Institution: London School of Economics and Political Science

Unit of Assessment: 10: Mathematical Sciences

Title of case study: Improving the design of flight control systems

1. Summary of the impact (indicative maximum 100 words)

Research by Amol Sasane and co-authors is the foundation of an invention patented and used by the aerospace company Boeing to design flight control systems. The invention is a method which aims to optimize aerodynamic performance of aircraft, thereby improving fuel efficiency and flight safety.

Sasane and his co-authors' research is explicitly mentioned as having been used to overcome a problem in flight control – one that arises in newer, more sophisticated aircraft designs – in Patent no. US 8, 185,255 B2, 'Robust control effector allocation'.

2. Underpinning research (indicative maximum 500 words)

Research Insights and Outputs:

Dr. Amol Sasane undertook research with Naira Hovakimyan (University of Illinois) and Eugene Lavretsky (The Boeing Company) to solve the problem of stabilizing a non-affine control system using time-scale separation. Their findings first appeared in a paper for the *American Control Conference* in 2005 [Reference 1]. A revised version of the paper was published in 2007 [Reference 2]. Subsequently, the US patent for an invention utilising their solution was applied for by Eugene Lavretsky, Ryan Diecker and Joseph Brinker ('the inventors'), and assigned to the Boeing Company. The patent was granted on 22 May, 2012.

Control theory is a branch of applied mathematics in which one considers systems governed by equations of the form $x'(t)=f(x(t),u(t))$, where x and u are vector-valued functions, and time t runs from an initial time ti onwards. This equation is underdetermined, in the sense that the function u, thought of as consisting of input variables, can be freely chosen. Once a particular input function u has been chosen, then the corresponding function x, given an initial condition $x(t_i)$, is uniquely determined for all future times. If one changes the choice of u, then the corresponding x changes too. Thus, there is a possibility of controlling the behaviour of the x variables by a suitable choice of the control input u. The aim in control theory is to find u which produces some desirable effect on x.

Control theory is particularly useful in aerospace engineering, where the models are typically nonlinear. Moreover, the control inputs appear in a non-affine manner. Affine systems are ones in which the input u appears in f in an affine manner, that is, $f(x,u)=g(x)+h(x)u$. Feedback linearization is a popular method in control design for nonlinear systems that are affine in the control inputs. However, an explicit feedback linearization for non-affine control systems is not satisfactory as often a transcendental equation appears when one attempts to find an appropriate control.

The 2005 conference paper set out a new general method for feedback linearization of non-affine nonlinear control systems. The method used time-scale separation, where the control signal is sought as a solution of fast dynamics, and is shown to asymptotically stabilize the original slow non-affine control system.

The control allocation method in the patent invention utilises this finding, allowing it to make real time allocation of control of pilot or auto-pilot flight commands among the aircraft’s control effector actuators despite possible nonlinear interactions which the control effector displacements may have on the aircraft and on each other.

Key Researcher: Dr Sasane has been full-time at LSE since 2004.

3. References to the research (indicative maximum of six references)

1. Naira Hovakimyan, Eugene Lavretsky and Amol Sasane. Dynamic inversion for nonaffine-in-control systems via time-scale separation: Part I. *Proceedings of the American Control Conference*, pages 3542-3547, Portland, Oregon, June 2005.

URL1:
http://www.nt.ntnu.no/users/skoge/prost/proceedings/acc05/PDFs/Papers/0632_FrA05_1.pdf

URL 2: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1470522

2. Naira Hovakimyan, Eugene Lavretsky and Amol Sasane. Dynamic inversion for nonaffine-in-control systems via time-scale separation. I. *Journal of Dynamical and Control Systems*, volume 13, pages 451-465, number 4, 2007.

URL: http://www.springerlink.com/content/w310861170h13557/?MUD=MP

Evidence of quality: publication in peer-reviewed outlets.

4. Details of the impact (indicative maximum 750 words)

Nature of the Impact:

The dynamic inversion control law developed by Sasane and his co-authors underpins an invention used and patented by Boeing in May 2012 [A] to design flight control systems (Patent no. US 8, 185,255 B2) [B]. This invention overcomes a challenge in newer aircraft which are designed with sophisticated flight control systems to achieve greater agility (in the case of military aircraft) or improved fuel efficiency (in commercial and private aircraft) and need advanced control laws to maximize their performance.

The in-flight control and manoeuvring of aerodynamic vehicles, such as aircraft, is accomplished by positioning the aircraft's control surfaces, the ailerons on the wings for example, to modify the airflow across them to affect an aerodynamic response from the aircraft. The control surfaces, along with other force and moment producing devices, are referred to as "control effectors".

New aircraft designs include an increasing number of control effectors, to improve fuel efficiency and increase flight safety. Advanced control laws are needed to make use of the larger range of control effectors. The flight control system must allocate the execution of commands among several control effectors. The allocation is determined by the type of action commanded, the flight conditions and the known responses of the aircraft. The previous generation of flight control systems, however, used control allocation algorithms which assume linearity of the control effector effects, and fail to account for the possibility of interactions between control effectors.

The US patent invention overcomes this problem by using as its foundation the dynamic inversion control law developed by Sasane, Hovakimyan and Lavretsky [C]. This formulates a solution to the nonlinear problem mentioned above by using an approximate dynamic inversion based on time-scale principles.

The US patent covers a new method for the allocation of control authority in real time among several control effectors of a controllable vehicle (in particular an aircraft) in execution of a commanded manoeuvre. The allocation takes account of possible nonlinear effects which those control effectors may have on the vehicle and on each other in affecting such a manoeuvre.

Wider Implications: The invention is applicable to any air, space, sea, under-sea or ground vehicle whose dynamics are controlled via a selected set of control effectors (Column 1, first paragraph, of [A]). The results can include improved passenger safety and increased fuel efficiency (and hence less environmental damage). The reach of the invention is therefore considerable.

5. Sources to corroborate the impact (indicative maximum of 10 references)

All sources listed below can also be seen at: https://apps.lse.ac.uk/impact/case-study/view/3

A. The US patent number 8,185,255 B2 is available in the public domain at the following address:
URL: http://www.spacepatents.com/patented_inventions/pat8185255.pdf
https://apps.lse.ac.uk/impact/download/file/1280

B. Private e-mail correspondence with a Technical Fellow at the Boeing Corporation confirms that Boeing is using the patent to design flight control systems for aerial platforms. This source is confidential.

C. Column 5, paragraph lines 40-50 in the patent:
“The present invention overcomes this control allocation problem by using as its foundation a dynamic inversion control law for nonaffine-in-control dynamic systems that was earlier developed by Naira Hovakimyan, Eugene Lavretsky, and Amol J. Sasane. This dynamic inversion control law formulates a solution to the nonlinear and/or non-monotonic problem by using an approximate dynamic inversion based on time-scale separation principles.”
URL: http://www.spacepatents.com/patented_inventions/pat8185255.pdf
https://apps.lse.ac.uk/impact/download/file/1281