BIO-INSPIRED AIRPLANE CONTROL

Pavel Zikmund **Petr Dvořák**
Brno University of Technology
Faculty of Mechanical Engineering
Technická 2, Brno
Czech Republic
zikmund@fme.vutbr.cz dvorak.p@fme.vutbr.cz

Miroslav Macík **Zdeněk Míkovec**
Czech Technical University in Prague,
Faculty of Electrical Engineering
Karlovo náměstí 13, Praha
Czech Republic
macikmir@fel.cvut.cz xmikovec@fel.cvut.cz

Abstract. The paper presents state of the art in emerging bio-inspired airplane control field of interest. The work is focused on small airplanes which are not equipped with an autopilot. The main review part of the paper gives overview of flow sensors and haptic feedback applications. Additionally, animal-borne flow sensors are discussed as they are an important data source for insects and birds. The paper also deals with haptic feedback and presents recent vibrotactile actuators and their applications in warning and navigation function. Recent projects touching pilot-airplane interaction are also mentioned in the text. The last part of the paper discusses pilot's perception psychology and suggests some requirements on bio-inspired airplane control system with a goal to improve the quality and safety of flight.

Keywords. Airplane control, Flow sensors, Human machine interaction, Haptic feedback.

1 Introduction

Airplane control radically changed because of electronic systems boom in last decades. Most airplanes are equipped with autopilot which help to reduce pilot's workload. The interaction of pilot and autopilot is key safety task[1]. The paper is focused on a particular category – small airplanes without autopilots. These airplanes are used mostly for sport and leisure time flying. The control system remains fundamentally the same from the beginning of powered flying. This system is well tested but still keeps the most dangerous element which is human factor [2-4].

What is the motivation to change something as obvious as an airplane control? Inspiration for an innovative flight control system comes from the nature. Birds are capable of perfect motion in the air just because they feel the airflow around their wings. This advantage is most prominent at low airspeed, near the stall condition, where the birds are able to safely exploit the maximum lift generated by their wings. This benefit is theoretically possible to apply on airplanes and pilot by artificial haptic feedback.

The second motivation to improve airplane control stems from the flight safety reports. EASA annual report [5] points to a trend that Loss of control in flight (LOCI) is the most frequent reason of fatal airplane accidents in general aviation below maximal take-off weight 2500 Kg. EASA states that in average 153 fatal accidents with 255 fatalities per year happened from 2009 to 2013. About 33% caused by LOCI. National Transportation Safety Board (NTSB) in USA [6] gives even higher number, approximately 100 fatal accidents a year caused by LOCI, which is about 40 % of all fatal accidents. Preventing LOCI is in NTSB Most Wanted List 2015 [7] and EASA is heading to change regulations for pilots training [8]. The goal of the new bio-inspired control system is to decrease the LOCI - induced accident count. LOCI is not only issue of small airplanes. Flight accident of A330 (Flight AF447) in 2009 was finally caused by LOCI after interplay of unfortunate circumstances.

The paper is organised as follows: The review part begins with flow sensors used in nature as well as in recent airplanes. The following part describes state of the art in haptic feedback and its applications which are mostly navigation and warning systems. The review section is concluded by haptic feedback already used in airplane applications. The last section of the paper deals with bio-inspired airplane control system idea. Recommendations for bio-inspired airplane control resulting from state of the art are specified.

2 State of the art review

This section summarizes related prior work. Firstly, the focus is put on conventional and natural air flow sensors. Follows haptics description as an important modality in airplane control. Vibrotactile actuators and its applications are presented in warning, navigation and airplane control domains. Finally, recent projects dealing with pilot-airplane interaction are described.

2.1 Conventional flow sensors

To understand flow conditions over an airplane's wing a number of sensors can be deployed. Historically, vanes have been among the first to be used e.g. [9]. They detect angle of attack (AOA), which is correlated to the flow regime around the wing. Certain commercial anti-stall systems feature this approach [10] among others. These sensors are simple yet delicate, rendering them less appropriate for operational deployment. To overcome the aforementioned hurdle, dynamic pressure probes have been used widely both for wind tunnel experiments and in-flight investigations e.g. [11]. This type of sensor is pivotal for a number of commercial anti-stall systems [12,13] among others. Another sensor used among stall avoidance systems is a latch reacting to the stagnation point position [14]. Constant-temperature-anemometry based systems have been used for more precise measurement of the stagnation point location in many research projects e.g. [15].

However, all the aforementioned sensors provide only indirect indication of the flow over the wing. To obtain direct reading of the pressure distribution and hence flow separation extent, pressure taps have been the reference tool for decades. Being used predominantly for wind tunnel measurements e.g. [16] and some in-flight experiments e.g. [17], they are not well suited for operational deployment due to blockage sensitivity, limited resolution and dynamic response. Arrays of MEMS-based sensors are a viable candidate to be used instead [18,19]. Constant-temperature-anemometry MEMS hot-film sensors[20] [21] have been developed and are used extensively, e.g. for laminar-turbulent transition in-flight monitoring [22]. Apart from knowing the transition/separation position, angle of attack and other parameters can be obtained from these sensors indirectly [23]. Calorimetric MEMS sensors [24,25] present a viable alternative to the CTA approach. MEMS shear-stress sensors are deployed [26] among other approaches (for review see [27]). Relevant commercial MEMS-based pressure sensors are readily available [28]. Lately, integrated MEMS sensor-actuator systems [29] are being successfully tested. MEMS microphone arrays might become a promising separation detector in the future.

Alternative to MEMS, piezoelectric sensors exploiting Surface Acoustic Waves (SAW) are being increasingly used among a number of industries [30]. They are passive components interrogated wirelessly by a remote transceiver. This attractive characteristic implies a straightforward integration. Although this technology has been known since decades [31] the real applications in transportation industry started to emerge only recently [32].

Perhaps the most complete characterization of the flow in a vicinity of wing can be obtained by optical methods such as Particle Image Velocimetry [33]. However, this technology is wind tunnel specific due to the inherent requirement on instrumentation and seed particle presence in the flow. It has therefore not been applied in-flight so far [34].

Another wind-tunnel method enables full-field surface pressure distribution measurement due to the luminescence properties of Pressure Sensitive Paints. This approach suffers from a number of problems – it typically requires artificial illumination, has considerable thermal dependence, limited pressure sensitivity, suffers from photo-degradation and is not resistant to elements. Furthermore, long exposure times (in the order of 10s) are required [35,36]. Although some problems have been negotiated and the paints are able to capture transient flows nowadays [37] with a relevant pressure resolution of up to 10Pa [38] other important limitations remain. Deployment of the technology for in-flight tests requires night-time operation [39] due to the homogenous artificial illumination requirement. It is therefore not a practical operational solution. Pressure sensitive films [40] might become an interesting option once they are adapted for transient events.

Thin tactile sensors based on Pressure-Sensitive Conductive Rubber [41] have been used for medical research e.g. [42] and might become available for aviation industry once adapted to the pressure ranges experienced on a surface of an GA aircraft. Analogically, resistive thin-film technology has found a number of applications [43]. Although suffering from limited accuracy, significant hysteresis, creep and long-term instability [44], it provides real-time full-field data on pressure distribution. Capacitive thin-film technology might possibly be a better alternative for flow separation mapping due to better long term stability, increased repeatability of the measurements and sufficient resolution down to 10Pa [45]. A novel thin film sensor featuring optical fiber Bragg grating principle has been demonstrated recently [45], however has not been commercialized yet. A review of conventional sensors has been performed by [46]. The same author evaluated bio-inspired sensor technology with a goal to improve MAV flight in turbulence [47].

2.2 Natural flow sensors

Insect is naturally equipped with number of sensilla hairs. These sensilla receptors differs by its architecture and supply a nervous system by various inputs [48-51]. The flow control sensilla are capable of detecting small amplitude low frequency air disturbances [52]. A conceptual air flow sensor was modelled and demonstrated by [53]. Cricket inspired artificial sensors were designed by [54-56]. Sensilla hairs cover insect body usually in thousands of pieces. The rich sensor control system with numerous feedback loops is described by [57]. The benefit of high density hairs in comparison to a single hair is discussed by [58]. Another research was focused on vibration receptive sensilla on a wing of silkworm moth [59]. Sensilla optimal frequency and physical limits in vibration frequency was evaluated by [60]. Comparison of Cricket sensilla with MEMS hairs was done by [61].

The only one flying mammal is a bat. For the first sight its wing appears hairless but microscopically small hairs can be found by detailed inspection. These hairs function is to provide aerodynamic feedback for flight control [62]. Birds' skin is covered by feather which works in similar way as sensilla in insect case. Several structural types of feathers were described by [63]. Feathers are attached to skin in follicles which are surrounded by mechanoreceptors with various response characteristics [64,65]. Birds use mechanoreceptors on the wing for airspeed and airflow separation indication. Angle of attack, speed and also flow separation is detected by dorsal elevation of coverts feather. The study [66] showed correlation between wind speed and feather vibrations which also correlate to a signal from mechanoreceptors. Barn owl and pigeon wings and feather are described by [67] in detail.

2.3 Haptic feedback

In aviation, vision is the primary modality to gather information for controlling an aircraft. Remaining modalities are typically used for communication or as a supplemental source of information. Haptic interaction is a natural way of information sensing and can be used as supplemental channel to represent additional information important for the pilot without compromising other modalities important for safe flight operation. In case of VFR (visual flight rules) flight, pilot must devote most attention to outside environment due to navigation and collision avoidance.

In aviation, the haptic sense is important for sensing controls feedback. For example, pilot can estimate airspeed just from resistance from the controls. Another example is the stall condition that in case of most small planes causes shaking of controls caused by turbulent flow hitting aircraft's control surfaces. In case of modern airplanes equipped with power steering or with flight-by-wire control system there is typically installed a stick shaker. This device simulates haptic feedback of forthcoming stall condition by similar stick shaking as in case of aircrafts with directly connected control surfaces.

In the aviation context touch is used to determine position of various controls. For instance, it is usually possible to assess position of flaps, gear handle etc. only by touch and control position with regard to pilot position.

Haptic interaction also has also several limitations. According to [68], a person continually adapts to a particular constant tactile input. Moreover, perception of multiple tactile inputs can induce specific sensations. Two inputs that are near to each other can be sensed as one input [69]. Intensity of one input can affect perceived intensity of another tactile inputs at the same moment [70].

2.3.1 Vibrotactile actuators

Standard haptic feedback is provided by Vibration actuators. Common types of vibration actuators are eccentric rotating unbalanced mass (ERM) and linear resonant actuator (LRA) with spring powered by electromagnetic force [71]. ERM is a simple device with off-centric mass powered by motor. The actuators are cheap, easy to control and able to produce strong vibrations. Vibration frequency and intensity are coupled. Disadvantages are slow reaction time around 30 - 50 ms and low fidelity of sensations. LRA are slightly faster with 20 - 30 ms response time. Power drain is half and dimensions smaller in comparison to ERM. The frequency of vibration is limited to single resonant frequency. Vibration strength is medium. Another option for haptic feedback device are piezo actuators [72]. Variable frequency with fast response up to 5 ms produces high fidelity feedback. Downsides of piezo actuators are cost and more complex electronic control in comparison to ERM and LRA. Similar solution to piezo actuators are electro-active polymers EAP. The main practical difference of EAP actuators is that they need high voltage power.

2.3.2 Warning and navigation applications

This section evaluates vibrotactile devices applied as warning system. Usually nondirectional tactile displays are used in this case. A stick shaker is a commonly used to warn a pilot about approaching stall conditions. One design of stick shaker was patented as early as 1951 [73]. The stall warning system is fed by variety of AOA sensing devices [74]. Human computer interaction is getting more important in last decades. [75] demonstrated that tactile feedback is more effective than visual for catching human attention. Tactile warning system has been studied in car driving research. Experiments with drive simulator with haptic feedback were performed by [76-78]. The result of the research is faster reaction of the driver to an unexpected situation. Multimodal feedback, a combination of tactile and visual and auditory feedback, is discussed by [79]. Usage of multimodal warnings demands balanced signals coming from different senses which are proportional to warning importance and urgency.

Directional tactile displays offer more possibilities than the warning function. Tactile vest [80] and waist belt [81,82] offer multielement tactile feedback. [83] even studied tactile display which consists of 64 vibrotactile elements. He also found that localized vibration on pilot body was easily coupled to spatial information like direction to a waypoint or a threat. Wrist tactor device for vibrotactile feedback is studied for various reasons. [84] studied vibrotactile feedback assistance for blind people. Human-computer interaction, telepresence and augmented reality are other applications studied in frame of haptics [85-87]. Vibrotactile device alerting a pilot about an airplane attitude is presented by [88]. Effect of haptics and automation on pilot performance and control behaviour was tested and evaluated by [89] recently. [90] focused the haptic feedback into personal aerial vehicle control by highway in the sky display with a goal to create easy to use control interface for non-expert pilots.

2.3.3 Airplane control applications

Other applications consisting of human-computer interaction and haptic feedback and flow sensing which were used directly in airplane control. Patent [91] is a similar device to stick shaker mentioned in the section Warning applications. The device alerts an airplane pilot to uncoordinated turn condition. [92,93] studied pilot-airplane interaction. The interaction affected flight quality and human role in airplane control significantly because of the rapid automation of airplanes during 1990s. [94] referred to importance of cognitive function analysis of human-computer-aircraft systems. Preliminary experimental evaluation of haptic feedback applied to remotely piloted vehicles was presented by [95]. The last application deals with biomimetics which imitates nature models and systems for the purpose of solving human tasks. [96] introduced a concept which enhances aircraft stability and manoeuvrability during flight. The design consists of feather-like components installed on wing surface. These structures act as sensors, actuators and load bearing at the same time.

2.4 Recent projects

This section describes recent projects which touch the topic of bio-inspired airplane control and human machine interaction and highlight some publications created within the projects. Project "All condition operations and innovative cockpit infrastructure" (ALICIA) [97] aims to increase time efficiency within the future air transport systems. A key objective is to deliver extensible solutions that can be applied to many aircraft types. This entails a new cockpit infrastructure capable of delivering enhanced situation awareness to the crew whilst simultaneously reducing crew workload and improving overall aircraft safety. The myCopter project [98] aims at personal aerial vehicles to be used by the general public within the context of such a transport system. Mentioned publications [89,90] were produced within MyCopter project. "Advanced cockpit for reduction of stress and workload" (ACROSS) project [99] assess workload volume and stress of pilots. ACROSS consortium develops new cockpit applications and human-machine interfaces with a goal of reducing crew workload and improving safety of two-pilot operations. "Applying pilot models for safety aircraft" (A-PiMod) project [4] contributes to improved human-centred design of future aircraft cockpits. The A-PiMod project evaluates whether during a flight the crew and/or the automation system must take action to guarantee that the overall human-automation system remains within a safe state. This is achieved by a real-time risk assessment and a real-time crew model. New architecture of cockpit with potential to improve the safety of future aircraft was published by [100]. Project "Towards certifiable hybrid powertrains for electric aircraft" (HypstAir) [101] concerns the design of components of a serial hybrid propulsion system for small aircraft. A serial hybrid propulsion system uses an electric motor to drive the propeller. A variable throttle friction force adapts haptic feedback and allows simple operation of a complex hybrid system.

3 Perception psychology

In aviation, multiple modalities are used for safe flight operation. The most important modality in aviation is vision [102]. Focal and ambient vision is important object recognition and spatial orientation. Other modalities like auditory or tactile are used as a source of additional information of for communication (for instance).

In [103], Wickens focuses on mental workload and divided attention. While an operator performs multiple tasks at the same time, the ability to successfully perform simultaneous tasks depend on various factors. Wickens introduces a term difficulty insensitivity which corresponds to a situation when an increase of a difficulty of one task does not degrade the performance of a concurrent task. He presents a model, where difficulty insensitivity depends on three dimensions: modalities (e.g. auditory or visual), codes of processing (verbal, spatial) and stages of processing (perceptual, cognitive). This model corresponds to physiological structure of human nervous system, where different "resources" correspond to units of dimension in the model mentioned. For example, auditory perception uses different resources than visual perception does. Wickens concludes that tasks with a greater degree of resource overlap suffer from greater dual task decrements. He suggests to employ an additional modality, e.g. tactile input.

In aviation, various illusions can interfere with human perception [102]. Most notably, visual illusions and spatial illusions can lead to pilot disorientation with possible severe consequences. An additional modality that is used for representation of information vital for safe flight operation could lead to faster recovery from illusions.

According to [104], situational awareness (SA) refers to "the perception of the elements in the environment within a volume of time and space. The comprehension of their meaning and projection of the near feature." It involves perceiving critical factors in the environment (Level 1 SA), understanding what those factors mean (Level 2 SA) and understanding what will happen in the near future (Level 3 SA). For a successful flight operation, it is necessary to create and maintain good situational awareness. Good perception of external factors is a vital precondition for such a process.

4 Discussion

4.1 Sensors and actuators

Nowadays, vanes for angle of attack measurement are mostly used in combination with anti-stall systems. Vanes give only an indirect indication of flow. Both angle of attack and angle of sideslip knowledge is required for determination of comprehensive flow characteristics. Direct measurement of flow has been historically carried out by pressure taps or MEMS pressure sensors. The taps are not suitable for flow field determination in the context of the proposed application, but MEMS pressure sensors and arrays can provide the required characterization of flow field. Natural flow sensors are represented by sensilla hairs among insect and feather among birds. Both are attached to skin in follicles surrounded by neural mechanoreceptors. Such natural sensors obtain numerous important flow characteristics at the same time: wind speed, direction and flow separation position. The artificial sense hair is under development [54,61] and a real-world application is still to be demonstrated.

Warning and navigation applications use haptic feedback mediated by different devices. The mentioned devices are control stick, wrist device, vest or seat connected to various types of actuators. Usually vibrotactile actuators are used but variable friction of control interfaces or their shape modification can be employed as well to provide haptic feedback to the operator. Multielement vibrotactile arrays are required for spatial information. The flow separation propagation on a wing could be a good application for such an array. The system can be implemented into a wrist device or a piece of clothing, e.g. a vest. Wireless connection to sensors and battery operation is planned to minimize the influence on pilot’s comfort. Piezo and EAP actuators are more suitable to mediate continuous information compared to LRA and ERM actuators, whose characteristics are limited by given resonant frequencies and amplitudes.

4.2 Proposed system architecture

Birds and flying insect are equipped with visual, airflow, inertial and wing loading sensors. These sensor inputs are processed in neural system. Therefore, animals fly as naturally as people walk. The goal of new bio-inspired airplane control system is to make flight more intuitive for the human kind. It means faster response and lower demands for pilot attention. The best result would be reached if a pilot's brain received inputs from all mentioned modalities in the same way as animals. Information should be presented in a natural way and the method should prevent sensory overload. This idea of connecting human nervous system to all sensors is technologically extreme. Therefore, partial suggestions for bio-inspired control are defined in the following points.

1) Visual modality is overloaded in traditional control system concept. It is not possible to check all important flight indicators at the same time; especially in an emergency situation. The recommendation for visual modality is as follows: the sight should be dedicated to navigation and sense and avoid roles. The amount of parameters checked by eyes should be limited. Variables that do not change too often, such as flap deflection, fuel state, throttle or altitude can be monitored by sight.

2) Touch is already an important sense in traditional airplane control concept. The touch modality is an encompassing term including pressure, vibration and balance sensing. Control surfaces provide the pilot with a force feedback. Good balance feeling enables the pilot to fly a coordinated turn. The airplane approaching stall should also warn the pilot with vibrations. The recommendation for bio-inspired airplane control system is to transfer additional inputs to touch modality. Magnitudes of speed or angle of attack and vertical speed should be mediated to pilot by touch. Artificial feeling of airflow and its separation over wing would bring a significant improvement of safety under the most dangerous flight phases. All these inputs are expected to make airplane control faster and more intuitive.

3) Hearing modality is commonly used for communication and warning signals. It is going to be unchanged in the bio-inspired airplane control.

5 Conclusion

The paper integrates topics leading to a bio-inspired airplane control focused on small airplanes. Reduction of workload and improvement of safety by human-centred cockpit design is a general trend in global aerospace industry. Therefore, similar development can be expected in the field of small airplanes. The proposed airplane control concept modification is aimed at increased controllability and flight safety at the same time. Pilot with haptic feedback of flow over the wing should be able to control the airplane with less workload, faster response time and in a more intuitive way. Proposed system architecture suggests modifications of traditional pilot-airplane interaction. The general intention is to alleviate the overloaded visual modality and exploit the underused touch modality. Future work is constituted by a real-world implementation of the proposed concept and subsequent comprehensive flight testing.

Acknowledgment

These outputs were supported by the project NETME Centre, regional R&D centre built with the financial support from the Operational Programme Research and Development for Innovations within the project NETME Centre (New Technologies for Mechanical Engineering), Reg. No. CZ.1.05/2.1.00/01.0002.

References

1 Degani A, Heymann M: Pilot-autopilot interaction: a formal perspective: Eighth International Conference on Human-Computer Interaction in Aeronautics. Tolouse, 2000,

2 Li G, Baker SP, Grabowski JG, Rebok GW: Factors associated with pilot error in aviation crashes. Aviation, space, and environmental medicine 2001;72:52-58.

3 Dekker SW: Reconstructing human contributions to accidents: the new view on error and performance. Journal of Safety Research 2002;33:371-385.

4 Applying pilot models for safety aircraft, 2013, 2016,

5 Agency EAS: Annual Safety Review 2013. Luxembourg, EASA, 2014,

6 Review of U.S. Civil Aviation Accidents, Calendar Year 2010. Washington, DC., National Transportation Safety Board, 2012,

7 NTSB Most Wanted List 2015. Washington, DC., National Transportation Safety Board, 2015,

8 Loss of Control Prevention and Recovery Training, European Aviation Safety Agency, 2015,

9 Kraft CC, Assadourian A: Experimental study of an angle-of-attack vane mounted ahead of the nose of an airplane for use as a sensing device for an acceleration alleviation: Technical Note 2415. Washington, NACA, Langley Aeronautical Laboratory, 1951,

10 Angle R: Why AOA?: It's all about measuring lift. Brush Prairie, WA, 2014,

11 Hahn K-U, Schwarz C: Alleviation of atmospheric flow disturbance effects on aircraft response; 26th Congress of the International Council of the Aeronautical Sciences, 2008

12 King B: KLR 10: Lift Reserve Indicator, for precise and instantaneous lift alerts for your experimental aircraft, 2014,

13 Avionics D: SkyView Pitot Probes: Angle of Attack/Pitot. Seattle, WA, 2013,

14 Flight S: SCc Leading Edge Angle of Attack. Shite Plains, NY, 2015,

15 Mangalam AS, Moes TR: Real-time unsteady loads measurements using hot-film sensors; AIAA applied aerodynamics conference, AIAA, 2004, vol 5371

16 Corke TC, Bowles PO, He C, Matlis EH: Sensing and control of flow separation using plasma actuators. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 2011;369:1459–1475.

17 Powers SG, Webb LD: Flight Wing Surface Pressure and Boundary-Layer Data Report from the F-111 Smooth Variable-Camber Supercritical Mission Adaptive Wing: NASA Technical Memorandum 4789. Edwards, California, Dryden Flight Research Center, 1997,

18 Holland M, Eccles L, Paradis L: A pressure belt system for an airborne pressure survey; Sensors for Industry, 2001 Proceedings of the First ISA/IEEE Conference, 2001, pp 156–161.

19 Kim NP, Holland MJ, Tanielian MH, Poff R: MEMS sensor multi-chip module assembly with TAB carrier pressure belt for aircraft flight testing; Electronic Components amp; Technology Conference, 2000 2000 Proceedings 50th, 2000, pp 689–696.

20 Que RY, Zhu R, Wei QZ, Cao Z: A flexible integrated micromachined hot-film sensor array for measuring surface flow vector; Solid-State Sensors, Actuators and Microsystems Conference (TRANSDUCERS), 2011 16th International, 2011, pp 108–111.

21 Zhu R, Liu P, Liu XD, Zhang FX, Zhou ZY: A Low-Cost Flexible Hot-Film Sensor System for Flow Sensing and its Application to Aircraft; Micro Electro Mechanical Systems, 2009 MEMS 2009 IEEE 22nd International Conference on, 2009, pp 527–530.

22 Marshall LA: Summary of Transition Results from the F-16XL-2 Supersonic Laminar Flow Control Experiment: AIAA 2000-4418 Paper. Edwards, California, NASA Dryden Flight Reesearch Center, 2000,

23 Que R, Zhu R: Aircraft Aerodynamic Parameter Detection Using Micro Hot-Film Flow Sensor Array and BP Neural Network Identification. Sensors 2012;12:10920.

24 Obermeier E, Kittel M, Petz R, Buder U, Nitsche W: AeroMEMS polyimide based wall double hot-wire sensors for flow separation detection. Sensors and Actuators A: Physical 2008;142:130–137.

25 Sturm H, Dumstorff G, Busche P, Westermann D, Lang W: Boundary Layer Separation and Reattachment Detection on Airfoils by Thermal Flow Sensors. Sensors (Basel, Switzerland) 2012;12:14292–14306.

26 Xu Y, Jiang F, Newbern S, Huang A, Ho C-M, Tai Y-C: Flexible shear-stress sensor skin and its application to unmanned aerial vehicles. Sensors and Actuators A: Physical 2003;105:321–329.

27 Löfdahl L, Gad-el-Hak M: MEMS applications in turbulence and flow control. Progress in Aerospace Sciences 1999;35:101–203.

28 Meggitt: Low profile microsensor for aerodynamic pressure measurement: Endevco technical paper 297. Irvine, CA, Meggit Sensing Systems, 2014,

29 Francioso L, Pascali Cd, Casino F, Siciliano P, Giorgi MGd, Campilongo S, Ficarella A: Embedded sensor/actuator system for aircraft active flow separation control; AISEM Annual Conference, 2015 XVIII, 2015, pp 1–4.
30 Senseor: SAW Pressure sensors: Customized wireless SAW pressure sensors. Valbonne Sophia Antipolis, FR, 2015,
31 Reeder TM, Cullen DE: Surface-acoustic-wave pressure and temperature sensors. Proceedings of the IEEE 1976;64:754–756.
32 Drafts B: Acoustic wave technology sensors. Microwave Theory and Techniques, IEEE Transactions on 2001;49:795–802.
33 Hu H, Yang Z: An Experimental Study of the Laminar Flow Separation on a Low-Reynolds-Number Airfoil. Journal of Fluids Engineering 2008;130:051101.
34 Bogue RK, Jentink HW: Optical Air Flow Measurements in Flight. Edwards, California, NASA Dryden Flight Reesearch Center, 2004,
35 McLachlan BG, Bell JH: Pressure-sensitive paint in aerodynamic testing. Experimental Thermal and Fluid Science 1995;10:470–485.
36 Klein C, Engler R, Henne U, Sachs W: Application of pressure-sensitive paint for determination of the pressure field and calculation of the forces and moments of models in a wind tunnel. Experiments in Fluids 2005;39:475–483.
37 Nakakita K: Unsteady pressure distribution measurement around 2D-cylinders using pressure-sensitive paint: Proceedings of the 25th AIAA Applied Aerodynamics Conference, American Institute of Aeronautics and Astronautics, Reston, VA, 2007,
38 Gregory JW, Sullivan JP, Wanis SS, Komerath NM: Pressure-sensitive paint as a distributed optical microphone array. The Journal of the Acoustical Society of America 2006;119:251–261.
39 McLachlan BG, Bell JH, Espina J, Gallery J, Gouterman M, Demandante C, Bjarke L: Flight Testing of a Luminescent Surface Pressure Sensor. Moffett Field, California, NASA Ames Research Center, 1992,
40 Fujifilm: Prescale: Extreme low pressure sensitive film,
41 Obara M, Tajima Y, Suzuki Y: Pressure-sensitive electrically conductive composite sheet, 1985,
42 Volf J, Holý S, Vlček J: Using of tactile transducer for pressure-distribution measurement on the sole of the foot. Sensors and Actuators A: Physical 1997;62:556–561.
43 Tekscan: Pressure Mapping, Force Measurement & Tactile Sensors. South Boston, MA,
44 Ashruf CMA: Thin flexible pressure sensors. Sensor Review 2002;22:322–327.
45 PPS: Capacitive Tactile Sensors. Los Angeles, CA, 2015,
46 Mohamed A, Clothier R, Watkins S, Sabatini R, Abdulrahim M: Fixed-wing MAV attitude stability in atmospheric turbulence, part 1: Suitability of conventional sensors. Progress in Aerospace Sciences 2014;70:69-82.
47 Mohamed A, Watkins S, Clothier R, Abdulrahim M, Massey K, Sabatini R: Fixed-wing MAV attitude stability in atmospheric turbulence—Part 2: Investigating biologically-inspired sensors. Progress in Aerospace Sciences 2014;71:1–13.
48 Keil TA, Steinbrecht RA: Mechanosensitive and olfactory sensilla of insects; Insect ultrastructure, Springer, 1984, pp 477-516.
49 Keil TA: Functional morphology of insect mechanoreceptors. Microscopy research and technique 1997;39:506-531.
50 Shimozawa T, Kanou M: Varieties of filiform hairs: range fractionation by sensory afferents and cereal interneurons of a cricket. Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology 1984;155:485-493.
51 Shimozawa T, Kanou M: The aerodynamics and sensory physiology of range fractionation in the cereal filiform sensilla of the cricketGryllus bimaculatus. Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology 1984;155:495-505.
52 Levin JE, Miller JP: Broadband neural encoding in the cricket cercal sensory system enhanced by stochastic resonance. Nature 1996;380:165-168.
53 Ozaki Y, Ohyama T, Yasuda T, Shimoyama I: An air flow sensor modeled on wind receptor hairs of insects; Micro Electro Mechanical Systems, 2000 MEMS 2000 The Thirteenth Annual International Conference on, 2000, pp 531–536.
54 Dijkstra M, Van Baar J, Wiegerink R, Lammerink T, De Boer J, Krijnen G: Artificial sensory hairs based on the flow sensitive receptor hairs of crickets. Journal of micromechanics and microengineering 2005;15:S132.
55 Krijnen G, Lammerink T, Wiegerink R, Casas J: Cricket inspired flow-sensor arrays: Sensors, 2007 IEEE, IEEE, 2007, pp 539-546.

56 Chen N, Tucker C, Engel JM, Yang Y, Pandya S, Liu C: Design and characterization of artificial haircell sensor for flow sensing with ultrahigh velocity and angular sensitivity. Microelectromechanical Systems, Journal of 2007;16:999-1014.
57 Zbikowski R: Sensor-rich feedback control: a new paradigm for flight control inspired by insect agility. Instrumentation & Measurement Magazine, IEEE 2004;7:19-26.
58 Casas J, Steinmann T, Krijnen G: Why do insects have such a high density of flow-sensing hairs? Insights from the hydromechanics of biomimetic MEMS sensors. Journal of the Royal Society interface 2010;7:1487-1495.
59 Ai H, Yoshida A, Yokohari F: Vibration receptive sensilla on the wing margins of the silkworm moth Bombyx mori. Journal of insect physiology 2010;56:236-246.
60 Bathellier B, Steinmann T, Barth FG, Casas J: Air motion sensing hairs of arthropods detect high frequencies at near-maximal mechanical efficiency. Journal of The Royal Society Interface 2011:rsif20110690.
61 Droogendijk H, Casas J, Steinmann T, Krijnen G: Performance assessment of bio-inspired systems: flow sensing MEMS hairs. Bioinspiration & biomimetics 2014;10:016001.
62 Sterbing-D'Angelo SJ, Moss CF: Air flow sensing in bats; Flow Sensing in Air and Water, Springer, 2014, pp 197-213.
63 Stettenheim PR: The integumentary morphology of modern birds—an overview. American Zoologist 2000;40:461-477.
64 Hörster W: Vibrational sensitivity of the wing of the pigeon (Columba livia)—a study using heart rate conditioning. Journal of Comparative Physiology A 1990;167:545-549.
65 Hörster W: Histological and electrophysiological investigations on the vibration-sensitive receptors (Herbst corpuscles) in the wing of the pigeon (Columba livia). Journal of Comparative Physiology A 1990;166:663-673.
66 Brown RE, Fedde MR: Airflow sensors in the avian wing. Journal of experimental biology 1993;179:13-30.
67 Bachmann T: Anatomical, morphometrical and biomechanical studies of barn owls' and pigeons' wings, Dissertation, RWTH Aachen University, 2010,
68 Craig JC, Evans PM: Vibrotactile masking and the persistence of tactual features. Perception & psychophysics 1987;42:309-317.
69 Verrillo R: Temporal summation in vibrotactile sensitivity. The Journal of the Acoustical Society of America 1965;37:843-846.
70 Hahn J: Vibrotactile adaptation and recovery measured by two methods. Journal of experimental psychology 1966;71:655.
71 Choi S, Kuchenbecker KJ: Vibrotactile display: Perception, technology, and applications. Proceedings of the IEEE 2013;101:2093-2104.
72 haptic driver overview, Texas Instruments, 2016, 2016,
73 M GL: Vibratory aircraft alarm of the rotary eccentric weight type, Google Patents, 1951,
74 Zalovcik JA: Summary of stall-warning devices. 1952
75 Sklar AE, Sarter NB: Good vibrations: Tactile feedback in support of attention allocation and human-automation coordination in event-driven domains. Human Factors: The Journal of the Human Factors and Ergonomics Society 1999;41:543-552.
76 Ho C, Tan HZ, Spence C: Using spatial vibrotactile cues to direct visual attention in driving scenes. Transportation Research Part F: Traffic Psychology and Behaviour 2005;8:397-412.
77 Spence C, Ho C: Tactile and multisensory spatial warning signals for drivers. Haptics, IEEE Transactions on 2008;1:121-129.
78 Meng F, Gray R, Ho C, Ahtamad M, Spence C: Dynamic vibrotactile signals for forward collision avoidance warning systems. Human Factors: The Journal of the Human Factors and Ergonomics Society 2014:0018720814542651.
79 Haas EC, Van Erp JB: Multimodal warnings to enhance risk communication and safety. Safety science 2014;61:29-35.
80 Jones LA, Nakamura M, Lockyer B: Development of a tactile vest: Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2004 HAPTICS'04 Proceedings 12th International Symposium on, IEEE, 2004, pp 82-89.
81 Van Erp JB, Van Veen HA, Jansen C, Dobbins T: Waypoint navigation with a vibrotactile waist belt. ACM Transactions on Applied Perception (TAP) 2005;2:106-117.
82 Weber B, Schätzle S, Hulin T, Preusche C, Deml B: Evaluation of a vibrotactile feedback device for spatial guidance: World Haptics Conference (WHC), 2011 IEEE, IEEE, 2011, pp 349-354.
83 van Erp JB: Tactile displays for navigation and orientation: perception and behaviour. Utrecht University, 2007.

84 Kammoun S, Jouffrais C, Guerreiro T, Nicolau H, Jorge J: Guiding blind people with haptic feedback. Frontiers in Accessibility for Pervasive Computing (Pervasive 2012) 2012
85 Stanley AA, Kuchenbecker KJ: Evaluation of tactile feedback methods for wrist rotation guidance. Haptics, IEEE Transactions on 2012;5:240-251.
86 Scheggi S, Chinello F, Prattichizzo D: Vibrotactile haptic feedback for human-robot interaction in leader-follower tasks: Proceedings of the 5th International Conference on PErvasive Technologies Related to Assistive Environments, ACM, 2012, pp 51.
87 Schönauer C, Fukushi K, Olwal A, Kaufmann H, Raskar R: Multimodal motion guidance: techniques for adaptive and dynamic feedback: Proceedings of the 14th ACM international conference on Multimodal interaction, ACM, 2012, pp 133-140.
88 Cardin S, Vexo F, Thalmann D: Vibro-tactile interface for enhancing piloting abilities during long term flight. Journal of Robotics and Mechatronics 2006;18:p 381-391.
89 Olivari M, Nieuwenhuizen FM, Bülthoff HH, Pollini L: An experimental comparison of haptic and automated pilot support systems: AIAA modeling and simulation technologies conference, 2014, pp 1-11.
90 Nieuwenhuizen FM, Bülthoff HH: Evaluation of Haptic Shared Control and a Highway-in-the-Sky Display for Personal Aerial Vehicles: AIAA Modeling and Simulation Technologies Conference 2014: held at the SciTech Forum 2014, Curran, 2014, pp 154-162.
91 Vavra GS: Tactile signaling systems for aircraft, Google Patents, 1984,
92 Sarter NB, Woods DD: Pilot interaction with cockpit automation: Operational experiences with the flight management system. The International Journal of Aviation Psychology 1992;2:303-321.
93 Sarter NB, Woods DD: Pilot interaction with cockpit automation II: An experimental study of pilots' model and awareness of the flight management system. The International Journal of Aviation Psychology 1994;4:1-28.
94 Boy GA: Human-computer interaction in aeronautics: a cognitive engineering perspective. Air & Space Europe 1999;1:33-37.
95 Alaimo SM, Pollini L, Magazzù A, Bresciani JP, Giordano PR, Innocenti M, Bülthoff HH: Preliminary evaluation of a haptic aiding concept for remotely piloted vehicles; Haptics: Generating and Perceiving Tangible Sensations, Springer, 2010, pp 418-425.
96 Blower CJ, Wickenheiser AM: Biomimetic feather structures for localized flow control and gust alleviation on aircraft wings: International Conference on Adaptive Structures and Technologies, 2010,
97 ALICIA Project, 2009, 2016,
98 myCopter, 2011, 2016, pp FP7 Project - Enabling technologies for personal aerial transportation system.
99 ACROSS Project, 2012, 2016, pp Advanced cockpit for reduction of stress and workload.
100 Javaux D, Fortmann F, Mölenbrink C: Adaptive Human-Automation Cooperation: A General Architecture for the Cockpit and its Application in the A-PiMod Project COGNITIVE'15, IARIA, 2015,
101 HypstAir, 2013, 2016, pp Towards certifiable hybrid powertrains for electric aircraft.
102 Gillingham KK, Previc FH: Spatial orientation in flight, DTIC Document, 1993,
103 Wickens CD: Multiple resources and mental workload. Human Factors: The Journal of the Human Factors and Ergonomics Society 2008;50:449-455.
104 Endsley MR: Design and evaluation for situation awareness enhancement: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, SAGE Publications, 1988, 32, pp 97-101.