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Human motion prediction for human-robot collaboration☆

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ABSTRACT

In human-robot collaborative manufacturing, industrial robots would work alongside human workers who jointly perform the assigned tasks seamlessly. A human-robot collaborative manufacturing system is more customised and flexible than conventional manufacturing systems. In the area of assembly, a practical human-robot collaborative assembly system should be able to predict a human worker's intention and assist human during assembly operations. In response to the requirement, this research proposes a new human-robot collaborative system design. The primary focus of the paper is to model product assembly tasks as a sequence of human motions. Existing human motion recognition techniques are applied to recognise the human motions. Hidden Markov model is used in the motion sequence to generate a motion transition probability matrix. Based on the result, human motion prediction becomes possible. The predicted human motions are evaluated and applied in task-level human-robot collaborative assembly.

1. Introduction

Industrial robots have been widely used in modern manufacturing systems. In the future, the industrial robots may share the same working environment with human workers. An industrial robot can provide better fatigue, higher speed, and greater strength and accuracy. A human worker, on the other hand, possesses better adaptability and sensorimotor capabilities. The concept of human-robot collaboration (HRC) combines in essence the advantages of both the industrial robots and the human workers. In an HRC system, human workers and industrial robots team up and work jointly on the same shared tasks. An essential requirement for such an HRC system is human safety [1,2]. Traditionally, by giving different instructions to the humans and the robots, time separation and space separation approaches have been common [3]. To ensure safe HRC, both humans and robots need to follow specific work instruction sheets strictly. According to the instructions, certain human worker's motions are predictable. However, to support and collaborate with a human worker at the task level, an industrial robot needs to work alongside the (coexisting) human worker [4].

Recently, much work has focused on HRC safety [1,2,5]. However, safety is only the first step towards a practical HRC manufacturing system. An HRC manufacturing system is more customised and flexible than conventional manufacturing systems. An efficient HRC system should be able to understand a human worker's intention and assist the human during an assembly task. Since a human worker's (work-related) motions are limited and repetitive, the authors have modelled an assembly task as a sequence of human motions. Existing human motion recognition techniques can be applied to recognise the human motions associated with the assembly task. The recognised human motions are modelled by Hidden Markov model (HMM). The motion transition and observation probability matrices are then generated after solving the HMM. Based on the result, human motion prediction becomes possible. The human intention is analysed with the input of predicted human motion. The predicted human intention can be used as input for assistive robot motion planning. The industrial robot can thus be controlled to support and collaborate with the human worker based on the planned robot motions. The workflow of human motion prediction in HRC is shown in Fig. 1.

The remainder of this paper is organised as follows. Section 2 reviews previous work in the area of human motion prediction. Section 3 discusses the problem formulation and representation. Section 4 introduces the HMM process in the human motion recognition context. Section 5 reports a car engine assembly test case to validate the presented concept. Section 6 discusses the result of the car engine assembly test case. Section 7 summarises the paper with future works and conclusions.

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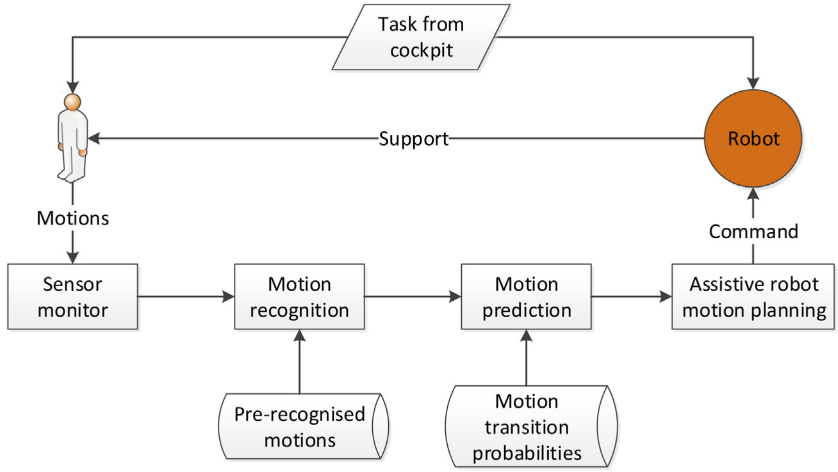

Fig. 1. Workflow of human motion prediction in HRC.

2. Related work

Human motion estimation and prediction can be analysed from different perspectives. Neuroscience researchers analysed human motions and behaviours through human brain neural network structures [6]. The human brain is a highly flexible computational system. Since a person has a limited amount of energy and resources, the possible future motions are always analysed by our brain before execution. It can predict the future outcomes of actions and change them when they are unlikely to achieve the expected results. Horowitz et al. [7] provided a feedback mathematical filter that determines human arm reaching intention. The proposed mathematical filter estimates and displays a human worker's underlying intended trajectory in real-time. The mathematical filter combines a human arm model with the force data collected from the human arm to determine the human worker's underlying intended reaching position. Their another paper [8] proved that the human motion is predictable even if the motion is only partially performed. The neuroscience researchers confirmed the hypothesis that human motion is predictable to a certain extent. These research efforts have established a theoretical foundation for human motion prediction in HRC applications.

Researchers in the field of computer vision are also interested in human motion estimation and prediction. Reddy et al. [9] explained a novel human motion estimation framework called feature-tree. The feature-tree framework utilised K-Nearest Neighbours (KNN) in features retrieval. Their system provided a simple solution for practical and incremental motion estimation problems. Lu et al. [10] introduced an HMM-based hand motion estimation system. The system utilised two levels of HMM. The hand detection features were abstracted by the Histogram of Oriented Gradient (HOG) algorithm first. The abstracted features were then sent to the HMM algorithm for hand motion classification and prediction. Feng et al. [11] combined the HOG and the Support Vector Machine (SVM) algorithm for static hand motion estimation. The HOG features are utilised in the SVM training process. The trained SVM classifier is used for motion prediction. Hasan et al. [12] introduced a hand motion estimation system. Several hand motions were predefined in the system. The system enabled a multi-layer artificial neural network (ANN) which applies a back-propagation learning algorithm. Li and Fu [13] introduced a general framework for human activity prediction. They compared their approach with HMM, SVM, and KNN based methods. Advantages and disadvantages of different approaches were discussed. Ryoo [14] presented a dynamic bag-of-words method for human motion prediction in streaming videos. The human motions were represented as an integral histogram of spatio-temporal features. Ding et al. [15] provided a human motion prediction approach in video sequences. Spatio-temporal patterns were modelled by a Hierarchical Self-Organising Map (HSOM). The continuous human motions were predicted by Variable order Markov Model (VMM). These researchers provided solutions for general human motion prediction problems. The applicability of the proposed solutions in the HRC field still needs to be carefully examined.

Some of the researchers in the HRC field also investigated into human motion estimation and prediction. Mainprice et al. [16] claimed that the single-arm reaching motion is an optimal trajectory with an unknown function. Human also provides the capability to adapt trajectory according to a collaborator's motion. The trajectory optimiser Stochastic Trajectory Optimisation for Motion Planning (STOMP) was applied to predict human motion [17]. The result of the paper shows that the predicted human motion in the robot's motion planner can increase interaction safety and efficiency between the human worker and the robot. Another paper from the same author presented a framework that can predict a human's motion early by using Gaussians Mixture Model (GMM) algorithm [18]. The predicted human motion is used as information support for HRC. Bascetta et al. [19] utilised visual tracking and human motion estimation for safe human-robot interaction cell design. Colour based model and the GMM algorithm were applied to the human detection task. The detected human is tracked by a partial filter. The human motion estimation problem was solved by the HMM algorithm. Li and Ge [20] introduced a human intention estimation method by using neural network technology. The estimated human motion was integrated into an adaptive impedance control. The proposed method enabled the robot to collaborate with its human partner actively. In a paper by Hawkins et al. [21], an HRC human motion prediction system was implemented. A Bayes Network modelled the assembly task structure. Another research [22] predicted human intention in medical applications. The human intention was predicted by the SVM algorithm.

In the HRC field, many researchers attempted to design coexisting HRC systems. Coupeté et al. [23] introduced an HRC system that helps human worker gesturally control an industrial robot in an assembly line. The acceptability of an operator to work with a robot on collaborative task was evaluated. Gesture recognition was applied to enable a natural collaboration between a human worker and a robot. Rozo et al. [24] demonstrated that a robot could learn movement from a human through programming by demonstration approach. The described motion was segmented into different stages. Various stages were modelled by an adaptive duration hidden semi-Markov model (ADHSMM). Fiore et al. [25] developed