Preface

The idea of this book emanates from my Ph.D. thesis that I, wrote at the University of Luxembourg, defended in January 2016. The book addresses one of the vital robotic applications in industry, the assembly processes. In this book force-guided (or force-controlled) robots are considered and the required skills in realizing the force-guided robotic assembly processes are studied. More precisely, this book covers developing novel Contact-State (CS) modeling, control strategy, and environment position localization (position searching) for force-guided robotic assembly processes of rigid and flexible objects.

For the CS modeling, the wrench (Cartesian force and torque) signals of the manipulated object are captured for different phases of the considered assembly processes and using the Expectation Maximization-based Gaussian Mixtures Model (EM-GMM), a recognizer is developed for each CS of the assembly. The suggested EM-GMM CS modeling scheme is shown to have excellent Classification Success Rate (CSR) with reduced computational efforts. For the control part, it is shown throughout the book that a force-guided robotic assembly process is a hybrid nonlinear system with arbitrary switching signal resulted from the arbitrarily-switched constraints during the assembly. Furthermore, the robot dynamics is frequently unknown, which is the case for many industrial robots that would make the force-guided robotic assembly process to be an unknown hybrid nonlinear system with arbitrary switching. In order to overcome such a control challenge, a Decentralized Robust Adaptive Fuzzy Control (DRAFC) strategy is derived that guarantees stable performance under arbitrarily-switched constraints and unknown dynamics. For the environment position localization, the EM-GMM CS modeling scheme is integrated with a spiral search path and the precise hole position is identified for cases of position uncertainty.

Experiments are conducted on a KUKA Lightweight Robot (LWR) doing different force-guided assembly tasks for rigid and flexible objects. Excellent performance is reported for the proposed EM-GMM CS recognition scheme, the DRAFC strategy, and the suggested position searching algorithm. The suggested EM-GMM CS recognition, DRAFC strategy, and position localization schemes are compared with the available corresponding schemes and the superiority of the suggested schemes is shown. The reasons behind the superiority of the EM-GMM CS recognition scheme are the accommodation of the captured signals nonstationary behavior, employing optimized number of GMM components in the modeling process, and employing the EM algorithm that iteratively increases the log-likelihood. The causes behind the superiority of the DRAFC strategy are addressing the unknown nonlinear dynamics of the robot, accommodating the arbitrarily-switched constraints, and the robustness against possible dynamics parameters drift. The reasons behind the surpassing of the suggested position localization strategy are the robustness against the surface roughness and reduced computational efforts. The proposed EM-GMM CS modeling scheme, DRAFC strategy, and position searching scheme are applied to the entire peg-in-hole assembly processes of rigid and flexible objects. Excellent Localization Success Rate (LSR) resulted when the suggested schemes were used. Furthermore, the proposed CS modeling scheme, control strategy, and localization approach are applied to a couple of applications in automotive industry; the first one is the camshaft caps assembly of a cylinder head and the other is the air-intake manifold assembly of a powertrain. Efficient force-guided robotic assembly processes are obtained for both considered applications. The book is organized as follows. Chapter 1 details the literature of the CS modeling part, the control of robots, and the searching algorithm of robotic assembly processes. It also summarizes the description of the problems and the main objectives addressed in the book. In Chap. 2, the CS modeling problem is thoroughly formulated and clear goals of the CS recognition system are set. First, the Gravitational Search-Fuzzy Clustering Algorithm (GS-FCA) is explained. Then, the EM-GMM CS recognition scheme is detailed. Based on the similarity measure between the distribution of the captured signals and the developed models, finding the optimal number of the GMM components is explained.

Chapter 3 lodges the control part of the book. First, the control problem of robots with arbitrarily-switched constraints, which is the case in the force-guided robotic assembly process, is formulated mathematically to be a switched nonlinear system with arbitrary switching signal. Then, an Adaptive Sliding Mode Control (ASMC) design is proposed for the given robot system. The suggested ASMC is proved to accommodate the arbitrarily-switched constraints by finding a Common Lyapunov Function (CLF) that is common to all subsystems of the switched constrained robots. Even though the ASMC strategy is shown to have a stable performance with all closed loop signals ascertained to be convergent and bounded, high control actions might result when using the ASMC design caused from ignoring the passivity property of the robot and the chattering phenomena. Hence, Improved Robust Adaptive Control (IRAC) scheme is derived, for the switched constrained robots, that considers the passivity property of the robot, reduces possible chattering, and accommodates the arbitrarily-switched constraints. The passivity property is incorporated in the derivation of the IRAC design that significantly reduces the control action. The chattering is reduced by using a modified filtered error signal, in the derivation, instead of the filtered error. Likewise to the ASMC design the notion of the CLF is used in the IRAC strategy for accommodating arbitrarily-switched constraints. In spite of its excellent tracking performance, the IRAC strategy requires the parameters of the precise robot dynamics and in order to relax the need for knowing these parameters, a Robust Adaptive Fuzzy Control (RAFC) strategy is derived. The RAFC strategy uses the notion of the Fuzzy Logic Approximators (FLA) in approximating the IRAC control term that depends on the parameters of the robot dynamics. The proposed RAFC strategy is actually based on the IRAC design with relaxing the need for knowing the robot dynamics. However, a shortage was noticed for the RAFC strategy which is the drastic increment of the size of the free parameter vector of the fuzzy control term causing a bottlenecking for robots with low computational abilities. Therefore, an Enhanced Decentralized Robust Adaptive Control (EDRAC) strategy was derived based on the fact that the torque for each joint can be composed into two terms; one as a function of the specific joint state variables (the state variables of the joint under consideration) and another term that is a function of all robot state variables. Then the EDRAC design is upgraded by proposing the DRAFC strategy in which only the term, of the EDRAC design, that relies on the specific joint state variables is approximated by the FLA and the other term is compensated by adapting its bound online. The DRAFC strategy is shown to provide stable performance despite the robot dynamics anonymity and the arbitrarily-switched constraints. The size of the free parameter vector is significantly reduced that would bring about a significant reduction in the computational cost and consequently make the DRAFC strategy applicable to a wider range of robots.

Chapter 4 explains the proposed searching strategy for accommodating position errors in the force-guided robotic assembly processes. Inspired by human operator doing a manual assembly process, the proposed searching strategy integrates the EM-GMM CS modeling, developed in Chap. 2, with the a search path in order to locate the precise hole position.

Chapter 5 details the experimental validations of the proposed EM-GMM CS modeling scheme, the DRAFC strategy, and the suggested position searching algorithm. Different kinds of rigid and flexible objects with various geometry are considered in the experimental validations. Comparisons are also conducted with the available CS modeling schemes, control design, and position searching methods. Furthermore, the proposed modeling, control, and searching schemes are tested on the robotic peg-in-hole assembly processes of rigid and flexible objects and the enhancement of the overall assembly process is demonstrated.

In Chap. 6, the proposed EM-GMM CS modeling scheme, the DRAFC strategy, and the developed position searching approach are applied to industrial applications of the automotive industry. The first considered application is the camshaft caps assembly of a powertrain which is basically a double pegs-in-holes assembly process. The second application is the air-intake manifold assembly of another powertrain which is a multiple pegs-in-holes assembly process.

Chapter 7 details miscellaneous topics that were not covered in the chapters above. More specifically, this chapter addresses the identification of human error in the CS modeling process and the enhancement of the estimation process of the interaction impedance parameters. In the framework of data outlier detection, a strategy is developed for identifying the signals contamination resulted from human error when conducting the CS modeling. This data outlier detection is based on computing the centers of the signals clusters and robust human error identification scheme is obtained. For the impedance parameters estimation, the joints velocity and acceleration, which are required for such estimation process, are smoothed. Thus, approximation error, resulted from numerical differentiation, is reduced which would enhance the impedance parameters estimation process.

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