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Review

Review of pilot models used in aircraft flight dynamics

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ABSTRACT

Mathematical representations of human control behaviour have played a very important part in manned aviation, especially in the definition of aircraft handling qualities requirements. New challenges posed by advances in aerospace technologies, such as fly-by-wire flight control, large flexible airframes and flight simulation, have led to increasingly complex mathematical representations of pilot behaviour. However, all these areas tend to be investigated separately and in parallel with human factors studies. The motivation behind this review is to promote discussion between the flight dynamicists and other engineers and scientists on the methods of modelling and simulation of today's pilot. A review of pilot model components used for flight control system design that focuses specifically on physiological and manual control aspects is presented in this paper. Models of varying complexity that are considered to be the state-of-the-art within the flight control and handling qualities engineering community are discussed. These include simple sensory models, biomechanics models and complex nonlinear pilot manual control models. In each area, the challenges posed by inter-subject variations and the need to understand the aircraft as a complex man–machine system are highlighted. However, the presented discussion is limited to a thin slice of this field thought to be fundamental to modelling manual control dynamics exhibited by aircraft pilots.

Pilot modelling has evolved to into a wide engineering field with contributions from many disciplines that consider interaction with human beings, either as an operator or a customer. Aspects from this field are included either implicitly or explicitly during the design of day-to-day objects like a cup to complex machines such as the space shuttle. Modern understanding of human perception and information processing alone has advanced considerably over the last twenty years, prior to which researchers focused on mainly qualitative descriptions of possible human actions. Present day scientists are taking advantage of the available computational power and investigating the deeper functions of the brain by identifying and developing functional maps of neurons within the brain [33,71,99]. Yet, each miracle landing credited to skilled manual control or an accident attributed to human error demonstrates the complexity of the human pilot and highlights our ignorance of his/her capabilities [13]. A detailed review of pilot modelling techniques merits many years of research and hence, the discussion presented in this paper is limited to a thin slice of this field that considers particular aspects thought to be fundamental to modelling manual control dynamics exhibited by aircraft pilots. These are the sensory, biodynamic and control aspects. The reader should note that the discussions presented in this paper augment past work done by Lone and Cooke [63,65] and more recent work done in the ARISTOTEL project [52,67].

Investigation of such scenarios not only requires an understanding of aircraft manual control, but also an understanding of the pilot–vehicle-system (PVS) as a whole. Modern civil aircraft effectively have three modes of operation:

1. Aircraft control can be established through complete manual control with objectives from the pilot's mind or objectives from a flight director.
2. The mode control panel which commands the various autopilots can also be used. The pilot plays a more supervisory role here and his/her input is required only at particular stages of the mission.
3. The flight management computer can be programmed on the ground. Based on this information the flight director can establish control through the autopilots. The pilot may presume a fully supervisory role for the duration of the mission.

Fig. 1 presents the key components involved in the manual control mode that are necessary to model manual control dynamics. Here, the system is motivated by an *objective* that is processed by *higher brain functions* to derive a process through which it can be achieved. In scenarios of high urgency the objective is simplified

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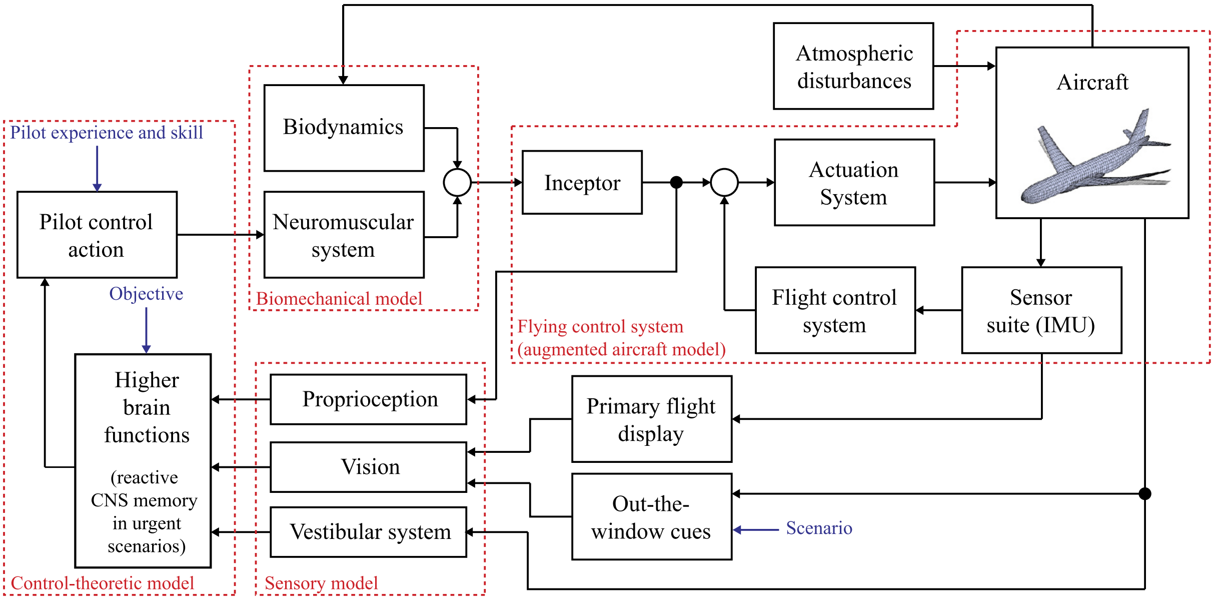

Fig. 1. Block diagram representing the pilot–vehicle-system under manual control.

and control action is either generated based on recall of emergency procedures or even reactive muscle memory. Pilot training plays a critical role at this stage. The resulting *pilot control action* then determines the cues and gains selected by the pilot to establish feedback control. These are typically a function of pilot *experience and skill*. The control action is executed via the forces generated by the muscles in the *neuromuscular system* and exerted on the *inceptor*. Signals from the inceptor are used by the *flight control system* as demands for flight dynamic parameters such as pitch rate or normal acceleration. These are met with the help of the *actuation system* that provides the appropriate movement of the control surfaces on the wings and empennage or changes in engine thrust. Thus, forces and moments are generated to change the orientation of the *aircraft* relative to the oncoming air flow. This change is perceived by the pilot primarily through his/her *visual sensory modality* that delivers information regarding the *scenario* from *out-the-window cues* to the brain. The *primary flight display* (PFD) delivers information from the *aircraft's sensor suite*. *Vestibular dynamics* play a critical role in the perception of aircraft accelerations. The pilot also perceives the commanded inceptor input via the *proprioceptive sense*. These cues effectively close the feedback control loops. However, the pilot's position within the aircraft also means his/her body is subjected to the resulting accelerations that arise either due to his/her commands or *atmospheric disturbances*. Therefore, the neuromuscular forces acting on the inceptor are affected by a disturbance generated when the aircraft accelerations pass through the pilot's *biodynamic* response. The key pilot model components can now be grouped together as the *control-theoretic*, *sensory* and *biomechanical* models.

1. Sensory dynamics

The natural sensory organs have evolved to become a very sophisticated sensory suite, which in conjunction with the central nervous system (CNS), is an elaborate example of data collection and fusion. However, this system is best suited for moderate angular rotations of short durations experienced on a daily basis on the ground. Although the dynamics of the individual sensory organs are well understood, their joint role with the CNS for perception is only being investigated now. Although it is normally taken for granted that reality is being perceived, (whilst true for most day-to-day scenarios) the frequent low intensity and long duration rotations experienced in flight can easily result in erroneous perceptions leading to disorientation. Spatial disorientation (SD) is defined as a situation when the pilot fails to correctly perceive position, motion or attitude of the aircraft within a fixed coordinate system provided by the surface of the Earth and its gravitational field. A human sensory model should at least be capable of simulating certain pilot SD.

Research in SD was initiated by Ernst Mach whose work in supersonics actually had roots in earlier studies of the human vestibular sense and audio perception. It was a decade later in 1877 that he published his work on supersonic projectile motion. Research in the context of aviation began later towards the end of World War I and true progress only came in the 1990s. SD has now been divided into three categories [108]:

- Type I: where the pilot is unaware that the perceived orientation is incorrect.
- Type II: where there is a conscious recognition of a conflict between the senses and instruments.
- Type III: where the pilot has a sense of helplessness and an inability to maintain control due to an overwhelming confusion about orientation.

It should be noted that majority of SD mishaps are of Types I and II, during which the pilot often refuses to believe the instruments and/or misinterprets out-the-window cues. For example, a near-fatal Type II SD occurred when the pilot of a United States Air Force (USAF) C-5 refused to believe the PFD just prior to entering a stall. The cause of this SD was found to be the perceived gravito-inertial force (GIF) vector (felt by the vestibular system) that falsely indicated level flight [108].

Mathematical modelling of SD requires knowledge of the mechanisms and processes involved in developing spatial orientation. At the conscious level auditory and focal visual cues are used to obtain estimates of aircraft states at any given time. Subconsciously the visual, vestibular and proprioceptive inputs are processed to provide positioning, angular and linear acceleration estimates. The CNS is then responsible for the interpretation and comparison with an internal model. These models are formulated from past experience and training that in turn generate expectations concerning aircraft dynamics [89]. Such qualitative descriptions and relationships can be found in most human factors literature. On the other