Dance Instructor Robot for Supporting Human Skill Learning Process

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論 文 内 容 要 旨

This thesis contributes to the robotics field through the design of a robot for physical human-robot interaction (pHRI) which is controlled for guiding a human within Waltz dance motions in a whole-body contact. Through the designed and constructed robot, the idea of robot guiding and supporting the human skill learning process is presented in a dance training framework, so that, the robot acts as a teacher in this process. Physically interacting with a human partner for guiding him/her in the dance, while simultaneously assessing their ability level and adapting its response for enhancing the skill learning acquisition. This document presents the design, construction, control and evaluation of the roboDANTE, in human interactions. Likewise, a teaching methodology for guiding physically in the context of Waltz dance training is presented through the concept of progressive teaching. Making this robot a unique example of robot lead interactions in close contact with humans.

Figure 1: Robot Dance Teacher (roboDANTE). Left side: photograph with a human partner. Right side: robot CAD accompanied

by a human model.

Formerly, human-robot cooperative tasks have been widely researched towards assistive robots capable of predicting and supporting humans in daily life activities, such as carrying heavy objects, handling tools and walking support. Most of such studies have focused on developing methods of control for exchanging the leading role between the human and the robot, however, giving a robot the role of fully guiding a human, moreover, teaching in a motor skill learning process is a new approach to human-robot interactions (HRIs), which could open the horizon of robotics application to closer contact activities with humans.

The Waltz dance as a context for pHRI has been selected for its clearly defined rules in interactions between partners. The predefined motions involved in the dance and the rules of transition between different dance figures (combination of steps) provide a well-structured interaction between the dyad, where one side assumes a leading role guiding the motions and making decisions, while the other side estimates those decisions of motion and follows with the rhythm of the music. Consequently, Waltz provides advantages for placing a robot as a guide of human motions by first: establishing rules in the interactions which have been predefined and tested for a long time among human (in the long history of dance). Second, it potentially grants a social setup where the robot could lead the human motions with his/her agreement, as the role of follower could be set to the human partner.

Under this framework of interactions, this dissertation initially presents the design and construction of a robot for achieving a research platform as described above. Analyzing the human body motions while dancing through a motion capture system and designing the structure with a minimal number of degrees of freedom (DOF), so that, the robot could perform a human-like motion in the Waltz dance with a lighter and simpler structure than the human body. Under these set of requirements, the robot was designed as a human-sized mobile humanoid robot, with a lower body formed by a mobile base with three omnidirectional wheels. Allowing displacements on the X-Y plane and rotation around the Z axis (vertical axis). In this design process, a multi-objective optimization was used for ensuring a stable motion during interactions (avoiding tip-over of the robot) and a comfortable human-like structure that allows enough space for the feet movements of the human partner while in a close contact posture with the robot.

The upper body of the robot is formed by four DOF: a prismatic joint over the z axis for a rise and fall motion of the upper body, a rotational joint around the z axis mimicking the rotation of the torso over the vertical axis, a rotation of the upper body perpendicular to the frontal plane emulating the motion of the upper torso (rotation of the chest), and a rotational joint at the shoulders height around the notch.

In this design, the main means of understanding the human partner's response in interactions is through a six axes force/torque sensor placed below the first rotational joint (the hips of the robot), so that all contact forces are sensed and used for controlling the robot during interactions.

Subsequently, a method of conveying the robot's intention of motion is presented. From analysis of the captured dancer's data while performing Waltz figures, a cueing motion of the center of mass (COM), which was utilized for conveying the motion intentions during the dance was observed. The data showed that the COM height was synchronized with directional changes during the Walt figures. As well, a similar motion was observed in the transition between figures. Consequently, it was hypothesized that the robot could convey its motion intention in the same way by varying its COM height, elevating the human partner's COM and making him/her more susceptible to any robot force at such pose.

The proposed guidance through an unstable equilibrium point (G-UEP) was tested under directional changes in the dance through a user-based study with10 subjects. The results showed a 20% more understanding when the G-UEP method was used, compared with the robot guiding motions in a pure force based interaction method. Furthermore, required force for conveying the robot's motion intention exhibited an average reduction of 10 N compared with the pure force control.

Under this close contact interaction, a further test was carried out for evaluating the effect that auditory commands could provide in robot guidance. It was tested voice-over of the robot's intention of motion, that is, the speaking the motion it would perform beforehand. It was hypothesized that such commands could provide better understanding of the robot's intention, thus, better performance. Nevertheless, the results showed that there was not significant difference in the understanding of the robot's intention neither in the interaction forces with or without the voice-over in contrast to initial hypothesis. However, the evaluation of human perceptions during interactions showed that people was more comfortable, and perceived the robot more human-like and with a better performance in its task when voice-over was used in the interactions.

Furthermore, an approach for supporting the skill learning process in dance is proposed through physical and cognitive guidance in the pHRI. Based on a progressive teaching (PT) methodology, the robot first assesses the partner's skill compared with the level of development in the skill acquisition. Subsequently, the robot adjusts its support based on those assessment results, thus, the robot adapts its interaction control for guiding with the required forces proportionally to an estimation of the partner's ability and its desired state of progress. That is, assuming a correlation of the count of practices with the state of development on the skill the robot would gradually increase the difficulty on the task for enhancing the skill formation.

On the low-level control this is reflected in variations of the robot's impedance parameters, decreasing the robot's damping as the human partner improves its skill, and increasing the damping in case the human performance decreases.

The interaction controller based on the PT methodology has been successfully used by multiple novice dancers in learning basic Waltz figures. A comparative user-study of the PT adaptive control and a reference controller with constant dynamics in the interactions presented significant difference in the learning rate with faster improvement in motions for the initial stage of the skill acquisition, as well as, in the human perceptions of comfort, peace of mind, and performance during interactions with the robot, with the higher rating always favoring the PT training.

This proposal integrates physical and cognitive support in the skill learning through the direct adjustment of the robot dynamics in the low-level control and constant feedback of performance to the human partner for enhancing the internal model formation. Therefore, establishing a teaching mechanism and controller for physically interacting with humans while considering the needs in the skill learning process.

For further improvement of the cooperative task in pHRI, the concept of Harmony in pHRI is introduced as the level of synchrony between the robot, the human and an attuning reference, where the latter is used to enhance the synchrony between the dyad. In the case of dance the music acts as such attuning reference. However, in the training scenario the voice-over commands counting the rhythm are used for easier understanding of the novice partners.

This harmony level is proposed as a probability based on experts' evaluation of dance interactions with the robot, using significant features in the haptic interactions from force and motion data. Features such as the mean power frequency (MNF) in interaction forces, velocity error in time and frequency domain were used to learn the probability of harmony based on evaluated data from 10 expert dancers on 12 videos data.

This estimation presents a measure of the partner's level of understanding of the robot leading, with an 84% match with the expert's evaluation. This could contribute for further improvement of the robot's dynamic response to new partners by adjusting the control parameters in order to initiate the teaching process in a more accurate way to the unique compliance characteristics of each human.

Concluding, this dissertation advances the field of physical human-robot interactions through the development of a robot that could guide humans in close contact interactions within a dance training framework. Moreover, an interaction methodology for enhancing the skill learning process in dance was introduced through a cognitive and physical adapting interaction. As well, a measure of the level of synchrony was presented and evaluated by expert dancers. Finally, the robot's motion intention conveyance was developed through a guidance method based on the unstable equilibrium point (G-UEP), nevertheless, its extension to other DOF remains an open question that could be addressed by the proposed harmony level estimation in combination with specific guidance forces profiles for transmitting the robot's intentions in accordance to the type of motion.

論文審査結果の要旨

人と共存し，人を物理的に支援するロボットの実用化が期待されている。人を物理的に支援するには，ロボットは人に対して受動的に振る舞うだけでなく，人に対して能動的に働きかけ，人の運動をリードする必要がある。本研究は，ダンスティーチングロボットの開発を通して，ロボットと物理的な相互作用を持つ人に，どのようにすればロボットの意図を伝え，そのパートナをリードできるかという問題に関して研究したものであり，全編６章からなる。

第１章は序論であり，本研究の背景，目的および構成について述べている。

第２章は，本研究で提案するダンスティーチングロボットの設計について述べている。ワルツを踊るダンサーの運動を計測し，それに基づきダンスティーチングロボットのハードウエアが満たすべき仕様を決定し，ロボットを設計・製作し，製作したロボットが当初の仕様を満足することを実験によって確認している。これまでにない新しい運動機構の設計によって，ダンスロボットの仕様を満足できるようにしたもので，これは有用な成果である。

第３章では，ワルツを踊っているダンサーの運動を計測・解析し，男性ダンサーが一緒に踊っている女性ダンサーを，どのようにリードしているかということを考察している。具体的には，ダンサーの質量中心の運動に着目し，男性ダンサーは，女性ダンサーの姿勢を不安定平衡点に誘導することで，効果的に女性ダンサーをリードしているということを明らかにしている。さらに，男性ダンサーのリードを可能にするロボットの運動制御系を提案し，ダンスティーチングロボットに実装し，実験によりその有効性を示している。これは重要な成果である。

第４章では，人のスキル獲得過程に基づき，ダンスの習熟過程において人がどのようにダンススキルを獲得するかという問題について考察し，ダンススキル習熟度の実時間アセスメント，その結果の実時間提示と物理的相互作用へのフィードバックから構成される新しい手法「プログレッシブ・ティーチング」を提案している。また，提案する手法に基づく制御システムを構築し，ダンスティーチングロボットを用いて被験者実験を行い，プログレッシブ・ティーチングが有効であることを示している。これは有益な結果である。

第５章では，人とダンスロボットの同調性のレベル推定手法について述べている。まず，複数の被験者にダンスティーチングロボットとダンスを踊ってもらい，ダンスにおける相互作用に関する運動データを計測するとともに，１２人のダンススクール教師にそのダンスの評価を行ってもらい，統計解析を行って，７種類の運動計測データによって，同調性が精度良く推定できることを明らかにしている。これは重要な結果である。

第６章は結論である。

以上要するに本論文は，人と物理的相互作用を持つダンスティーチングロボットの開発を通して，人との物理的相互作用を有するロボットが，どのようにすればその意図を人に伝え，人の運動をリードできるかという問題を研究し，不安定平衡点を用いた運動のリード，プログレッシブ・ティーチングによる効率的な教示，同調性の客観的なレベル推定手法を提案するとともに，実験によってそれらの有効性を検討したもので，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。