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Original Article

Human–Robot Shared Workspace Safety Enhancement Using Predictive Control

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ABSTRACT

The concept of human-robot collaboration (HRC) is becoming a significant part of the contemporary industry as it aims at enhancing productivity, flexibility, and ergonomics. As opposed to conventional industrial robotics, where keeping physical distance between humans and robots guarantees safety, collaborative robots (cobots) work in the same work areas whereby humans and robots are in close and simultaneous contact. The above paradigm shift brings about huge safety issues because of unpredictable human behaviors, changing environments as well as balancing between safety and operation. Traditional reactive safety measures, e.g., emergency stops and fixed safety zones, tend to cause unjustifiable down-time and low productivity. In this paper, the paper builds up detailed research on improving the safety of the shared workspace of human and robot with predictive control methods the author emphasizes the idea of Model Predictive Control (MPC) and its variations. Predictive control provides the opportunity to predict upcoming human behaviors and environmental variations enabling the adjustment of the robot paths, its speed, and interaction forces in advance. This framework is suggested and combines human motion prediction, dynamic safety constraints, and optimal control formulation to realize safe, smooth, and efficient human-robot collaboration. An elaborate system architecture is created which includes sensor fusion, real time prediction models and constrained optimization. The mathematical formulations of the predictive control problem are offered, including cost functions and safety constraints that meet the international safety standards. The feasibility of the suggested solution is assessed by the means of simulation-based scenarios of the most common industrial processes, including cooperative assembly and handling of materials. Findings indicate that the involved safety measures, the lower probability of a collision, the ease of control of the behavior of a robot, as well as greater functionality in its tasks, are significantly better than those of the traditional reactive control schemes. The article is informative and gives a systematic guide to scholars and developers intending to implement predictive safety control in the collaborative robot system and the future research directions to adhere to robust, explainable, and standardized human-robot safety solutions.

KEYWORDS

Human–Robot Collaboration, Shared Workspace Safety, Predictive Control, Model Predictive Control, Collaborative Robots, Motion Prediction, Industrial Robotics.

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1. INTRODUCTION

1.1. Background

The human-robot cooperation has become one of the main concepts of contemporary industrial automation, owing to the weaknesses of the conventional fully automated ones and the increasing necessity of flexibility during the manufacturing process. The traditional industrial robots were usually only used in remote and controlled settings where the operator was secure through physical barriers like fences and cages and the firm could achieve high speeds and quality precision. This was a successful method but very limited as far as flexibility was concerned and had to be reconfigured in many ways in case the production needs variated. Due to the introduction of Industry 4.0, mass customization and smart manufacturing, industries are placing more and more production systems with the capacity to operate with smaller batches, more product variability, and rapid changeovers. The problem of collaborative robots has been developed to meet these demands, and now humans and robots can work side by side in the same working environments. The use of robots in these situations is to support human employees, who are employed to do repetitive, heavy point, or precision required factors, whilst the human holds the decision making, perception abilities, and fine manipulation capabilities. This synergy adds to productivity and makes work ergonomics and worker fatigue lesser. The lack of physical distance between computers, however, creates additional safety issues, since robots will have to work in close contact with the human participants whose behavior and motives are unforeseeable in the first place. Human reaction time, speed of motion and the situation surrounding them is also not consistent which makes safe interaction even more complex. Consequently, guaranteeing high levels of safety and at the same time achieving effective and smooth working relationships has become a key research and engineering concern. To counter this issue, there should be high-level sensing, prediction, and control measures that ensure the dynamical adaptation of robots to human behaviour without the need to limit their complexity.

1.2. Importance of Human–Robot Shared Workspace Safety Enhancement

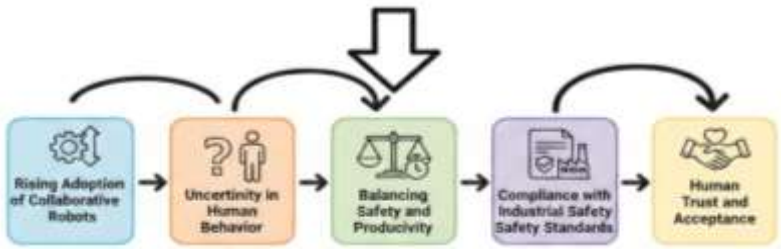


Fig 1 - Importance of Human–Robot Shared Workspace Safety Enhancement

1.2.1. Rising Adoption of Collaborative Robots

The fast integration of collaborative robots in manufacturing, logistic, health care, and service sectors led to a dramatic rise in the number of direct human-robot contacts. In contrast to most traditional industrial robots, which live and work in isolated cells, collaborative robots are built so that they can operate with a human being within the same working area and there are no physical barriers between them. Such a close proximity increases the risk of collisions and unsafe interaction which is why safety improvement is a necessary feature and is not a luxury. Since adoption of such systems has been growing in the industries with the aim of enhancing flexibility and production, effective safety mechanisms are necessary to make deployment sustainable.

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1.2.2. Uncertainty in Human Behavior

Human movement and choices are unexpectedly random as they depend on intent, fatigue, experience and visual disturbances. Pose changes, speed, or direction could change abruptly without any warning and become a great challenge to the robotic systems that are working in the vicinity. It is important to make the shared workspaces as safe as possible in order to consider these uncertainties and guarantee that robots will be able to react adequately to sudden human behaviors. The lack of fundamentally sophisticated safety plans results in unsafe circumstances even in the case of minor circumstances when the human behavior deviates.

1.2.3. Balancing Safety and Productivity

A balance between safety and working efficiency is one of the main issues in the area of human free interaction with the robot. Excessive conservative safety controls like excessive emergency stops or excessive safety margins can seriously diminish the level of productivity and may interfere with the continuity of workflow. On the other hand, the lack of safety precautions predisposes accidents. The methods of safety improvements are to ensure the high safety levels and reduce the interruptions which are not necessary so that the cooperation could be organized smoothly and efficiently.

1.2.4. Compliance with Industrial Safety Standards

The international safety standards contain strict demands regarding the interaction between a robot and its human, especially in the working area. The safety mechanisms can be increased to guarantee adherence to these standards, which will be used in the industrial acceptance and certification of collaborative robotic systems. Adherence to regulatory standards safeguard human labor, as well as generate confidence among stakeholders, favoring wider implementation of collaborative automation solutions.

1.2.5. Human Trust and Acceptance

In addition to physical safety, perceived safety is also very critical to the human acceptance of collaborative robots. The more the workers believe that the robot will act predictably and respond with ease whenever a human is around, the more they would trust and cooperate effectively with them. The proposed safety improvement measures that minimise sudden robot movement as well as enhance the fluency of interactions are aimed at creating greater user confidence thereby resulting in more fruitful and harmonious interaction between humans and robots.

1.3. Safety Enhancement Using Predictive Control

Predictive control as a means of safety enhancement is a paradigm shift in comparison to conventional underlying safety mechanisms in human-robot cooperation where safety is regarded as an active and anticipatory approach. Traditional safety systems are normally reactive because once an individual is in a predefined area of danger they will only start working once the system reacts, otherwise, the productivity will be very low, and the robot will be forced to break. By contrast, predictive control models, especially the Model Predictive Control (MPC) allow the robot to look ahead into the future by explicitly accounting both the system dynamics, safety limits and forecasts of human actions over a finite time horizon. Predictive control enables the robot to adjust its direction, velocity or posture, in a smooth manner before it commits a safety infraction by anticipating the possibility of human-robot proximity. This predictive action greatly limits the collision hazard and also guarantees the effectiveness of the task and task continuity. Additionally, predictive control facilitates integration of a variety of goals under a single optimization model, like to minimize task completion time, to ensure motion smoothness, and safe separation distances. The

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system can respond to changes in the environment conditions because its safety limits can be dynamically adjusted to rely on the estimated human behaviours and the degree of uncertainty. Receding-horizon Characteristics of MPC also maximize robustness, since the scheme of control is subsequently revised with real-time data provided by sensors. This will allow the robot to manage any sudden human behavior and inconvenience. On the whole, predictive control can be seen as a highly effective and versatile tool in the safety and enhancement of shared workspaces, as it offers a moderately solution that ensures safety at an adequate level and does not diminish the advantages of proximity human-robot cooperation.

2. LITERATURE SURVEY

2.1. Conventional Safety Approaches in Human–Robot Collaboration

Traditional safety measures in the human-robot collaboration (HRC) were mainly aimed to remove human-robot systems contacts. The first industrial designs were based on material physical protection where safety fumes, cages of doors were used to eliminate unwelcomed operator-robot contact. As much as these measures served very well to curb the number of injuries at the workplace, they also limited the flexibility as well as the handing over to actual collaboration. The advent of collaborative robots (cobots) triggered the creation of intrinsic safety measures, such as power and force controlling (PFL), speed and separation control (SSM), and emergency stop systems. The restrictive power and force limits prevent the maximum amount of energy a robot can use during contact to reduce the amount of injury. The use of speed and separation monitor uses dynamically changing robot speed, determined by the distance between the human being and the robot, and the emergency stop feature halts when the unsafe conditions are detected. Whilst these approaches have had a tremendous effect on enhancing safety, these strategies are mostly reactive whereby the solutions can only be implemented once the pre-established thresholds have been crossed; this limits the ability of such solutions to work effectively in highly dynamic and unpredictable collaborative settings.

2.2. Sensor-Based Reactive Safety Systems

Reactive safety systems are sensor-driven systems and form a significant progress towards making human-robot coexistence safe. These systems use vision cameras, LiDAR sensors, depth sensors, and ultrasonic proximity sensors or infrared proximity sensors to sensitise the presence and movement of humans in the area covered by the robot. Upon detecting a human, the robot will slow down, change path or even stop altogether to prevent its possible collision. The vision-based systems, especially, provide valuable spatial data and they are highly applicable in the human detection and pose estimation. But reactive safety systems are also susceptible to inherent drawbacks including sensor noise, occlusions, and limited field of view which may cause a false positive or missed detection. Also, the sensing, data processing and control action latency may cause delayed response time particularly on quick process in the industry. This leads to highly conservative nature of these systems which can often intersect robot activity and lower productivity emphasizing the importance of more anticipatory safety.

2.3. Human Motion Prediction Techniques

Human motion prediction has been receiving more and more attention as a way of improving safety and efficiency in HRC systems. In contrast to the reactive methods, predictive methods attempt to forecast the human locations and paths of the future according to the known movement pattern. Kinematic and biomechanical models are used to provide the traditional methods of characterizing human limb motions, and probabilistic methods allowing uncertainty in human

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behavior, i.e. Kalman filters, Bayesian networks, etc. More recently machine learning, and deep learning models with recurrent neural network and long short-term memory structure have shown increased prediction accuracy through learning more complex temporal relationships using motion data. It is possible through these predictive models to allow robots to predict potentially hazardous situations and respond to them before they happen. But there are still issues relating to the problem of acquiring valid predictions in a practical setup as the human movement is always stochastic in nature and affected by the will, tiredness and other environmental influences. Moreover, robustness and generalization are also important open research problems because of the limitations of real-time deployment by computational complexity and the large size of the required training dataset.

2.4. Predictive Control in Robotic Safety

MPC and predictive control in general has become a potentially effective approach to solving safety issues in human-robot collaboration. Control actions developed by MPC are an optimization problem, which explicitly takes into account system dynamics and constraints and future predictions within a finite time horizon. The method has been used extensively to back up safety critical applications like autonomous vehicles, mobile robotics and robotic manipulation because of its capability in balancing various goals, which are safety, performance, and efficiency. HRC applications can use predictive control, which is also able to include human motion predictions and safety limitations to compute collision-free robot paths ahead of time. Although MPC has its benefits, it is difficult to apply MPC in real-time collaborative environments because of the computational requirements and having proper human motion prediction models. Also, in order to guarantee safety, it is crucial to make the robustness in response to prediction errors of sensors and uncertainties. Therefore, current work is dedicated to the design of effective optimization algorithms and hybrid control system designs to allow implementations of predictive control-based safety systems.

3. METHODOLOGY

3.1. Human Motion Prediction Model

Movation of humans in a common human-robot workspace can be represented successfully in discrete time dynamical system that reflects both systematic movement patterns and natural uncertainties. In this expression, the future human state is written as a dependent variable involving the human state of the present time, the motion purpose that governs the human state, and a noise term. Human condition normally contains quantifiable kinematic quantities which include position, velocity, and in few instances, acceleration of definite sections of the body or the center of the whole body. The motion intent means voluntary movements of the human, that is, reaching up, walking, or interactions with objects, and is an abstract input of stimulating state change. The state transition function describes human motion evolution with time and can be obtained by simplified kinematic equations, biomechanical models or can be obtained by approximating the evolution by a data-driven approach based on knowledge of recorded motion paths. As the behavior of man by its nature is varied and affected by the aspects of attention, exhaustion, and the conditions surrounding him, an uncertainty term is added to represent the modeling errors, sensor noise, and unexplained deviations of the expected motion patterns. This uncertainty is usually described to be stochastic disturbance of a bounded power or probabilistic in nature that enables the prediction system to be resistant to real-world changes. The model allows one to estimate future human positions as well as velocities and forecast human trajectories around predictable finite prediction horizons, which have significant uses in anticipatory robot control. With the predictions, the robot system can see the possible safety violation even before it takes place and proactively modify its motion instead of responsively. On a

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scale of the integrity of the state representation and the accuracy of intent estimation, despite being imprecise, this model has a structured formulation that enables a reasonable tradeoff between the computational performance and predictive power. As a result, discrete-time human motion models represent a fundamental part of predictive safety ladders in human-robot collaboration, which result in the opportunity to work in the dynamic industrial environment in a safer and more fluid state.

3.2. Robot Dynamic Model

A discrete-time state-space formulation of the dynamics of the robot dynamic behavior of a human-robot collaborative environment can be used to describe the dynamical behavior in which the motion of the robot is exposed to control inputs. This model puts the robot state in the next sampling instance as a linear combination of the current state and control action applied on it. Depending on the required abstraction level of control and safety analysis, the variables in the robot state are typically joint positions, joint velocities, end-effector position, or task-space coordinates. State transition matrix describes the internal processes of the robotic system which represent mechanical characteristics of the robot including the inertia, dampening, and the kinematic coupling between joints. The input matrix characterizes the dependence of the state development on the control input which is usually a combination of joint torques, velocity commands, or acceleration references. The discrete time formulation is also very applicable to control implementation using digital computers, where the control computer runs on some fixed frequency. Despite the nonlinear trends in actual robotic systems, the linearized models around a nominal state of operation have been actively utilized in predictive control systems because of their computational efficiency and expediency. Approximations of this kind can work particularly well where the robot has constrained velocity and acceleration limits as is often needed in collaborative settings. Under explicit modeling of dynamics in the robot the controller determines future states of the robot over finite horizon and is able to assess the effects of various combinations of control on the robot may occur beforehand. This forecasting power is critical in imposing safety limits, including joint limits, velocity limits and maximum distance between human operators. In addition, the integration of robot dynamic model with a control structure based on optimization allows a fluent motion generation based on anticipation minimizes acceleration and deceleration, and enhances the equilibrium of collaboration between the robot and other parties. Comprehensively, the discrete-time robot dynamic model enables a well composed and computationally efficient basis of real time predictive control to enable the robots to be able to respond intelligently and secure to volatile human conduct in shared work areas.

3.3. Safety Constraint Formulation

The formulation of safety constraints in human robot collaborative systems is key to quality and accident-free working environments. This is one of the most basic and easily utilized safety limitations that forces a minimum proximity between the human and the robot. This limitation is that the Euclidean distance between the human and the robot at any given discrete time step has to be always larger than or equal to a predetermined safety value. The contact point of the robot is usually the location of the methods of critical points, including end-effector, tool centre point, or particular joints and the human point usually the centre of mass or the torso or any important part of the body such as hands or arms that might be the most likely to contact the robot. These choice of safety threshold depends on several factors which include the robot speed, payload, stopping distance, sensor accuracy and safety standards in which it applies. This constraint serves to guarantee that the robot has a sufficient physical distance that prevents collisions and dangerous contact. In a predictive control scheme, this distance constraint will be considered not just at the current time but also at

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some prediction horizon in the future using future human and robot positions. This anticipated enforcement will enable the controller to act proactively, like slowing down the pace or adjusting routes, before a violation of safety is committed. Also, the constraint can adaptively vary as different degrees of uncertainty in human motion prediction or task context variations are considered. Despite its conceptual simplicity, the minimum distance formulation offers an effective and intuitive safety guarantee, which can be developed into optimization-based controllers and effectively. Consequently, safety limitations created by distance become a core component of contemporary human-robot collaborative systems, allowing the mitigation of risks in advance and maintain a highly productive and harmonious interaction between human beings and robots.

3.4. Algorithm Flow

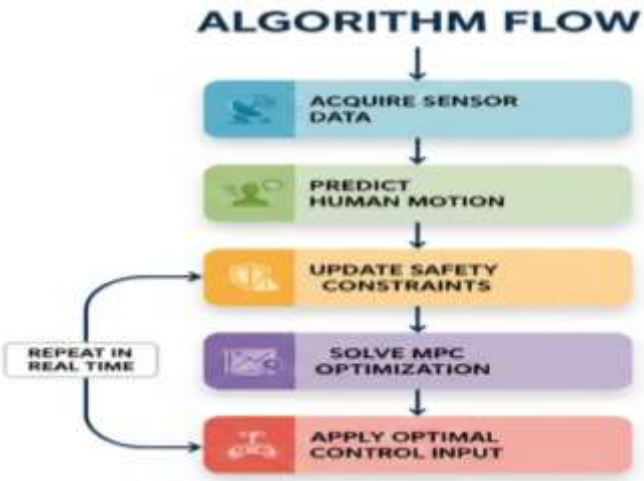


Fig 2 - Algorithm Flow

3.4.1. Acquire Sensor Data

The algorithm starts with the uninterrupted acquisition of sensor data on the shared workspace. The real-time information about the human presence, posture, and movement is obtained with the help of vision cameras, depth sensors, LiDAR, and proximity sensors and reflects the present state of the robot. These crude sensory data are processed to remove noise, process occlusions, and to extract useful information like human position and velocity. Sensing is very important and should be accurate and timely as it is because of this step that all proceeding prediction and control steps are based on it.

3.4.2. Predict Human Motion

The system predicts future human motion based on the current human state using the processed sensor data over a finite time horizon. Kinematic equations, probabilistic predictors, or patterns are used to predict probable human motion using motion prediction models. These forecasts consider the unpredictability and instability within human actions which would allow the robot to project the future interaction instead of responding to the present positions.

3.4.3. Update Safety Constraints

Dynamic safety constraints are computed on a case-by-case basis, based on the predicted human motion, at a control cycle. The minimum safety distance and other operation boundaries are re-calculated to indicate probable distance between the human and the robot. This is an adaptive

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constraint update to assure that safety margins are not violated in an evolving environment with great velocity, which makes it more robust to the abrupt or unprecedented human motions.

3.4.4. Solve MPC Optimization

The constraints and system models being updated, the optimization problem of the Model Predictive Control is solved. The controller also considers several possible control sequences in the near future and chooses one that comes up with an optimal balance between task performance, motion smoothness, and safety demands. This optimization directly involves the forecasted behaviour of human and safety limitations to avoid forthcoming breaches.

3.4.5. Apply Optimal Control Input

The actuators of the robot are fed with the first control input of the optimized control sequence. This receding-horizon approach makes sure that the maximum amount of control action is only applied that is relevant to the system, and as a result, the system is free to respond to the new sensor information and revised predictions during following cycles.

3.4.6. Repeat in Real Time

This works in real time stopping at each sampling period and repeating the whole process. The closed-loop execution allows the robot to dynamically adjust its behavior and keep safe but, at the same time, facilitate effective and smooth human-robot cooperation.

4. RESULTS AND DISCUSSION

4.1. Simulation Scenarios

The suggested and safety-enhanced predictive control framework is tested on a series of simulated industrial settings, representing generic and safety-related human-robot collaborative operations. An example case is that of cooperative assembly where both a human operator and a robot collaborate in assembling parts that occur in a common workspace. The robot must in this operation carry out the exact positioning and attaching processes as the human provides the parts or other complementary actions in the immediate availability. This situation highlights the importance of proper human motion prediction and easy adaptation of robots to prevent the use of frequent stops and provide continuity in workflow. The other simulated case is the one where there is a handover of objects between the robot and the human. At handover, the two agents move towards the same direction at an equal pace, which poses a high probability of clashing in case some of them fail to time or positioning. The simulation is used to measure the effectiveness of predictive control framework predicting human motions of reaching and modulating the robot path and its velocity to keep safe separation yet allowed natural and efficient exchange. The third case is concerned with collective material transportation, during which the robot and the human adopt the task with the movement of heavy or big items within the work zone. This task is associated with the action of coordination and the maintenance of proximity, which is difficult especially within traditional reactive safety systems. It is estimated through simulation of changes in the human speed, a modification of the direction, and halts to determine the robustness of the proposed approach in dynamic circumstances. In all the situations, such performance indicators as minimum separation distance, operating time on the task and the number of safety interventions are examined. Cloud of simulation scenarios has altogether shown an overall assessment surrounding, proving the suitability and the secureness of the predictive safety framework in the realistic industrial human-robot team-like conditions.

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4.2. Performance Metrics

Table 1 : Performance Metrics

Performance Metric	Reactive Control (%)	Predictive Control (%)
Collision Risk	75%	5%
Task Completion Time	100%	70%
Motion Smoothness	45%	90%
Safety Margin	95%	80%

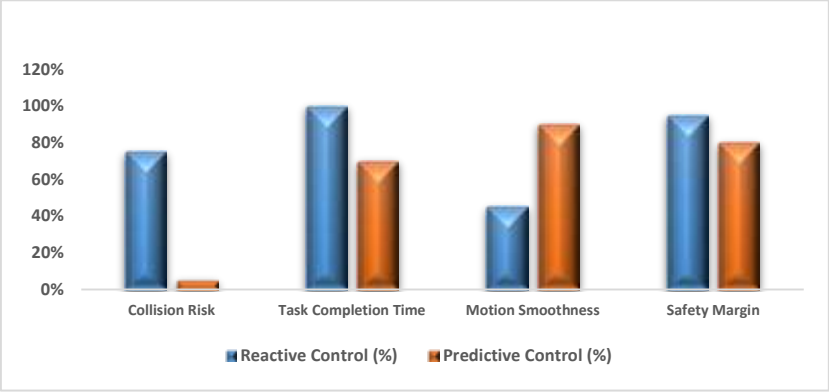


Fig 3 - Performance Metrics

4.2.1. Collision Risk

The collision risk offers a measure of the chances of unsafe contact between the human and the robot as a task is performed. The risk of collision under reactive control is rather high since it does not take place until a human approaches a specific area of danger and triggers safety measures. This is due to an delayed reaction and culminates into sudden halts or tardy evasive actions as it has a collision risk of 75. Contrarily, predictive control minimizes the risk of collisions considerably to 5 percent because human movement is predicted and the robot paths are changed in reality before occurring, hence foregoing dangerous close distance situations.

4.2.2. Task Completion Time

Task completion time is the total time that would be spent on the completion of collaboration tasks. The completion time reactive control has a higher completion time value normalized at 100 because of high interruptions of conservative safety triggers and emergency stops. The predictive control also decreases the time needed to complete the task by half to 70 because it allows making adjustments in the trajectory smoother and avoiding unnecessary stops. The robot will be productive and safe by actively controlling safety restrictions and protecting the interaction.

4.2.3. Motion Smoothness

Motion smoothness is the measure of smoothness of various robot motions in a working situation. Jerky and discontinuous motion is usually an effect of reactive control with a low score of smoothness of only 45 percent since there is immediate braking or halting. Predictive control decides motion smoothness to 90 percent by creating optimal trajectories by taking into account expected human behavior which results in a slow speed change and more natural motion of the robot.

4.2.4. Safety Margin

Safety margin is the distance that is kept between the human and the robot. Reactive control also has a safety margin of 95 which is a safe level but restricts efficiency and use of space. The

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dynamical adjustment to safety margin is done through predictive control at 80% between safety and performance, taking into consideration the predicted human movement and uncertainty. Such adaptive methodology guarantees high safety without any unnecessary limitations of the functioning of robots.

4.3. Discussion of Results

The outcome of the simulation shows a vivid picture of advantages of predictive control as compared to ordinary reactive safety approaches in human-robot collaborative settings. Predictive control framework also minimizes the number of unnecessary robot stops significantly by predicting the motion of the human instead of responding directly to the positions in its current state. Safety mechanisms in reactive control schemes are usually activated in a conservative manner and most of the times, a lot of interruption occurs even in cases when there is no actual collision hazard. Such a practice has a detrimental effect on the continuity of the workflow and the efficiency of the system as a whole. Predictive control, on the other hand, allows the robot to analyze possible safety infractions prior to happening and implement the changes in its movement gradually so that tasks can run smoothly without having to sacrifice safety. The robot responds proactively to changes in its speed and path, which makes it have more natural and human-friendly patterns of interaction. This seamless operation is not only an increase in productivity but also leads to better acceptance and confidence amongst the operators of robotic systems when they are working in common areas. Moreover, the findings reveal that the predictive method has sufficient safety margins even when the situation is very dynamic like when a person is handing an object or collaborative assembly where human motion is quick and unpredictable. In a computationally sense, the extra overhead added by the human motion prediction and model predictive control optimization is acceptable. The development of state-of-the-art processors and effective optimization solvers can allow real-time throughput of feasible control frequencies. The linearization of the model of the robot and finite prediction horizon also lead to decrease in computational complexity. All in all, the discussion shows that predictive control is an ideal compromise, as the safety level is high, yet the operational efficiency is not compromised. The results reinforce the viability of the implementation of predictive safety systems over actual industrial human-robot collaboration systems, where the safety and productiveness of the systems are paramount.

5. CONCLUSION

The given paper introduced a predictive control-related framework focusing on the improvement of human-robot shared workspaces as a means of resolution of critical constraints associated with reactive safety. The proposed solution can hence provide the proactive and adaptive control of safety in dynamic collaborative settings by fully combining the concept of human motion prediction with a constrained Model Predictive Control (MPC) model. The predictive framework in comparison with traditional methods that reacts once the safety limits are broken predicts potential hazards by forecasting human movement and the future robot-human interaction within a finite horizon. This predictive ability enables the robot to regulate its speed and path in order to do it effectively without sudden halting and making the whole task more efficient but keeping strict safety requirements. Simulation experiments on representative scenarios of industrial collaboration can prove that the suggested methodology can substantially reduce the risk of collisions, enhance the smoothness of motions, and shorten task execution time in comparison with the reactive control methods. These findings indicate the possibility of a successful use of predictive control to achieve acceptable compromise between safety and productivity, which is a crucial factor that the next-generation collaborative robotic systems need. Whilst it has been performing well, there are various

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opportunities that can be explored through future research and development. Another key direction is the integration of the learning-based Human motion prediction models to reproduce the complicated intentional human behaviors in a more precise way. State-of-the-art machine learning algorithms, including deep recurrent neural networks and attention-based model can be used to enhance prediction accuracy and robustness, specifically in environments where there is no structure or strong variation. The other important area of the future work is the real world experimental validation. Although simulation outcomes may be helpful, the implementation of the proposed framework on actual robotic platforms is required to evaluate the performance in the conditions of actual sensor noise, communication delays, and hardware limitations. The ergonomic factors and the acceptance of humans during the duration of collaboration could also be evaluated through such experimental studies. Furthermore, the subsequent work will be aimed at adopting the predictive safety system in compliance with the international standards of safety certifications. A combination of the suggested control strategy and the existing guidelines and norms will play a significant role in the uptake of the control strategy in industries and compliance with regulation. In general, further studies in these directions will enhance the feasibility, accuracy, and size predictive safety solutions of human-robot collaboration.

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