Coordination between a Human and a Dance Partner Robot

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論文内容要旨

This dissertation discusses effective human-robot coordination with physical interaction. In most of human-robot coordination system developed by several researchers, robots are controlled so as to move/behave passively based on force/moment applied by humans. In simple words, the robots move along the same direction as one that the humans apply force along. Such robotic systems are intuitive and easy for human to use them. However, if robots could move not only passively but also actively based on human intentions, environments, knowledge of tasks, etc., we could realize more effective human-robot coordination than the conventional ones. Considering the case of coordination among humans, each human would move not only passively but also actively based on the above information. In this research, human-robot coordination with physical interaction between a human and a robot is discussed to execute tasks more effectively, in which the robot is required to move not only passively but also actively based on such information.

As an example of the coordination tasks, ballroom dances are focused. In ballroom dances, a male dancer selects the next dance step based on transitional relationships of dance steps, information on the environments, manners of dances, and so on, and also leads his female partner through the physical interaction between them. The female dancer estimates the next dance step intended by him based on his lead and the transitional relationships. We develop a dance partner robot that acts as a female partner and performs dancing with the human, and design its control architecture based on features of ballroom dances. Three issues are considered in order that the robot dances in coordination with the human. At first, the robot has to know the information on ballroom dances such as dance step trajectories and transition rules of dance steps. Next, the robot has to estimate the next dance step intended by the human. Furthermore, the robot has to correct a step if the robot mistakes the estimation. Thirdly,

Fig. 1: Dance Partner Robot

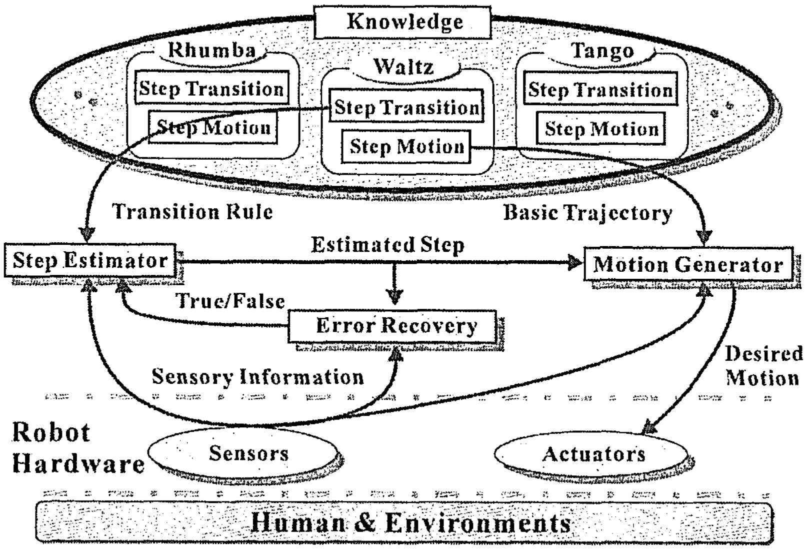

Fig. 2: Control Architecture -CASTER-

the robot has to generate cooperative motion to dance in coordination with the human by fitting own length of dance step stride to human's stride. These three issues are addressed in the body text of this dissertation as follows.

In chapter 2, the dance partner robot -MS DanceR- and its control architecture -CAST- are introduced, which have been designed based on features of ballroom dances in the previous research. The CAST consists of three modules, i.e. Knowledge, Step Estimator, and Motion Generator. The Knowledge stores the information on dancing such as basic trajectories of dance steps and transitional rule of dance steps. The Step Estimator estimates the next dance step intended by the human male dancer based on his lead and the transitional rule. The Motion Generator generates cooperative dancing motion based on the physical interaction with him and the basic trajectories. Although the MS DanceR and the CAST work successfully, there exist issues that should be improved for the previous robot system. In chapter 2, we develop the new dance partner robot -MS DanceR II- and re-design its new control architecture -CASTER-. We remark issues concerned with Step Estimator and Motion Generator in the CASTER to improve them. Furthermore, a new mechanism for the error recovery of dance step selections, referred to as Error Recovery, is added into the CASTER.

In chapter 3, a dance step estimation mechanism -Step Estimator- in the CASTER is improved, which estimates the next step intended by the human based on time series of leading force/moment applied by the human. In order to use time series data, we have to consider uncertainty characteristic of time series data such as time lag and

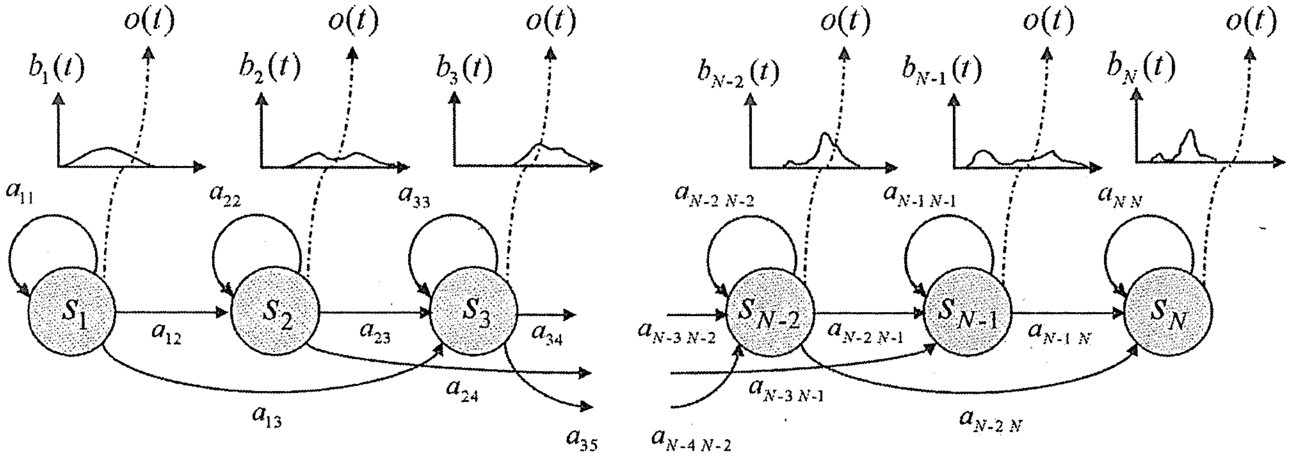

Fig. 3: Left-to-Right Continuous Hidden Markov Model that Models Time Series Data Stochastically

variation for repeated trials. A main estimation module in the Step Estimator is designed using Hidden Markov Models (HMMs), which model stochastically time series of the leading force/moment including the uncertainty. The new Step Estimator is tested whether it can estimate the step at high success rates compared with the old Step Estimator. The experimental results illustrate the validity of the HMM-based Step Estimator.

An error recovery problem for the step estimation, i.e. a problem how to treat the case that the robot could not estimate the correct step, is divided into two problems, i.e. an error detection problem and an error recovery problem after the error detection. In chapter 4, the error detection method for the step estimations is designed based on human dancing motions. In the error detections, human legs' motions are measured using a laser range finder installed at robot's mobile base. The human dancing motions are modeled stochastically using HMM. The HMM-based error detection method could works completely in experiments on the error detection. Experimental results have also described that time required for the detection would be short if human's motion is quite different from robot's motion, and would be long if human's motion is similar to robot's motion.

In chapter 5, the error recovery problem after the error detection is addressed, which consists of two processes, i.e. step re-estimation and modification of robot's trajectories. Although the human dancing motion model in chapter 4 would also be expected not only to detect the error of dance step estimation but also to re-estimate the step intended by the human, it could not re-estimate the step completely because the human dancing motion would be affected by robot's incorrect step motion when the first step estimation is failed. Paying attention to human leading force/moment, the force/moment would include not only the information on the most possible step intended by the human but also one on the second most possible step. Therefore the force/moment could be useful information for

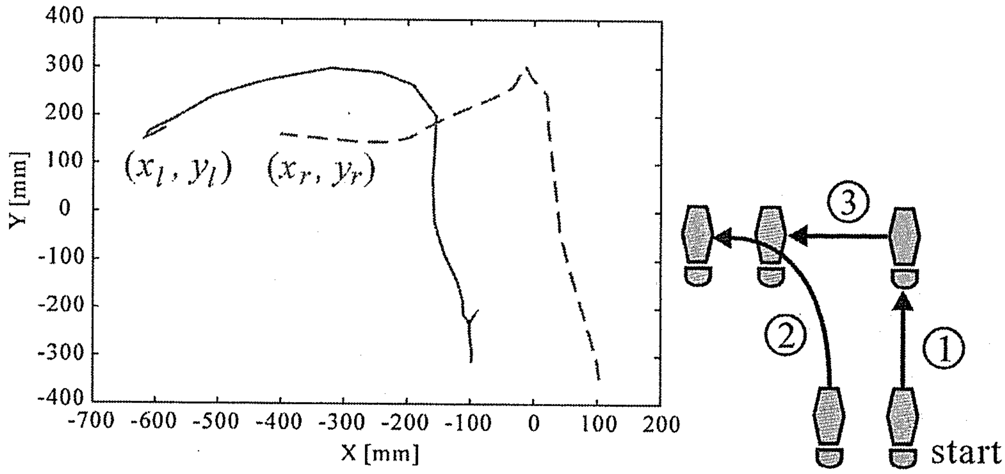

Fig. 4: Human Dancing Motion Measured by Laser Range Finder

the re-estimation if the estimated step, i.e. the most possible step at the first step estimation, is excluded from possible steps for the step re-estimation. In the step re-estimation method, the estimated step is excluded from the possible steps. And both of human leading force/moment and human dancing motion are used for the step re-estimation, in order to increase the reliability of step re-estimation. With respect to the modification of robot's trajectories, a simple modification method is used as an example, in order to realize the error recovery. The error recovery method could correct robot's incorrect motion to human's motion completely. The experimental results have also described that the length of time required for the error detection could not matter to changing robot's motion from incorrect behavior to correct one in the error recovery, because differences between the correct step motion and the incorrect one would be small when the time is somewhat long, according to the experimental results.

In chapter 6, a motion generation method for cooperative dancing by the human and the robot is proposed. In ballroom dances, each dancer fits own length of dance step stride to partner's by considering physical interaction with his/her partner in repetition of dancing. And he/she could realize the cooperative dancing motion with his/her partner. The motion generation method enables the robot to perform dancing motion actively with fitting own motion to human's dance step stride by itself based on the physical interaction.

Finally, chapter 7 concludes this dissertation.

論文審査結果の要旨

社会の高齢化にともない，生活環境下で人間と共存・協調し，人の作業をサポートするパートナロボットの開発が望まれている。人とロボットの協調作業を実現するには，ロボットの運動をどのように生成するかが問題となる。これまで，何らかの方法でロボットの運動を直接指示したり，人がロボットに加えるインテンショナルフォースに基づいて，ロボットの運動を受動的に生成するシステムが提案されているが，より複雑な協調を実現するには，ロボット自身が，人の行動を予測したり，その意図を推定したりすることが必要である。そこで，本論文は，人との協調運動そのものが作業である社交ダンスパートナロボットを題材として，人とロボットのより密な協調メカニズムの構築を目指したもので，全編７章よりなる。

第１章は序論であり，本研究の背景と目的を述べている。

第２章では，本論文で題材とする社交ダンスの特徴とそのモデル化について説明するとともに，本研究で用いる男性と社交ダンスを踊る女性側ダンスパートナロボットのメカニズムと，その制御アーキテクチャ CASTER（Control Architecture based on Step Transition with Error Recovery）を提案している。提案するアーキテクチャは，本論文で提案する制御系共通のアーキテクチャである。

第３章では，ダンスをリードする男性がダンスパートナロボットに加える力情報に基づき，次のダンスステップを推定する方法を提案している。ステップが切り替わる直前の力情報だけで次のステップを推定する従来の方法と比較して，ステップが切り替わるまでの力情報を，不確かさを有する時系列データとして扱い，隠れマルコフモデルに基づくステップ推定器を構成することで，ステップ推定の精度が格段に良くなることを実験によって示している。本手法は，時系列データに基づく人の行動予測や意図推定に適用可能な極めて有効な手法である。

第４章では，人間がリードを間違える場合など，絶対に避けられないステップ推定エラーを，足の運動を観測することによって実時間で検出する方法を提案し，実験によりその有効性を確認している。推定エラーは絶対に避けて通れない問題であり，エラー検出が可能な本手法は，重要な成果である。

第５章は，ダンスパートナロボットがステップの推定エラーを起こした際に，エラーをリカバリーする手法を提案している。前章で提案したエラー検出手法に加えて，本手法は，男性がロボットに加える力情報も利用することで，男性のステップを特定できることを示し，それに基づいてエラーリカバリーを行うもので，ダンスパートナロボットを実現するための有効かつ重要な成果である。

第６章では，ダンスパートナロボットと男性が前章で推定されたステップに基づいて踊っている場合において，男性の体格やダンスの技量によって変化するステップスライドを推定し，そのステップスライドに適応させながらダンスを実現する実時間適応型協調運動制御手法を提案している。人間とロボットの力学的相互作用において実時間適応型運動制御系の実現は極めて重要な成果である。

第７章は結論である。

以上要するに本論文は，女性側ダンスパートナロボットの研究開発を通して，社交ダンスのような，人とロボットの複雑な協調が実現できることを示したもので，バイオロボティクスおよび機械工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。