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A CHRONOLOGICAL BIBLIOGRAPHY ON SATURATING ACTUATORS

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In assessing system performance, the control engineer armed with linear analysis and design techniques soon encounters a fundamental *nonlinear* problem that threatens the operation of otherwise sound designs: unexpectedly large amplitude disturbances can push a system's actuators into saturation, thus forcing the system to operate in a mode for which it was not designed and from which it may not be able to recover. The prospects for failure are both pervasive and frightening[64].

All control actuation devices are subject to amplitude saturation. Force, torque, thrust, stroke, voltage, current, flow rate, and every conceivable physical input in every conceivable application of control technology is ultimately limited. The extent to which the effect of saturation needs to be accounted for in the control-system design process depends upon the required control-system performance in relation to the capacity of the actuators as well as the level of expected disturbances. Although in some applications it may be possible to ignore these effects, the reliable operation and acceptable performance of most control systems must be assessed in the light of actuator saturation.

In spite of these concerns, the study of saturation effects within feedback control design has received far less attention than linear control theory. This Special Issue on Saturating Actuators is therefore intended to stress the importance of the saturation problem in control-system technology.

The chronological bibliography given below shows the broad concern toward the saturation problem within the feedback control community. Theoretical developments that consider the impact of saturation range from robust control to adaptive control, to optimal control, to sampled-data control and numerous other areas. The study of saturation effects in applications such as aerospace, chemical, and mechanical engineering emphasizes the broad technological concern for this problem.

Progress in addressing the saturation problem now continues at an increasing rate. Anti-windup techniques proposed in earlier years are now giving way to nonlinear multivariable design theories that account *a priori* for the presence of saturation nonlinearities rather than as an *a posteriori* design modification. Numerous mathematical settings for modelling and handling saturation effects have been proposed and are now undergoing extensive development.

We predict at least three trends in future research. First, the reliability of saturation controllers will depend on realistic assessments of the domain of attraction of the closed-loop

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system under saturation, including both the free response and the response under external disturbances. Although the chronological bibliography does not include general work on estimating the domain of attraction or the effect of disturbances on nonlinear systems, these areas will play an increasingly crucial role.

The second trend in this area will be the treatment of more realistic actuator models. For example, while input amplitude saturation is one limiting factor, in some applications rate saturation also constrains the ability of the system to respond to commands and disturbances. Additional limitations such as quantization of input levels and hysteresis in the actuator response play a lesser but nonetheless important role.

Finally, the third trend is the requirement to constrain the system's states to specified regions. In numerous practical applications, physical systems can sustain damage unless the states are confined within given bounds. Such constraints are implicit in both the amplitude and rate saturation problems under feedback control, but have significantly broader implications[100].

In summary, the saturation problem is of central concern in virtually all control applications. The reliable operation of control systems thus depends upon our understanding the effects of saturation and developing techniques for addressing these problems.

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