercial aviation with the goal to transfer the scenario to possible future RCO which do not exist yet. Thirdly, STPA is not limited to numbers and offers a qualitative understanding of accident causation. It includes software and human operators into one analysis whereas traditional methods mentioned previously consider human and technical components separately. Systems theory is applied to safety by understanding accidents as a complex process involving interactions in the sociotechnical system. Thus, STPA helps to identify possible contributing factors to an incident/accident as a lack of safety constraints.

STPA is conducted in following two steps. Firstly, the UCAs that can lead or lead to an incident or accident are identified. These are the four different types of UCAs in STAMP (Leveson, 2017, p. 588). They define inadequacies of control in the system. Secondly, the reasons for UCAs in the control loop(s) are investigated. How a control action could be improved to provide protection is also investigated. The reasons contributing to the UCAs’ occurrence have to be identified.

STAMP and/or STPA have been applied to different complex sociotechnical systems of various domains. Among these are several applications in aviation (Allison, Revell, Sears, & Stanton, 2017; Fleming & Leveson, 2014; Kogelbauer, 2016; Plioutsias & Karanikas, 2015; Plioutsias, Karanikas, & Chatzimichailidou, 2017) and aerospace (Ishimatsu et al., 2014; Leveson, 2007). Other application areas are the automotive domain (Abdulkhaleq et al., 2017; Bagschik, Stolte, & Maurer, 2017; Mahajan, Bradley, & Pasricha, 2017), road transport (Kazaras, Kirytopoulos, & Rentizelas, 2012; Salmon, Read, & Stevens, 2016), maritime transport (Aps, Fetissov, Goerlandt, Kujala, & Piel, 2017; Kim, Nazir, & Øvergård, 2016; Rokseth, Utne, & Vinnem, 2016, 2018), and rail transport (Ouyang, Hong, Yu, & Fei, 2010; Siegel & Schraagen, 2017; Underwood & Waterson, 2014). In a broader methodological scope, systems theory was used in several other systemic accident analyses. An example is Rasmussen’s Accimap method (Goode, Salmon, Lenne, & Hilliard, 2014; Newnam & Goode, 2015; Waterson, Jenkins, Salmon, & Underwood, 2017). Different techniques of system theory methods were also combined to analyse the Edge Hill railway accident (Santos-Reyes & Beard, 2015), the management of distracted driving (Young & Salmon, 2015), and road safety strategies (Hughes, Anund, & Falkmer, 2015). In summary, STAMP and STPA include all fifteen core systems thinking tenets which assess system performance holistically (Grant, Salmon, Stevens, Goode, & Read, 2018).

We applied STAMP and STPA to the laser incident of the scheduled passenger flight of Boeing 737-8AS approaching Porto (Portugal) which is described in the beginning of the present paper (AAIU, 2016). The scenario was used to create a model for current Multi-Crew Operation (MCO) and was subsequently applied to RCO. Additionally, we used several materials to construct the hierarchical control structure (Oxford Aviation Academy, 2008). Afterwards, we validated the results of the STAMP and STPA of the laser incident in two video conferences with a commercial pilot as Subject Matter Expert (SME). The pilot was male, aged 28 years, holding a CPL and frozen ATPL. He had flight experience of 1,800 hrs flying time of which 1,400 hrs were done on a B747-800. He had experienced a laser illumination strike during approach without long-lasting effects of visual sight loss.

# 3. Results

## 3.1 Multi-crew operations

To start with, we identified the countermeasures against laser attacks by creating a hierarchical control structure of current MCO in commercial aviation (Fig. 2). The structure represents MCO in an abstracted and formal way. Hereby, multi-crew refers to current flight operations by two-manned cockpit crew of airliners including relief pilots on long-haul flights. Table 1 lists the regulations currently in place according to their level in the hierarchical control structure (Fig. 2). Each of them is subsequently specified top-down of the structure.

On the upper level, the ICAO (2017b, pp. 6–9) provides a general base for national legislation and supports the multinational and national aviation agencies in laws and rulemaking. It has defined protected zones around aerodromes to prevent laser attacks on aircraft and crew which are summarized in Table 2. These zones should be established and represent an optional regulation without lawful character. ICAO’s Doc series 9815 *Manual on Laser Emitters and Flight Safety* (2003) provides general information and guidance on the hazard arising from laser attacks on aircraft.

On the national level, governments have acted to restrict the danger of lasers to aircraft over the last two decades. They have restricted the sale and use of laser devices. Furthermore, governments have amended criminal statutes associated with laser devices interfering with flight operations (Elias, 2005). Under U.S. national law, aiming to shine a laser pointer at an aircraft is under punishment with an imprisonment of 5 years, a fine of $25,000 or both ("Aiming a laser pointer at an aircraft," 2012). In the UK, laser attacks are currently covered by the Air Navigation Order article 225 and 240 as an offense with a maximum penalty of a fine of £2,500 (Civil Aviation Authority, 2016). A laser attack is not specified directly, rather it is covered within formulation of an “endangerment of an aircraft“. Hence, this legislation may not be as effective as it could for the police to prosecute the perpetrators. At the moment, the British government calls for evidence to address serious public safety concerns and diminish them by different countermeasures (Margot, 2012). In Germany, the total number of laser attacks has decreased and is according to § StGB 315 is covered as “dangerous intrusion into rail, maritime and aviation transport“ under punishment with an imprisonment of at maximum 10 years (Luftfahrt-Bundesamt LBA, 2017; Tagesschau, 2017). After the incident described above, the AAIU Ireland recommended that the Portuguese civil aviation authority should review the current civil aviation legislation and specify the illumination of an aircraft with a laser, as well as attempting to do so, as a criminal offense (Flynn, 2017). The legislation regarding shining, and attempting to shine, a laser pointer at an aircraft varies by country, none directly specifying against laser attacks. Therefore, we cannot assume this control action is completely fulfilled.

Other countermeasures may be more efficient against laser attacks. Firstly, a simulation software solution can determine the position of a laser attacker on aircraft by using geospatial analyses (Talhofer, Baláž, Racek, Hofmann, & Hošková-Mayerová, 2012). This approach can support the authorities in investigating a laser attack report and aims to make their interventions more effective. Secondly, industrial, military and research-related lasers belong to Class 4 and represent authorized laser activities (International Civil Aviation Organization, 2017b). These high power lasers are not readily available for public use by private individuals because they can damage skin, enflame materials, and cause severe eye damage when viewed directly. Nonetheless, they are often used for purposes that inadvertently interfere with aircraft during departure and arrival phases, such as for laser shows and research observatories. The hazard of a possible unintentional laser attack on aircraft had already been recognized. Research has developed different technical solutions to detect aircraft automatically and prevent a laser illumination of them (Coles et al., 2012; Rahmer, Lefebvre, & Christou, 2016; Stomski, Goodrich, & Shimko, 2008; Stomski, Murphy, & Campbell, 2012). For example, a technical system can detect aircraft in vicinity to a laser beam. A simple electronic radio system was developed to detect aircraft by using ATC radio transponders which are installed on every business and commercial aircraft (Coles et al., 2012). When an aircraft is close to the beam the system automatically shuts the laser down. This solution has been validated as a possible countermeasure for lasers that are operated by observatories. Thus, there are several activities already being conducted which aim to minimize the hazard that arises from public laser activities for airliners.

On lower levels of the STAMP control hierarchy, countermeasures internal to the aircraft try to minimize the danger for the flight deck crew. Technical solutions provided by the aircraft manufacturer on the flight deck are not mature yet. Classical optical protections, so-called Laser Eye Protections (LEP) absorbs light but represents a significant drawback in terms of colour distortion and low transparency (Airbus innovation, 2016; Pierre, 2017). Hence, they are not compatible with a safe aircraft operation. At the moment, Airbus is investigating a retrofittable laser protection film for cockpit windscreens in cooperation with Metamaterial Technologies Inc. (MMI) with the aim of validating and certificating the film (Warwick, 2017). The windscreen film should reduce laser illuminations to a safe optical level, whilst also complying with safe flight operations (even at night), as well as being integrated to aircraft environment. Currently, there are no visual laser protection shields in place because they are either under development, like the retrofit for the cockpit windows, or they do not comply with aircraft safety regulations like the classical optical protections (Airbus innovation, 2016).

Combinations of approaches are recommended to ward off a laser attack on the flight deck. Pilot operational procedures have initially been suggested by ICAO (2003) and were further specified and formally published as a standard by SAE International (2009). This document defines pilot operational procedures which are recommended after encountering a laser illumination depending on the flight phase. For example, the SME was introduced to pilot operational procedures regarding laser attacks by the airline. We could not find any further data on how this is undertaken in any specific airlines. Hence, we only can assume that airlines include these operational procedures and train pilots on responses to laser attacks.

The focus in this paper is on the flight phases most associated with arrival because they are often the most affected by laser illuminations (Nakagawara et al., 2010). It is generally recommended that crew members avoid looking into the source of the laser, do not rub eyes, and that they seek medical assistance if necessary. In areas of known authorized outdoor laser activity, NOTAMS report the location and distance of its source, schedule of activity, relative power and colour. In this case one pilot is optionally recommended to look head down into the flight deck and to shield their eyes. Table 3 shows the recommended operational procedures and corresponding checklist for a laser attack during approach and landing. This checklist begins with preparations for a missed approach procedure. It includes the communication of a laser attack to other crew members and ATC. The optional increase of background light of the cockpit should minimize the light differential between cockpit and laser. Consequently, it potentially enables the crewmembers to recognize and control flight instruments until their eyes adapt back to normal visual function after a laser illumination. Furthermore, the procedures contain an additional check of legibility of instrument indications during whole approach which is not common during normal conditions. During departure, the operating procedures are comparable apart from the missed approach procedure (SAE International, 2009). The operating procedures during ground operations differ and are separated into three checklists for illumination in taxi-out, landing-rollout, and taxiing to the gate. All involve a stop of the aircraft on its position, setting the parking brake, contacting ATC and report incident, the cycling of external lights for ATC identification, request taxi instructions or a tow depending on individual circumstances.

The STPA of the exemplary laser incident is used to analyse how far any special operational procedures are established as control actions against a laser attack in practice. It considers the processes of the control loops between both pilots, and between each pilot and the aircraft. We could identify 6 control actions in the laser illumination incident:

1. Detect laser and inform crew member;
2. Look away or shield eyes from the light;
3. Increase the brightness of interior lights and put additional light on instrument panel;
4. Engage autopilot or transfer control to other pilot if they are not affected (use autoland if available);
5. Inform the controlling agency and provide location of source;
6. Land aircraft safely.

We omitted the general recommendations of: ‘do not rub the eyes for health reasons’, ‘report incident to the police’ and ‘consult a doctor’ because they apply in all instances. Additionally, we assumed that the autopilot was operating, as it was in the present incident. The use of an autoland system is always recommended in case of a laser attack (Derenski, 2010; SAE International, 2009). The control action (1) can be delayed if the pilot first detects a laser beam outside which later shines into the cockpit. He has always to inform his crew member(s) about a laser outside the cockpit windshield because it could shine into the cockpit. If so, the laser strike usually disrupts crew coordination, as it did in the example. Here, the absence of control action (1) “Detect laser and inform crew member” affected the operations during approach so that a missed approach procedure had to be carried out. The FO (PF) detected the laser but did not inform his crew member. Consequently, the laser also flashed the Captain (PM).

Fig. 3 shows the control loops for this laser illumination in MCO. Table 4 lists the corresponding UCAs. The inner state of the pilot glared by laser (PM) is shown in the middle box whereas the inner state of the healthy pilot (PF) is shown in the upper box. The pilots’ dominating goal of “approaching descent” is additionally highlighted inside the boxes. The control loop involving both pilots represents the crew coordination inside the cockpit. The instruments and control of the aircraft is presented separately in its own control loops for each crew member. The aircraft as “automated controller” was added at the bottom of the loop. Both human controllers affect the aircraft’s state with UCAs. All UCAs are numbered in chronological order in the control loops of Fig 2. The PM is not aware of the laser, looks up and suffers a flash-blindness. As a consequence the PF’s actions following the late “approaching descent“ call get delayed. The crew coordination disrupted by the laser attack resulted in an unstable approach. The aircraft was above the ideal flight profile. Hence the crew conducted a missed-approach procedure. The STPA identified the UCAs to explain how this incident happened.

## 3.2 Reduced crew operations

We examined the laser attack scenario in RCO to assess the possible impact on a new concept of operations. In applying STAMP and STPA to SPO/RCO we assumed that a single-pilot in the cockpit is supported by a remote-copilot in a ground station (GS) when needed. Several research approaches have employed a ground support to assist the single-pilot during high workload or emergency situations (Lachter et al., 2017; Schmid & Korn, 2017; Stanton et al., 2016; Vu, Lachter, Battiste, & Strybel, 2018). This high-level function allocation was adopted. In addition, we made following assumptions to specify the concept of operations for analysis. A flight planning and navigation support by a remote-copilot is mandatory during departure and approach because these flight phases are characterized by high workload (European Commission, 2015; Federal Aviation Administration, 2001). They act as PM for the single-pilot during normal situations. This mandatory support during arrival is advantageous if an emergency situation arises, because the remote-copilot could assist and even take over control as they are familiar with the context. It may help the remote-copilot in “control hand-back” because they are already in the flight control loop (Endsley & Kiris, 1995). Being in the loop should help them to resume control and acquire situation awareness (Eriksson & Stanton, 2017). In one study investigating off-nominal situations in the cruise phase of flight where a remote-copilot assisted as PM (Brandt, Lachter, Battiste, & Johnson, 2015). The remote-copilot was able to acquire situation awareness without any prior knowledge about the flight. The GS presented the relevant flight information and flight instruments on its displays. Nonetheless, the flight phases of departure and arrival have much higher workload, as mentioned previously. Hence mandatory support may still provide the remote-copilot with useful prior knowledge for taking over control during approach. A similar concept providing a PM’s assistance during arrival was investigated already (Koltz et al., 2015). The remote-copilot could monitor 4–6 arriving single-pilot aircraft in sequence.

RCO as described cannot operate without adding additional automation systems and a data-link connecting single-pilot aircraft with the GS. Automation issues are as important as handling an incapacitation in RCO (Johnson et al., 2012). Hence we have to predefine these automation systems which directly relate to operational procedures regarding a laser attack in approach. Here, we assume a remote-copilot call lever and switch for a hand-over of aircraft flight control. The system directly establishes a connection via data-link to ground support. Firstly the single-pilot can immediately call for support via the remote-copilot call lever. Secondly the single-pilot can directly transfer control to the remote-copilot at the GS by pressing an additional switch. Other automation systems are omitted because they are not relevant for the present type of incident (for the interested reader we suggest consulting: Lachter et al., 2017; Schmid & Korn, 2017; Stanton et al., 2016).

The hierarchical control structure of system operation for RCO changed because the infrastructure for RCO had to be added (Fig. 4). The remote-copilot was placed at the same level in the hierarchy as the single-pilot. Only the crew interaction changed inside the control loop, which is presented later as the result of the STPA. The remote-copilot’s work station, the GS, was built in at the same level as the aircraft. These workplaces would be located at an airport at remote-copilot centres. An external incident support may be established on a higher level as depicted. It could assist in rare emergency situations, such as terroristic attacks. All four elements required for RCO were added to the control structure of MCO. In sum, the flight operations only changed at the flight crew’s level by addition of the ground support function. Therefore we assumed that the countermeasures against laser attacks of laws, regulations and industry would be valid for RCO.

STPA is applied to investigate the possible changes in the operational procedures and corresponding control loops on the crew interaction’s level. The box of the remote-copilot of Fig. 4 refers to following two types of support. As mentioned previously, during departure and arrival phases of flight the support is mandatory due to the high workload (European Commission, 2015; Federal Aviation Administration, 2001). The remote-copilot would be a professional commercial pilot, with a supplementary license for RCO. He would perform his job as both a single-pilot and a remote-copilot on a shift roster. The shift roster fulfils the purpose of keeping the skills as single-pilot and remote-copilot up-to-date. A high-speed and safe data link is assumed to connect RCO aircraft and GS. In general, the remote-copilot has the monitoring function but can take over control if required.

For the transfer of the scenario of a laser attack, we assumed that the single-pilot as PF is illuminated by the laser and suffers a flash-blindness. In the example, they are approaching Porto and had not been aware of the laser from the city centre. Therefore, the control actions address the single-pilot as pilot-in-command in the air. If a control action refers to the remote-copilot it is indicated. Six control actions were identified:

1. Detect laser;
2. Shield eyes and hand over control to remote-copilot;
3. Remote-copilot: Take over control and inform ATC;
4. Increase brightness of interior lights;
5. Inform remote-copilot when sight has recovered;
6. Take over communication management.

These control actions were applied to the laser incident on the approach to Porto. Table 5 lists the corresponding UCAs and safety constraints and Fig. 5 depicts them as control loops. In case of a laser illumination, the single-pilot can immediately hand-over control to the remote-copilot via the remote-copilot call lever for hand-over control. When the single-pilot is struck by the laser he is mandated to hand-over control. The remote-copilot takes over control, confirms it, and informs ATC about the laser attack. Meanwhile the single-pilot increases brightness in the flight deck and informs the remote-copilot when his visual function has returned. After that the single-pilot takes over the communication management and informs ATC again about the present state of the flight. This is the last control action for the single-pilot when his visual function had come back. Following this procedure, the aircraft maintains at its flight profile and could be landed safely without requiring missed-approach procedure. The missed approach procedure would usually not be required because the remote-copilot can pursue the flight plan without any disruptions. The autopilot remains turned on. Furthermore, the remote-copilot can apply autoland, which every single-pilot aircraft is assumed to be equipped. The single-pilot’s visual function should return because irreversible damage to eyesight resulting from a laser attack on an aircraft are very rare (Gosling et al., 2016). Hence the single-pilot can take over the communication management and further assist the remote-copilot in landing the aircraft safely. Nevertheless the laser poses still a hazard and consequently the single-pilot should not resume flight control back.

# 4. Discussion

Using the holistic model of STAMP and STPA for hazard analysis, we analysed a laser illumination incident of a Boeing 737-8AS on its approach to Porto. In this example, the PM was temporarily blinded. By creating the hierarchical control structures, we could identify the safety constraints regarding a laser attack at each level at their current state. The reference and implementation to practice was complemented by a STPA of the laser illumination incident. We identified control actions for handling a laser attack in MCO operations. In a further step, we applied the scenario to RCO and modelled it based on a hierarchical control structure extended by RCO’s components. The control actions differed from those in MCO because the remote-copilot was displaced to a GS. In sum, all UCAs and the corresponding safety constraints were collected and presented on their current state.

The airlines train the pilots to handle a laser strike with recommended operating procedures (AAIU, 2015). By comparing the control actions in the MCO scenario with the recommended pilot operating procedures for unauthorized laser illuminations (SAE International, 2009) we can draw following conclusions. Detection of the laser and communication of the hazard to the rest of the crew is the first priority. This step is essential to create awareness of a laser hazard and to be prepared for a possible laser glare into the cockpit. Only if the flight deck crew are aware of a laser hazard they can shield his eyes or look away. This was not done in the present example. In this case, the PF did not inform the PM about a laser light outside. Hence the PM was glared and could not call out “approaching descent” which in turn delayed subsequent procedures. The control action of increase of light at the instrument panel and transfer control to the unaffected pilot could be undertaken although they were not conducted in the exemplary incident. All other control actions are in agreement with the SAE Standards and fall under the last control action of landing aircraft safely. This includes deciding on a missed-approach procedure. ICAO (2003) kept it similar to our control action and lists protection of the eyes as a first priority and communication with the other crew member as the second priority (see as well: Derenski, 2010). Here increasing the lighting of instruments and the missed-approach procedure were omitted. It is debateable if the increase of background light should be a mandatory procedure. It is currently considered as an optional operational procedure to minimize light level differences between laser and instruments (SAE International, 2009). It should enable pilots to read flight instruments more easily while their eyes adapt back to normal visual function in darkness after a bright illumination. We can conclude that the control actions defined in the present paper imply that an awareness of laser and communication to crew member are of the highest priorities. Taking up the awareness and communication of a laser as the most important issue in the management of a possible subsequent laser attack is desirable. The subsequent control actions match the SAE Standards and are known among pilots. Nonetheless, an emphasis on education about laser strikes and reinforcement of applying the recommended operational procedures is needed to reduce the consequences of the hazard.

For RCO, the detection of the laser is crucial as well to shield eyes or look away. Whether glared or not, the single-pilot should hand over control to the remote-copilot. Both control actions are required to continue landing the aircraft safely. Hence the remote-copilot also informs ATC about the laser attack. They remain in control and land the aircraft safely due to the laser hazard, which can only strike the single-pilot. Meanwhile the single-pilot should wait to recover their visual sight and take over the communication management of the aircraft. For each type of operation, it is important to detect the operation of a laser outside the aircraft to successfully implement the countermeasures that guard against the effects. This is what pilots can currently apply during flight to minimize the laser hazard.

Furthermore politicians, regulators and industry have recognized the threat arising from laser attacks and reacted with different strategies. Most of them are currently in progress but not yet implemented. Nonetheless, it does mean that the topic of laser attacks is being taken seriously. Fig. 6 shows the time course how different stakeholders have been counteracted laser strikes in aviation on different levels. It also summarizes the results of STAMP. Around the turn of the millennium, the laser hazard was known but not countered frequently. ICAO had published SARPs on it as a whole manual on laser emitters and flight safety in 2003. Politicians have taken up the issue and started working on it (Elias, 2005). In USA, data were collected about the frequency of the strikes and research was undertaken on the topic (Murphy, 2009; Nakagawara & Montgomery, 2001; Nakagawara et al., 2010). SAE International (2009) formulated and published standards, including operational procedures which are now in use. Most states have now begun to systematically document the occurrences of laser strikes in aviation (Fig. 1).

Over the last decade, laser attacks initially increased and then plateaued (Fig. 1). The absolute frequencies of laser attacks have increased, which might be the reason why further counteractions were taken. Observatories have developed a fully automatic aircraft detection system to comply with the national legislation of the FAA (Coles et al., 2012; Rahmer et al., 2016; Stomski et al., 2008; Stomski et al., 2012). These countermeasures are accompanied by political and legislative measures which vary across the different countries. Legislative countermeasures against laser attacks, which define the act or intent to shine a laser against an aircraft under punishment, are a necessary requirement for a successful combat of them. In the US their number has increased at times despite 18 C.F.R. § 39A ("Aiming a laser pointer at an aircraft," 2012). In contrast to US, the number of laser attacks has decreased very slightly in Germany since 2012 where the act contains punishment as well (Luftfahrt-Bundesamt LBA, 2017). The existing regulations and guidelines are the same for all countries but the legislation and handling of the issue inside of the airlines differ. It is assumed that the airlines inform the pilots about laser strikes but no data are published on how the FAA’s material on educating about laser strikes is being used in practice (Federal Aviation Administration, 2009). Our findings coincide with the FAA’s educational material published on laser attacks, that training is the most important strategy to handle the hazard in practice. The pilot who validated the results could name all the operational procedures which SAE recommends (2009). For example, the airline he is working for has introduced operational procedures and conducts training for its pilots. These procedures included almost all operational procedures of SAE (AAIU, 2015). The decision for a missed approach procedure remains dependent of the individual situation because a laser attack does not always blind a pilot nor do the effects last very long. It seems the latest promising solution of a retrofittable laser protection windshield for cockpit windows would be welcomed by pilots (Warwick, 2017). This would protect pilots against a laser strike even if it occurs. Therefore, we concluded that the open issue to counter laser attacks is a joint venture of all stakeholders being concerned with the hazard. This includes the legislation by governments, technological developments by aircraft manufacturers, procedures by airlines, training of pilots and prosecution by authorities.

Fortunately, no laser attack is known to have resulted in the crash of an aircraft thus far. Nonetheless, the present regulatory and political approaches do not manage to prevent laser illuminations and attacks. At the moment, less is known about which countermeasures do actively influence the occurrences of laser attacks. It is unclear how effective higher penalties against laser attacks would stop them. A further analysis of the factors influencing the prosecution of a laser attacker in the field is beyond the scope of the present paper. At this point, further international cooperation and research is needed. Systematic mandatory data collection on laser attacks would be a good start. Each nation state currently collects the occurrences of laser strikes in aviation (Nakagawara et al., 2010). The only international approach to systematically collecting data on laser attacks is on a voluntary basis. Eurocontrol provides to its member states a voluntary Air Traffic Management (ATM) incident reporting scheme (EVAIR – Eurocontrol Voluntary ATM Incident Reporting) to obtain a systematic picture of the occurrences of laser incidents (Eurocontrol, 2016). Hence, a systematic consistent international statistics on laser incidents is difficult to obtain.

The future concept of RCO for commercial aviation seems promising in adding additional safety measures against laser attacks. The fact that a remote-copilot should be available at a GS during approach leads to following implications for laser attacks against a single-pilot aircraft. The support by a remote-copilot and their availability at a GS should provide support in the event of pilot incapacitation (ICAO, 2012; Lachter et al., 2017; Schmid & Korn, 2017; Stanton et al., 2016). The presence of a remote-copilot enables the single-pilot to hand over control to the remote-copilot in the event of laser illumination. The remote-copilot is safe from laser attacks at the GS. During the period of the attack, the single-pilot can increase the brightness of interior lights in the cockpit and wait until his visual function to return. Then, the single pilot can inform the remote-copilot and take-over the communication management until end of flight. It is assumed that RCO, such as that modelled in the present study, can handle a laser illumination in a manner that is as least as safe as, or even safer than, MCO. This assumption has to be evaluated more formally in a human-in-the-loop simulation of RCO, which will give further insights into variables related to flight operations (Vu et al., 2018).

# 5. Conclusions

In summary, the operational procedures for pilots being illuminated by a laser seem to be established quite well. Nevertheless, the detection of lasers operating in the vicinity of aircraft and protection of pilots’ eyes could be improved. Industry is currently tackling this issue, but nation states could improve the legislative and executive handling of a laser attack as a criminal offense. Statistics regarding laser attacks are collected by different aviation authorities and serve as a reference for current countermeasures. This remains a high priority in Europe and the USA (Civil Air Navigation Services Organisation, 2014). The factors influencing a laser attack are currently under investigation. This includes the classification of their threat, the colour and power of lasers, their harmful effects on vision and possible eye damage(s), their correlation with natural light, day of week, and month, and flight phases (Gosling et al., 2016; Murphy, 2009; Nakagawara et al., 2007; Nakagawara et al., 2008).

The present paper presented STAMP and STPA (Leveson, 2004, 2011, 2017) to model the current handling of laser attacks. These analyses showed the effects of the safety constraints already in place. Their state of elaboration is sufficient to have countered laser attacks without any fatalities so far. Nonetheless, there is a need for improvements in legislation and prosecution. Further research is needed to understand why laser attacks are increasing in some countries and declining in others (Fig. 1). In most countries, laser attacks are a criminal offense (e.g. 18 C.F.R. § 39A & StGB § 315). Information about airlines training for laser attacks is difficult to collect. Our example suggests that the airlines are well aware of the hazard and have developed countermeasures into operational procedures. It is argued that an emphasis should be placed on the detection and communication of a laser operating outside the aircraft so that the procedures can be applied promptly. In addition, the high frequency of the attacks has led the aviation industry, such as Airbus, to the develop a retrofittable cockpit laser protection for the windshield (Warwick, 2017). Furthermore, it seems the future development of RCO could be at least as safe as, or even safer than, contemporary operational procedures. This latter option should be formally evaluated in an aircraft simulator before operational trial. The growing concern in civil aviation about laser attacks is legitimate but research is underway to help develop effective strategies to prevent, control and mitigate the effects on pilots.

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Table 1. The existent safety constraints with relations to the hierarchical safety control structure of commercial aviation operations.

|  |  |  |
| --- | --- | --- |
| **Safety control structure** | **Regulatory measure** | **Current state (available countermeasures)** |
| ICAO | * SARP for civil aviation * Guidelines | * SARP: Adequate steps shall be taken to prevent emission of laser beams from adversely affecting flight safety (Annex 11 – Air Traffic Services: 2.18.5) * SARP: Laser beam protected zones around aerodromes (Annex 14 – Aerodromes: 5.3.1.2) * Manual on Laser Emitters and Flight Safety (DOC 9815) including operational procedures |
| STATE | Laws | * Per state: Different laws and varying sanctions on shining a laser pointer on aircraft * Regulations on sale of lasers: usually Class II and IIIa lasers available for sale to public * Technical aircraft protection system at lasers of observatories |
| Multinational and national agencies for flight safety | Data collection  Air law | * Statistics of laser incidents * Comply with SARPs, transform them to national law, and check their fulfilment |
|  | SAE ARP5598 | Pilot Operational Procedures |
| Airline | Procedures for flight crew | Operator should inform flight crew about procedures which handle being exposed to laser or high-power light |
| Aircraft manufacturer | Protection systems | Development of a retrofittable laser protection film for cockpit windscreens |
| ATC – Crew | NOTAM | Information on authorised or detected laser outdoor activities |

*Notes*. We refer to several sources (International Civil Aviation Organization, 2003, 2016a, 2016b, 2017a; Oxford Aviation Academy, 2008; SAE International, 2009).

Table 2. Laser beam protected zones around aerodromes according to ICAO.

|  |  |  |  |
| --- | --- | --- | --- |
| **Flight zone** | **Range [NM]a** | **Range [feet]** | **Description** |
| Laser-beam free flight zone (LFFZ) | [0;3] | [0; 2,000] | Intensity of laser light is restricted that it is unlikely to cause any visual disruptions (< 50 nW/cm2). |
| Laser-beam critical flight zone (LCFZ) | [3;10] | [2,000; 10,000] | Irradiance must not exceed 5µW/cm2. Glare effects are possible. |
| Laser-beam sensitive flight zone (LSFZ) | [10;∞] | [10,000;∞] | Irradiance must not exceed 100 µW/cm2. Flash-blindness or after-image effects possible. Protection from more serious harmful effects. |
| Normal flight zone (NFZ) | – | – | Any navigable airspace not defined as LFFZ, LCFZ, LSFZ. Must be protected from all irradiance causing biological damage to eye. |

*Notes*. Contents taken from: (International Civil Aviation Organization, 2003; 2017b, pp. 6–9).

a From the aerodrome reference point.

Table 3. Operational procedures and checklist for post laser illumination of crew during landing of SAE International.

|  |  |
| --- | --- |
| **Operational procedures** | **Checklist** |
| 1. Executed missed approach procedures | 1. Execute missed approach procedures |
| 2. AUTOPILOT on |  |
| 3. Increase background cockpit lighting at pilot’s discretion | 2. Increase background cockpit lighting, optional (PM). |
| 4. COMMUNICATE with the other crew member to determine visual condition and status of the aircraft. | 3. Communicate (PM) & (PF). |
| 5. If PF is illuminated, TRANSFER control of aircraft to PM. | 4. Transfer control of aircraft if required. |
| 6. CONTACT ATC to report laser incident and request priority handling if necessary. | 5. Contact ATC. |
| 7. ENGAGE autopilot and coupler for approach and manual landing. | 6. Engage autopilot and coupler for approach. |
| 8. If aircraft has auto land capability, crew may elect to autoland. | 7. Autoland if available, pilots discretion. |
| 9. ALLOW eyes to regain visual function and check aircraft instruments for any deviations from assigned flight landing. | 8. Check aircraft instruments for aircraft status. |
| 10. Continue to CROSS CHECK and verify instrument indications for visual legibility during approach and landing. | 9. Cross check and verify instruments for approach and landing. |
| 11. DISENGAGE autopilot and coupler as per company policy. | 10. Disengage autopilot and coupler for landing as per company policy. |
|  | 11. Report incident to ATC per FAA AC: 70-2. |

*Notes*. SAE International, 2009, p.12.

Table 4. UCAS and Safety Constraints generated for Control Loops comprising “Healthy Pilot”, “Incapacitated Pilot” and “Aircraft” for pilot response to a laser attack.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Control Action/ Feedback** | **(1) Control action is not provided** | **Safety Constraints 1** | **(2) Unsafe control action is executed** | **Safety Constraints 2** | **(3) Control action is executed too early or too late** | **Safety Constraints 3** |
| (1) Detect laser and inform crew member | Not informing about laser light form city centre | Inform crew member |  |  |  |  |
| (2) Look away or shield eyes from the light | Not aware of laser and looking up | Look away or shield eyes from the light |  |  |  |  |
| (3) Increase brightness and put additional light | No addition of light | Operate switch to brighten lights at instrument panels |  |  |  |  |
| (4) Engage autopilot or transfer control if he is not affected (use autoland) | No “approaching descent” call by PM |  | Approaching with too high speed and descent rate  Late request of extension gears and flaps | Request for missed approach procedure | Late “approaching descent” by PF  Delayed corresponding actions  Delayed support and confirmation  Late request of extending gears and flaps | ATC instruction to contact tower frequency  Missed approach procedure |
| (5) Inform agency and provide location of source |  |  | Informing ATC about laser (blind) | Wait until flash-blindness is over |  |  |

*Notes*. The incident of on the flight from Lille Airport (France) to Porto (Portugal; AAIU, 2016). We could not identify any control action applied too short/long and therefore deleted its column.

Table 5. UCAS and Safety Constraints generated for Control Loops comprising “Single-Pilot”, “Remote-Copilot” and “Aircraft” for pilot response to a laser attack.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Control Action/ Feedback** | **(1) Control action is not provided** | **Safety Constraints 1** | **(2) Unsafe control action is executed** | **Safety Constraints 2** | **…** |
| (1) Detect laser | No possibility to know about laser light from city centre (remote-copilot)  No announcement of “approaching descent” call followed by corresponding actions (single-pilot) | Registration for use of laser devices in public  Restriction to sell laser devices |  |  | … |
| (2) Shield eyes and hand over control to remote-copilot | Failure to look away or shield eyes | No solution for eye protection yet | Alert to GS: Take over control and verbal information about laser | Know about laser before | … |
| (3) Remote-copilot: Take over control and inform ATC |  |  |  |  | … |
| (4) Increase brightness of interior lights |  |  | Addition of light |  | … |
| (5) Inform remote-copilot when sight is not affected anymore |  |  | Removal of additional light  Information on visual function came back |  | … |
| (6) Take over communication management |  |  | Informing ATC about taking over communication |  | … |

*Notes*. The laser attack of the flight from Lille Airport (France) to Porto (Portugal; AAIU, 2016). We could not identify any control action too early or too late executed as well as applied too short/long. Therefore, we deleted the corresponding columns.

Fig. 1. The occurrence of reported laser attacks measured by annual air traffic compared with the total number of laser attacks per state.



Fig. 2. Hierarchical system control structure of multi-crew operations.



Fig. 3. Control loops for the laser illumination incident in multi-crew operations.



Fig. 4. Hierarchical safety control structure for system operation in RCO.



Fig. 5. Control loops for the laser illumination incident in RCO.



Fig. 6. The countermeasures against laser illuminations/attacks in commercial aviation.

