High Accuracy Nonlinear Control and Estimation for Machine Tool Systems

Component mass production has been the backbone of industry since the second industrial revolution, and machine tools are producing parts of widely varying size and design complexity. The ever-increasing level of automation in modern manufacturing processes necessitates the use of more sophisticated machine tool systems that are adaptable to different workspace conditions, while at the same time being able to maintain very narrow workpiece tolerances. The main topic of this thesis is to suggest control methods that can maintain required manufacturing tolerances, despite moderate wear and tear. The purpose is to ensure that full accuracy is maintained between service intervals and to advice when overhaul is needed. The thesis argues that quality of manufactured components is directly related to the positioning accuracy of the machine tool axes, and it shows which low level control architectures are used to position the machining tool relatively to the material being processed. While existing algorithms provide sufficient accuracy after commissioning of the machine by experts, the thesis shows how they fall short in keeping required tolerances in the presence of equipment wear, unless they are re-tuned by experts. The goal of this research has therefore been investigation and development of advanced control and estimation algorithms, which facilitate high-accuracy machinetool axis positioning, and are robust to equipment degradation and wear. This thesis presents the findings of the research conducted during the three years of the PhD program at the Technical University of Denmark. The research has been carried out in close collaboration with Siemens AG in Nuremberg, who sponsored the research. Siemens also provided state-of-the-art industrial equipment to facilitate experimental testing and validation. DTU added mechanical components to test the development of friction and backlash. The scientific-technical contributions of the research fall into three parts, which also constitute the structure of the thesis. The first part concerns the development of an efficient description of a generic machine-tool axis system. A detailed mathematical model is derived that captures the most important axis dynamics. Positioning degrading phenomena, such as friction and backlash, are expressed as nonlinear axis torques. Identification of the test rig parameters and sensitivity analysis is carried out, to highlight the significance of individual model parameters. The second contribution of this research pertains to the investigation of different nonlinear control strategies and architectures for the positioning of the axis. Eight position controllers based on sliding-mode and adaptive principles are designed, implemented and tested on the experimental setup. A set of quantitative and qualitative criteria is used for the systematic comparison of the methods. The evaluation results show that four out of the eight designs provide superior positioning accuracy and resilience to unknown and varying friction, in comparison to the state-of-the-art proportional-integral control solutions. The third part of the research relates to the development of online backlash estimation algorithms for machine-tools. The proposed method utilizes position and velocity measurements in a cascaded scheme consisting of a sliding-mode velocity observer and an adaptive deadzone angle estimator. A series of experiments is conducted for testing the algorithm in various operation scenarios under different levels of uncertainty. The results show that the estimator identifies the unknown deadzone angle and changes in it with sufficient accuracy and can, therefore, facilitate backlash compensation, as well as equipment wear assessment and prognosis. The scientific results of this research have been summarized in three journal articles, which have been submitted, and an article presented at the IFAC World Congress 2017 that has been published.

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