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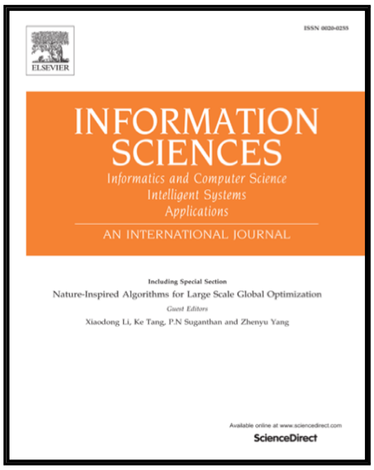

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Direct Adaptive Compensation for Actuator Failures and Dead-Zone Constraints in Tracking Control of Uncertain Nonlinear Systems

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***Abstract*—In this paper, a new tuning function backstepping control scheme is proposed for a class of parametric strict feedback nonlinear systems to accommodate actuator failures/faults and dead-zone constraints, where the failures/faults are uncertain in time, pattern, and values, and the dead-zone parameters are not available for feedback control design. Roughly speaking, such a scheme is developed in two steps below. First, by using an adaptive smooth inverse function to compensate for the dead-zone nonlinearity, we separate the coupling actuator dynamics into two parts, i.e., the dead-zone compensation errors and the nominal failure dynamics. Afterward, we further handle these two parts based on the techniques of robust adaptive approach and parametrization method. With our scheme, the global boundedness of the signals in the closed-loop system are ensured, and the tracking error is steered to zero asymptotically, regardless of the presence of uncertain failures/faults and dead-zone constraints. These results have also been verified through simulation studies.**

***Index Terms*—Adaptive control, fault-tolerant control, backstepping, actuator failures, dead zone.**

I. Introduction

IN a practical control system, actuator components may suffer from nonsmooth nonlinearities such as dead zone, saturation, backlash, hysteresis, etc. In most cases, these nonlinearities will impose damaging effects on the system performance, or even lead to instability of the closed-loop system. To compensate the hysteresis and backlash nonlinearities in some physical systems and devices, several adaptive control schemes have been proposed in [6]–[11], [16], [21], [24]–[27], [42], [47], [48], [55]. Apart from these, it is particularly important to point out that dead-zone characteristic ubiquitously exists in gear friction, hydraulic valves, DC motors and mechanical connection, which usually degrades the performance of the system. In recent years, adaptive compensation control schemes for dead-zone nonlinearity in the presence of parametric uncertainties have been developed. In [15], [22], [28], [31], [32], [40], [49], the dead-zone nonlinearity is regarded as an external bounded disturbance which can be mitigated through robust control design by using a direct decomposition method (DDM). Based on the DDM, in Zhang et al. [51], [52] and Li et al. [17], [18], several outstanding adaptive robust control schemes are further proposed to compensate generalized actuator dead-zones. Apart from DDM, the inverse compensation method (ICM) is another effective strategy to eliminate the effects of nonsmooth nonlinearities. Compared to the compensation method DDM, ICM can completely cancel actuator dead-zone by constructing an inverse compensator through parameter identification; see [31]. However, it is usually interminable and costly for offline parameter identification. Thus it is of significance to develop an adaptive inverse compensation method (AICM) by using the adaptive technique to estimate unknown dead-zone parameters online; see [38]. Furthermore, AICM is utilized to construct an advanced adaptive dead-zone inverse compensator in [39]. Moreover, in [54], a smooth adaptive dead-zone inverse for avoiding chattering phenomenon is proposed, and a different adaptive compensation scheme for unknown dead-zone is achieved in [14].

Besides the inherent actuator nonlinearities mentioned above, the failures/faults of suddenly getting stuck and losing partial effectiveness may also occur in practical actuation mechanisms, as pointed out in [33]–[35]. To handle such faults, the adaptive control methodology is mostly applied to the nonlinear system, see, e.g., [1]–[3], [5], [41], [43]–[45], [53]. Recently, studies on actuator failures started by handling the linear system failure in [36], [37], and the results were further extended to nonlinear system failure in [33]–[35] by the utilizing backstepping technique. With backstepping recursive design, a new prescribed performance bounds (PPB) based controller is proposed in [44] to guarantee the tracking error within the prescribed lower and upper bounds. Moreover, in the recent work [20], a robust adaptive fault-tolerant control scheme is further proposed for compensating failures in dead-zone actuators. However, such a scheme mainly treats the actuator failures and dead-zone nonlinearity as bounded disturbance-like effects, and thus the perfect asymptotic tracking performance cannot be obtained even for the case of finite number of actuator failures.

Motivated by observations above, in this paper, we study the problem of direct adaptive failure compensation control for a class of uncertain multiple inputs and single output (MISO) nonlinear systems with actuator failures and dead-zone con-

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