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A Control Theorist's Perspective on "Reactive Control of Autonomous Drones"
— John Baillieul

In the late 1990's, at about the time of an upsurge of interest among theorists in real-time control in which feedback loops were closed through rate-limited communication channels, the Bluetooth communication standard was introduced to enable "local area networks of things." Various research groups, including my own, became interested in implementing feedback control using Bluetooth channels in order to evaluate the design principles that we and others had developed for communication-limited real-time systems. With device networks taking on ever increasing importance, our Bluetooth work was part of an emergent area within control theory that was aimed at systems using existing infrastructure rather than systems of sensors, actuators, and data links that were co-optimized to work together to meet performance objectives. The main challenge of using infrastructure that was designed for purposes other than real-time applications was that none of the infrastructure-optimized computation and communication protocols are well suited to closing feedback loops of control systems. The work of Mottola and Whitehouse that follows is somewhat along these lines – with the infrastructure in this case being the control logic and feedback control algorithms that are found on popular UAV autopilot platforms such as Ardupilot, Pixhawk, the Qualcomm Snapdragon, and the now discontinued OpenPilot. Several such autopilots are target platforms for the software described in the paper that follows.

The paper introduces the authors' notion of "reactive control" in which an autopilot's control logic is run only intermittently based on whether readings from sensors indicate a need to react to something in the environment. Thus, they employ the off-the-shelf existing control infrastructure, but only when their algorithms decide it is needed. For Mottola and Whitehouse, reactive control is distinguished from the more common approach to motion control that they refer to as "time-triggered" control. The meaning of the terminology is a bit different from the way it is used in most current work on mobile robot control where the term "reactive control" is used to distinguish fast, low-level, sensor-driven loops from slower "deliberative" control that involves path planning or goal seeking navigation. The deliberative parts of motion control involve high-level decisions and choices of ways to achieve an overall objective --- say obtaining food in the case of animals or finding areas of high concentration of a chemical species for an extremum-seeking robot. Reactive control in the robotic literature normally involves processing real-time streams of sensory data to guide low-level motor response to follow a preplanned path or a path created in the deliberative layer. There is always more urgency in executing the reactive layer of a control implementation, but a balance of reactive and deliberative is essential for achieving robot autonomy.

Reactive control in the paper that follows involves a protocol for determining when sensor readings call for the autopilot's control to function. Whereas classical feedback control corrects for deviations from a setpoint or desired trajectory at every tick of a system clock, reactive control in the paper takes control action only when a sensor input at a clock reading differs "significantly" from the previous reading. One of the paper's contributions is an algorithmic approach to deciding when sensor reading differences are "significant." The authors use a probabilistic logistic regression approach to decide when a sensor reading requires reaction. Throughout flight experiments, the parameters of the logistic-based decision rule are tuned with the aim of minimizing false positive and – more importantly – false negative assessments of the significance of sensor reading differences. Although the concept of "act-only-when-necessary" is simple and intuitive, the fact that there are multiple sensors and actuators means that there are very complex data dependencies that must be accounted for in real-time execution.

How well does it work? The authors deserve a great deal of credit for meticulous testing. They have logged more than 260 hours of flight testing and experimental bench marking on three different flight vehicles--a quadcoptor, a hexacoptor and a challenging tricoptor. They also report work with three different off-the-shelf autopilot implementations. The applications to which reactive flight control is best suited are those where setpoints do not change dramatically over the path – e.g. hovering and following relatively straight paths as opposed, say, to aerial acrobatics. Nevertheless, the experiments show convincingly that the approach can handle challenging situations – particularly in outdoor flights where wind gusts provide significant disturbances to which the control system must react. A thought that occurred to me after reading the paper is that animal movements are guided by neurological circuits that must continually refocus attention on the most relevant features in the environment. The current work may open a promising new thrust toward understanding such aspects of biological motor control.

Biosketch: John Baillieul is Distinguished Professor of Engineering at Boston University. He is past editor-in-chief of the *IEEE Transactions on Automatic Control* and also past editor-in-chief of the *SIAM Journal of Control and Optimization*.