Safety-critical control of hybrid systems with applications to power electronics

Keywords : Physical constraints; Safety; Hybrid systems; Power converters.

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Abstract – Control of safety-critical systems requires to explicitly handle constraints acting on the states, the control inputs, the communication and the available computational power. Our research aims to address such challenges using advanced methods from control and optimization theory. Among others, our goal is to characterize (potentially non-convex) constraints sets in a safe way, compute the largest and smallest invariant sets and propose systematic ways of studying the stability and safety of hybrid systems.

Important applications are for instance in energy conversion, such as the DC-DC converter. In this case, the goal is to quickly reach predefined set-points without violating physical constraints on the output power, voltage and current and by respecting the constraints on the switching dynamics.

Hybrid systems, and more generally *Cyber-Physical systems*, are dynamical systems whose behavior involves both the laws of nature (let it be the Laws of Mechanics, of Biology, the Human Behavior,...) and computerized control commands, interacting in closed loop. Typical examples include: a set of autonomous robots whose behavior depends on the communication technology, and the network-topology of their interactions, Human-in-the-loop systems, like traffic control systems, where embedded and decentralized optimization algorithms have to cope with unpredictability and human interactions; a hybrid embedded control system which intertwines continuous-time (the physical laws) and discrete-time (the computerized control loop) dynamics. There are numerous other applications, from Wireless Control Networks to smart grids, embedded medical devices, Cyber-Physical Social Systems... All these situations need automated algorithms for making them evolve optimally under many constraints (safety, energy, resilience, sustainability,...).

When a set is invariant with respect to a system, all trajectories starting from it will remain there forever. Safety-critical systems are by essence subject to some type of constraints on their states or outputs, and thus the notion of invariance is crucial in these safety and viability problems [1]. Our work shows that these problems can be addressed efficiently, even for complex (nonlinear, nonconvex,...) safety constraints.

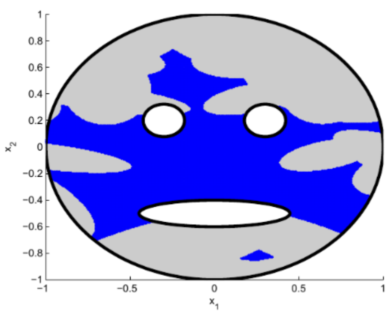

Figure 1: The gingerbread man (grey) represents the physical state constraints for a linear switching system. The blue area is the computed maximal safe domain of operation [3].

In our research [3] we recover the safe domain of operation for systems under complex, non-convex, nonlinear constraints. To achieve this, we represent the complex constraints sets by polytopic ones, in a higher dimensional space, induced by the so-called Veronese embedding. Moreover, we study the safety problem for systems which possess an equilibrium set [4] rather than a singleton equilibrium.

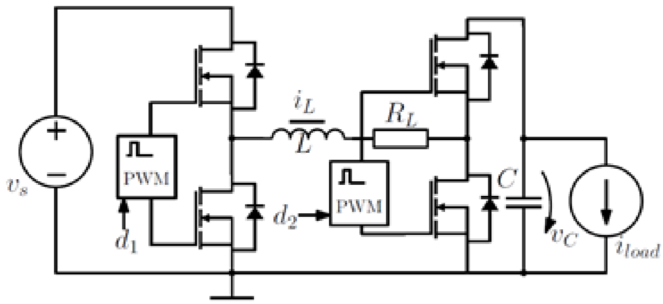

Figure 2: Schematics of the DC-DC Buck Boost converter. The circuit allows to provide higher of lower output voltage V_c than the input voltage V_s by appropriate switching.

Modern algebraic optimization techniques open new ways for safety-critical control of cyber-physical systems.

Our results can be customized for the control of power systems, such as the DC-DC buck-boost converter shown in Fig. 2. The control problem concerns the regulation of the output voltage V_c and current I_L to a pre-specified point by controlling the switching d_1, d_2 of the two PWMs without violating hard constraints on the voltage, current, and maximum switching frequency. Our results provide ways to successfully address these problems. Moreover, we can ask more refined questions regarding safety and optimality, such as 'what is the largest set of initial conditions that can be driven to the desired set-point', 'what is the most energy-efficient control strategy' and 'what is the control strategy that leads to the fastest convergence'.

References

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