# Practical Loop-Shaping Design of Feedback Control Systems

**Actuator rates are incorporated into a design from the start.**

*John H. Glenn Research Center, Cleveland, Ohio*

An improved methodology for designing feedback control systems has been developed based on systematically shaping the loop gain of the system to meet performance requirements such as stability margins, disturbance attenuation, and transient response, while taking into account the actuation system limitations such as actuation rates and range. Loop-shaping for controls design is not new, but past techniques do not directly address how to systematically design the controller to maximize its performance. As a result, classical feedback control systems are designed predominantly using *ad hoc* control design approaches such as proportional integral derivative (PID), normally satisfied when a workable solution is achieved, without a good understanding of how to maximize the effectiveness of the control design in terms of competing performance requirements, in relation to the limitations of the plant design.

The conception of this improved methodology was motivated by challenges in designing control systems of the types needed for supersonic propulsion. But the methodology is generally applicable to any classical control-system design where the transfer function of the plant is known or can be evaluated. In the case of a supersonic aerospace vehicle, a major challenge is to design the system to attenuate anticipated external and internal disturbances, using such actuators as fuel injectors and valves, bypass doors, and ramps, all of which are subject to limitations in actuator response, rates, and ranges. Also, for supersonic vehicles, with long slim type of structures, coupling between the engine and the structural dynamics can produce undesirable effects that could adversely affect vehicle stability and ride quality.

In order to design distributed controls that can suppress these potential adverse effects, within the full capabilities of the actuation system, it is important to employ a systematic control design methodology such as this that can maximize the effectiveness of the control design in a methodical and quantifiable way.

The emphasis is in generating simple but rather powerful design techniques that will allow even designers with a layman's knowledge in controls to develop effective feedback control designs. Unlike conventional *ad hoc* methodologies of feedback control design, in this approach actuator rates are incorporated into the design right from the start: The relation between actuator speeds and the desired control bandwidth of the system is established explicitly. The technique developed is demonstrated via design examples in a step-by-step tutorial way. Given the actuation system rates and range limits together with design specifications in terms of stability margins, disturbance rejection, and transient response, the procedure involves designing the feedback loop gain to meet the requirements and maximizing the control system effectiveness, without exceeding the actuation system limits and saturating the controller. Then knowing the plant transfer function, the procedure involves designing the controller so that the controller transfer function together with the plant transfer function equate to the designed loop gain. The technique also shows what the limitations of the controller design are and how to trade competing design requirements such as stability margins and disturbance rejection. Finally, the technique is contrasted against other more familiar control design techniques, like PID control, to show its advantages.

*This work was done by George Kopasakis of Glenn Research Center. Further information is contained in a TSP (see page 1).*

*Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Innovative Partnerships Office, Attn: Steve Fedor, Mail Stop 4–8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-18365-1.*

# Fully Printed High-Frequency Phased-Array Antenna on Flexible Substrate

**This flexible design enables applications in high-frequency RFID sensors, smart cards, electronic paper, and flat-screen displays.**

*John H .Glenn Research Center, Cleveland, Ohio*

To address the issues of flexible electronics needed for surface-to-surface, surface-to-orbit, and back-to-Earth communications necessary for manned exploration of the Moon, Mars, and beyond, a room-temperature printing process has been developed to create active, phased-array antennas (PAAs) on a flexible Kapton substrate.

Field effect transistors (FETs) based on carbon nanotubes (CNTs), with many unique physical properties, were successfully proven feasible for phased-array antenna systems. The carrier mobility of an individual CNT is estimated to be at least 100,000 cm$^2$/V·s. The CNT network in solution has carrier mobility as high as 46,770 cm$^2$/V·s, and has a large current-density carrying capacity of ≈ 1,000 mA/cm$^2$ , which corresponds to a high carrying power of over 2,000 mW/cm$^2$ . Such high carrier mobility, and large current carrying capacity, allows the achievement of high-speed (>100 GHz), high-power, flexible electronic circuits that can be monolithically integrated on NASA's active phased-array antennas for various applications, such as pressurized rovers, pressurized habitats, and spacesuits, as well as for locating beacon towers for lunar surface navigation, which will likely be performed at S-band and attached to a mobile astronaut.

A fully printed 2-bit 2-element phased-array antenna (PAA) working at 5.6 GHz, incorporating the CNT FETs as phase shifters, is demonstrated. The PAA is printed out at room temperature on 100-μm thick Kapton substrate. Four CNT FETs are printed together with microstrip time delay lines to function as a 2-bit phase shifter. The FET switch exhibits a switching speed of 0.2 ns, and works well for a 5.6-GHz RF signal. The operating frequency is measured to be 5.6 GHz, versus the state-of-the-art flexible FET operating frequency of 52 MHz. The source-drain current density is measured to be over 1,000 mA/cm$^2$, while the conventional organic FETs, and single carbon nanotube-based FETs, are typically in the μA to mA/cm$^2$ range. The switching voltage used is 1.8 V, while the state-of-the-art flexible FET has a gate voltage around 50 V. The gate voltage can effectively control the source-drain current with an ON-OFF ratio of over 1,000 obtained at a low $V_{ds}$ bias of 1.8 V. The azimuth steering angles of PAA are measured at 0°, –14.5°, –30°, and 48.6°. The measured far-field patterns agree well with simulation results. The efficiency of the 2-bit 2-element PAA is measured to be 39 percent, including the loss of transmission line, FET switch, and coupling loss of RF probes. With further optimization, the efficiency is expected to be around 50–60 percent.

*This work was done by Yihong Chen of Omega Optics, Inc. and Xuejun Lu of UMass Lowell for Glenn Research Center. Further information is contained in a TSP (see page 1).*

*Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Innovative Partnerships Office, Attn: Steve Fedor, Mail Stop 4–8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-18428-1.*