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Motion harmonization for human-robot collaborative handling tasks

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Abstract

In human-robot collaboration (HRC), robots work alongside humans within a shared workspace. When repeating a handling task together, the movement of the human co-worker varies each time while the robot's movement stays the same. To enable smooth collaboration, the robot's path needs to be harmonized with the movement of the human co-worker. This work proposes a concept to plan robot trajectories that best fit natural human movement while considering the speed and acceleration limits of the robot joints.

Keywords: Human-robot collaboration, Path planning, Human motion modeling

1. Introduction

The landscape of industrial manufacturing is transforming as collaborative robots emerge as key players in augmenting human capabilities within assembly processes [1]. HRC aims to leverage the complementary strengths of humans and robots to foster a more inclusive and human-centered future in manufacturing. With production systems evolving toward greater personalization, HRC offers the opportunity to increase process speed and accuracy while also enhancing the co-worker's ergonomy. Despite its potential, HRC is not yet widely adopted in production systems, with performance and safety concerns, particularly at higher operational speeds, posing significant challenges [2]. The robot's maximum speed is harshly limited because of the lack of knowledge of human motion. That implies better mutual consideration enables the robot to move faster and leads to smoother collaboration [3]. With a proper human motion model that can predict natural human motion, the robot can anticipate human behavior and adapt its trajectory. The goal of this work is to enable smooth collaboration with high mutual consideration between a robot and a human co-worker. Therefore, the safety aspect is excluded from this work and will be an objective of future work.

This work focuses on the collaborative handling of a rigid body object. It is still unclear how robots and humans should behave in order to handle an object with great mutual consideration. The proposed procedure to plan robot trajectories with constrained joint velocities and accelerations is a novel approach that aims to harmonize the robot's movements with a human hand movement generated by a constrained functional principle component analysis (FPCA) based human motion model. This paper introduces criteria that evaluate mutual consideration, providing a promising solution to the challenges of HRC.

2. State of the Art

This section explores various techniques for generating human and robot motion in the context of HRC.

Zhu et al. [4] survey different data-driven generation techniques, which focus on modeling the underlying

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distribution of motion in an unsupervised manner. Human motion synthesis can be realized with deep learning-based models, as shown by Holden et al. [5]. The disadvantage of such models is that hard constraints for a desired position or physical correctness cannot be applied easily [6], which leads to unnatural-looking movements. On the other hand, statistical model-based motion synthesis, as introduced by Min et al. [7], enables the application of spatial and time constraints by optimizing motion parameters obtained through dimensionality reduction. Specifically, this is achieved via functional principal component analysis (FPCA), which compactly represents both spatial and temporal variations within the motion data. Herrmann et al. [8] increased the speed of motion synthesis by combining a statistical motion model with a motion retrieval approach, using a space partitioning tree (constructed via k-Means++) to efficiently search for and optimize motion samples that meet user-defined constraints. Manns et al. [9] extended the model for use in an assembly context. The model can identify clusters of natural motions by mapping human motion data into a low-dimensional latent space (LS), where a single point represents a whole-body movement. By learning the distribution of these points, the model can generate new motions that fit within the learned natural variation. Any movement that does not align well with the distribution in the LS (e.g., that falls outside the clusters of typical motions) could be flagged as unnatural. Therefore, the LS can serve as a reference to assess whether a synthesized motion appears realistic.

The main problem when implementing an HRC application is the lack of knowledge about the motion behavior of the human co-worker. In an industrial context, only conservative strategies are permitted for modifying the robot's speed, strategies where the path is adapted are not considered. An overview of the trajectory adaptation strategies is given by Miro et al. [10]. One strategy is *speed and separation monitoring* (SSM), where a speed-dependent separation distance between the robot and the human must always be maintained [11], [12]. Glogowski et al. [13] proposed a method for determining the dynamic separation distance between a human and a robot, enabling precise calculation of the robot's speed to meet requirements set by SSM. Another method is *power and force limiting* (PFL), where low-intensity collisions with a human, which must not exceed biomechanical limits, are allowed because the robot moves slowly enough (e.g. [14]). Those two strategies only adapt the robot's velocity while the preplanned path remains unchanged. For the highest form of HRC, when a human and a robot work together at the same workpiece, it is inevitably necessary that the robot not only adapts its velocity on a preplanned path but also changes the path itself. Otherwise, tasks like handling an object and adapting to deviations in human movement become impossible. Haddadin et al. [15], [16] developed an impedance control scheme for robots with torque sensors in every joint, where specified torque values define poses. In this control scheme, external forces on the robot are allowed, which makes the robot compliant. With impedance control, the robot allows deviations from its path but cannot change it, for example, when the human becomes significantly slower or changes his destination. While impedance control enhances compliance, it lacks the ability to proactively adjust the trajectory based on anticipated human motion, necessitating more adaptive planning approaches. Makris et al. [17] propose a model-based motion planner that simulates fabric distortion using a spring-mass model, enabling real-time adaption of robot trajectories based on human handling inputs for the co-manipulation of deformable objects. Faulwasser et al. [18], [19] presented a model predictive path-following approach based on a torque controller, which allows path-following with and without speed assignment.

If the robot should handle an object together with a human co-worker with great mutual consideration, it becomes necessary to enable the robot for real-time trajectory adaptation. Kaltsoukalas et al. [20] propose an intelligent search algorithm that refines robot motion paths by iteratively selecting optimal configurations. Due to its short computational time, it is capable of real-time planning in HRC applications. Another approach to achieve real-time adaptation is through piecewise online trajectory generation, where control points are defined based on human movement. To accomplish this, interpolation methods (overview in [21]), like splines, can be used. There, the pose, velocity, acceleration, and jerk can be defined as input values for the control points, and it can be guaranteed that a trajectory that contains the control points is found. The disadvantage of interpolating a trajectory in cartesian space (CS) is that it lacks a connection to the joint space. Before applying the inverse kinematics, it is unclear what the joint velocities and acceleration will look like and whether their limits will be violated.

Reproducing human hand movement with a robot is difficult because the TCP velocity and the velocity of the single joints must be constrained. Path-following only in CS leads to difficulties because most strategies lack a connection to joint space. Therefore, this paper proposes an optimization algorithm that allows constraints to be applied in the joint space while also approximating the hand movement in the best possible way.

3. Planning human-like Trajectories

3.1. Setup of a collaborative handling task

Collaborative scenarios where humans and robots work together on the same workpiece are rare [22]. Assuming a scenario where the robot can help increase the human's ergonomy could be applicable in an industrial context. This paper assumes a scenario where a human and a robot simultaneously handle a rigid body object. The handling task is to pick up the object at a predefined start location and move it to a target location. An experiment was conducted to generate the human motion model, where two humans perform the handling task (see Fig. 1). Those humans act within defined roles: One is the leader, and the other is the follower. The full body motion of the human was recorded with IMU sensors. With that data, the stochastic motion model was constructed (e. g. [5]). This motion model can generate realistic human motion and export it into the BVH format [23]. From this file, the trajectory of the endpoints of the rigid body object can be extracted.

Fig. 1. Experimental setup for the handling task.

3.2 Objective

This paper aims to test whether the execution of human-like trajectories is possible and then to provide a concept that generates such trajectories. Therefore, whether the robot can exactly reproduce a recorded human hand movement while also maintaining velocity and acceleration constraints in the joint space is evaluated. Afterward, a concept is presented that generates human-like robot trajectories to smoothen collaboration. For that reason, the robot must meet the following requirements:

- Follow the human trajectory; therefore, the human hand's path, velocity, and acceleration must be matched.
- Do not violate the maximum joint velocities and acceleration of the robot
- Generate natural-looking movement, which is acceptable to human co-workers. (Avoid high accelerations, velocities, or reorientation).

3.3 Requirements for planning trajectories

This section presents evaluation criteria for determining how well a planned trajectory matches a human reference trajectory. Therefore, it distinguishes between criteria that evaluate the closeness of the planned trajectory in CS and those that evaluate the naturalness of the trajectory by analyzing it in a learned LS that captures essential movement patterns [9].

In CS, the planned trajectory should be spatially close to the reference trajectory defined by the control points. Those control points correspond to the sampled positions of the human hand, which are extracted from the BVH file. The international standard ISO 9283 [24] defines performance criteria for path accuracy, but when evaluating a trajectory, those criteria are not reliant because the time is disregarded. Speaking of a trajectory means that not only the path should fit, but also the control points should be reached at the specified time. So, it is not sufficient to calculate the closest distance between a control point and the planned trajectory. Instead, the distance between a control point and the point on the planned trajectory at the corresponding time must be evaluated. Because the planned trajectory is time-parametrized, that distance could be calculated. So, the minimum, maximum, and mean square error between the control points and time-dependent corresponding points on the planned trajectory are good evaluation criteria in CS.

The concept of an LS criterium is to evaluate whether the planned trajectory for the robot looks smooth and natural. Humans are used to working with human co-workers in manual assembly, which is why they are often surprised by the sudden movements of a robot. For a human, the movements of others are rarely unsettling in this context, as humans naturally anticipate each others actions. Making the movement of the cobot understandable is essential to increase its acceptance by a human co-worker. The idea is to transform the planned trajectory from CS to LS. The smaller the distance between the point of the planned trajectory and the human motion in LS, the better the acceptance by the human co-worker will be.

3.4 Planning a human-like trajectory in cartesian space

The scenario described in *3.1* should be modified regarding replacing one human with a robot. The goal is to reproduce exactly the recorded human hand movement. Therefore, the movement of the endpoint of the rigid object, which is attached to the hand of the human, is used as a reference for the TCP of the robot. Thus, the demand is that the robot should match the cartesian position, velocity, and acceleration. The orientation of the human hand is out of this paper's scope because it is assumed that the robot, once the object is grabbed, does not change the orientation of the gripper. The BVH file of the recorded motion contains the full body movement of the human and the end of the rigid body object with 60 frames per second. From that, only the relevant movement of the object is extracted. Every frame corresponds to one control point in the reference trajectory. Those control points specify the hand’s position at distinct moments in time. So, every control point contains information about the position, velocity, and acceleration the robot's TCP should reach.

The cartesian trajectory of the TCP is planned using a method given by Richter et al. [25]. This trajectory planner uses the control points given by the hand movement and the corresponding times as waypoints. These points are interpolated with minimum jerk polynomial splines, which minimize the third derivative of the position to ensure smooth movement. Therefore, the trajectory is divided into polynomial segments that are jointly optimized to ensure smooth transitions across waypoints while maintaining the continuity of higher-order derivatives such as velocity, acceleration, and jerk. Afterward, the cartesian trajectory is transformed into joint configurations using inverse kinematics. For simplicity, it is assumed that the orientation of the end effector of the robot does not change during the movement.

3.5 Evaluation of human-like trajectories in joint space

The following two example movements are evaluated. As depicted in Fig.1, two humans move a rigid body object from location A to location B. For the movement, it is assumed that the human and the robot have already grabbed the object and are ready to move it to the target location. Now, one human is replaced by a robot placed at an appropriate spot where both locations can be easily reached. The 7-DoF collaborative robot KUKA iiwa7 is used for the evaluation. At first, the robot's movement is evaluated in the simulation to prove whether a human-like trajectory is feasible or not.

For the first example, a movement from location A to location B is investigated. In Fig. 2, the given waypoints and the interpolated trajectory are depicted component-wise. With the minimum jerk planning method, all waypoints are reached with a smooth-looking trajectory in CS. In Fig. 3, the cartesian velocity of the TCP, which corresponds to the cartesian speed of the replaced hand, is illustrated. It can be seen that the maximum of the total velocity is around 0.7 m/s. This corresponds to about half the speed of the maximum of common human reach movements, which is about 1.5 m/s (see Gaveau et al. [26]). The joint configurations and velocities are depicted in Fig. 4 and Fig. 5. As seen in Fig 4, it is assumed that the trajectory does not violate joint limitations because the whole movement is placed in the reachable area of the robot. The maximum joint velocities of the Kuka iiwa7 are specified in its data sheet [27] and are listed in Table 1. With Fig. 5 it can be seen that the maximum joint velocity is not violated during the first example movement.

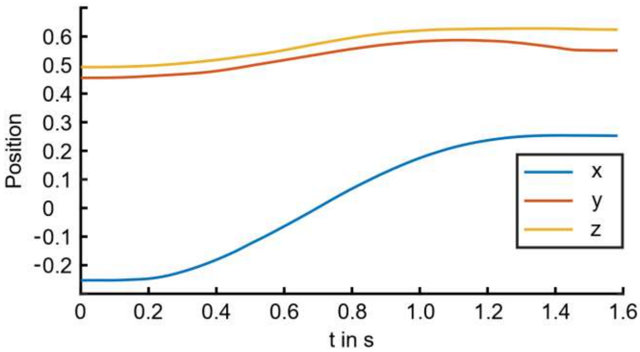

Fig. 2. Cartesian trajectory through the interpolated waypoints of ex. 1.

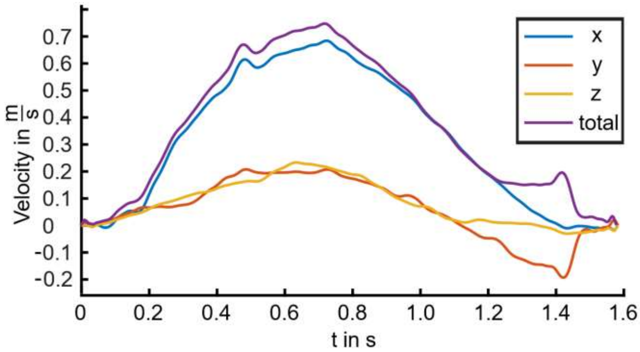

Fig. 3. Cartesian velocity of the TCP of ex. 1.

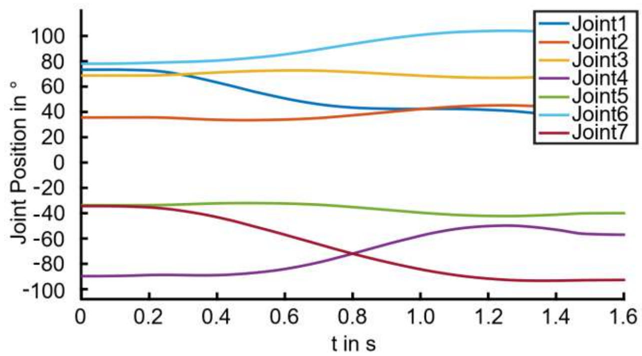

Fig. 4. Joint angles of ex. 1.

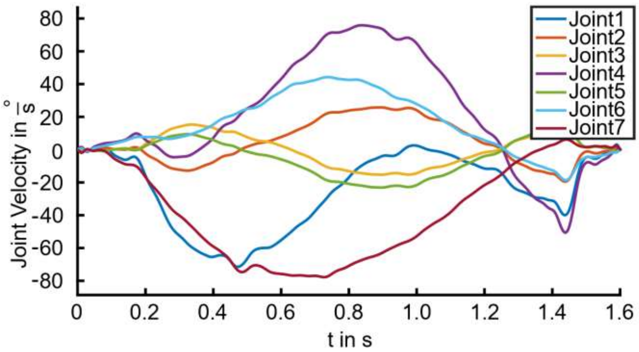

Fig. 5. Joint velocities of ex. 1.

In the second example, a movement from location B to location A is investigated. The cartesian positions and velocities are depicted in Fig. 6 and Fig. 7. The movement looks similar to a reversed version of the first example (see Fig. 2 and Fig. 3), with a slight increase in the total velocity from a maximum of 0.7 m/s to 0.9 m/s. Although the profile of the joint angles looks smooth in Fig. 8, the profile of the joint velocities in Fig. 9 looks different than in Fig. 5. Here, the maximum velocity for the first joint is violated (see Tab. 1). It is shown that cartesian trajectories that look applicable or slight increases of the cartesian velocity can lead to a big increase in joint velocities. When the orientation of the gripper is fixed as necessary for this study, even slow robot movements can lead to fast reorientations. Since the joint velocities result from the joint configurations, which are calculated with the help of the inverse kinematics of the trajectory planned in CS, no velocity constraints in the joint space can be considered. So the real robot would not be able to follow the movement of this example.

Table 1. Joint Velocity limits of the Kuka iiwa7 [23].

Joint	J1	J2	J3	J4	J4	J5	J6
Velocity	98°/s	98°/s	100°/s	130°/s	140°/s	180°/s	180°/s

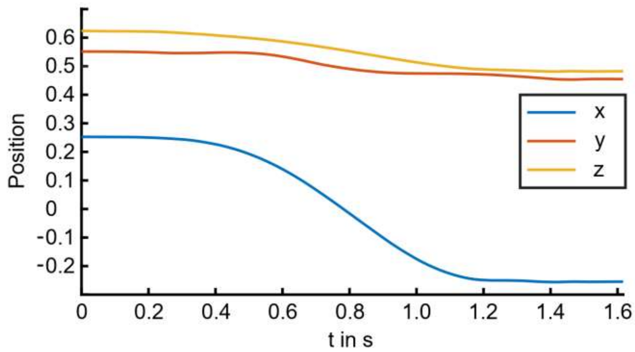

Fig. 6. Cartesian trajectory through the interpolated waypoints of ex. 2.

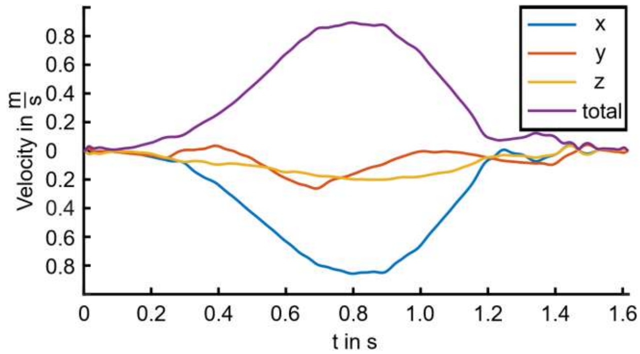

Fig. 7. Cartesian velocity of the TCP of ex. 2.

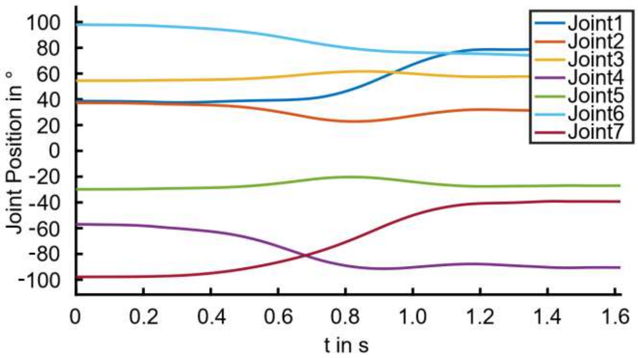

Fig. 8. Joint angles of ex. 2.

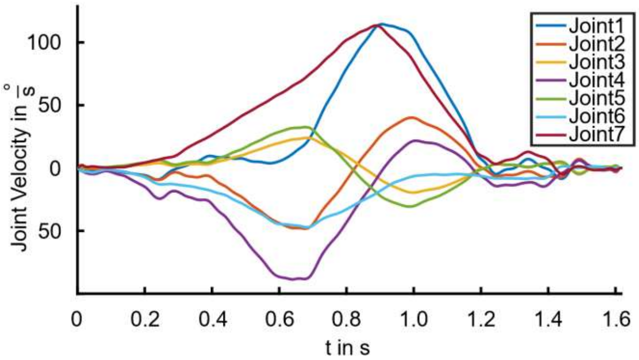

Fig. 9 . Joint velocities of ex. 2.

4. Optimization Concept

As the previous section shows, small cartesian velocity or position changes can lead to big velocity changes in joint space. The optimization concept shown in Fig. 10 is to find a good approximation of human hand movement while constraining the robot's joint velocity and acceleration. The criteria from *3.3* define whether an approximation is good.

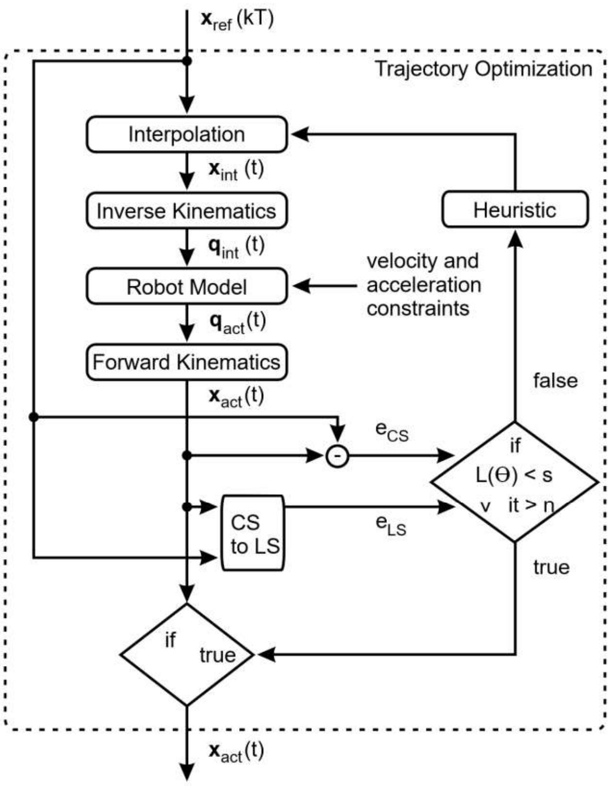

Fig. 10 Optimization Concept for planning human-like trajectories.

The goal is to minimize the error between the reference trajectory $\mathbf{x}_{ref}(kT)$ given by the movement of the human hand and the trajectory $\mathbf{x}_{act}(kT)$ that the robot can execute while considering the joint velocity and acceleration limitations. The reference trajectory $\mathbf{x}_{ref}(kT)$ is given by the discrete control points of the hand movement with k as the index of the control points and T the time between two control points. These control points are continuously interpolated in $\mathbf{x}_{int}(t)$. Then, the inverse kinematic is applied to this trajectory to obtain the corresponding joint angles. This trajectory is then simulated with a robot model where joint velocity and acceleration are constrained. The output of this robot model are the reachable joint states $\mathbf{q}_{act}(t)$. These joint states are transformed back into CS with the help of forward kinematics in order to evaluate the movement of the TCP.

Now, the trajectory is evaluated in CS and LS. The mean error e_{CS} between $\mathbf{x}_{ref}(kT)$ and $\mathbf{x}_{act}(kT)$ is calculated at the control points in the CS comparison. For the LS comparison, however, $\mathbf{x}_{ref}(kT)$ and $\mathbf{x}_{act}(kT)$ need to be transformed so that the distance e_{LS} between these trajectories can be estimated. In order to transform a robot trajectory from CS to LS, movements from the human motion model [6] are first transformed from LS to CS. From these, the corresponding right-hand movements, which the robot should imitate, are extracted. These extracted right-hand movements are then compared to the robot trajectory $\mathbf{x}_{act}(t)$ in CS to identify the best match. Once the closest matching right-hand movement is found, it is used as the basis for mapping the robot trajectory $\mathbf{x}_{act}(t)$ from CS to LS.

The overall goal of the optimization concept is to minimize these two errors, which correspond to the criteria defined in *3.3*. This is the case when the cost function $L(\Theta)$ converges, or a certain number of iterations have been performed. The only way to influence the shape of the $\mathbf{x}_{act}(t)$ trajectory is by changing the interpolation of the trajectory itself. Interpolation methods have their means to change the trajectory by different parameters. For this algorithm, the trajectory is interpolated with Bézier curves, as they offer smooth transitions between control points and allow for precise control over the shape of each segment. Therefore, a curve segment is planned between every two consecutive control points the reference movement gives. The great advantage is that the trajectory can be planned piecewise and that velocity and acceleration constraints can be applied at those points. The shape of the curve is defined by its control polygon [28]. Changing the shape of the control polygon means changing the shape of the interpolated curve. For optimization the control polygon and the position of its points are the only applicable lever for the shape of the trajectory and so on for the $\mathbf{x}_{act}(t)$ trajectory. So, the cost function of this optimization should minimize the two errors, e_{CS} and e_{LS}. Therefore, a heuristic that changes the control polygon that defines $\mathbf{x}_{int}(t)$ needs to be found.

5. Conclusion

This paper introduces a novel concept for harmonizing robot motion with human collaborators in handling tasks by optimizing trajectory planning to align with human movement. The approach utilizes a stochastic model of human motion to generate reference trajectories and employs minimum-jerk polynomials for planning robotic movement while ensuring smooth transitions across waypoints. Unlike previous methods, the human motion model allows for real-time anticipation of natural movements, facilitating smoother collaboration between robot and human co-workers. By incorporating constraints on joint velocity and acceleration, this method enhances safe interaction with humans. Additionally, it enables the robot to make dynamic adjustments in response to the variability of human movements, which should increase the acceptance of HRC among human co-workers..

Although the proposed algorithm is promising in generating human-like motion trajectories for a priori known human movements, further improvements are necessary. When working with humans, their next movement is uncertain, so the trajectory must be adapted in real-time. Therefore, the trajectory could be planned piecewise, for example, with Bézier curves, which allow interpolating the position, velocity, and acceleration of the start point and end point of a segment. These segments can be optimized by choosing their parameters with the goal of minimizing the deviation in cartesian and latent space defined by the proposed criteria.

Future work will aim to develop a cost function for optimization and to identify a suitable heuristic for selecting the interpolation method. Additionally, future studies will focus on estimating the necessary computation time to ensure that each trajectory segment can be planned efficiently while maintaining real-time responsiveness. The proposed method can potentially enhance industrial HRC applications, particularly in tasks requiring precise motion coordination, such as assembly tasks and cooperative handling of rigid body objects.

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