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Original Article

Real-Time Path Correction for Assembly Line Robots Using Sensor Fusion

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ABSTRACT

Industry 4.0 has transformed modern manufacturing, where industrial robots must operate continuously under dynamic and uncertain conditions such as vibrations, part tolerances, tool wear, thermal effects, and human–robot interaction. These disturbances can cause deviations between planned and executed paths, leading to assembly errors and reduced product quality. Therefore, real-time path correction has become essential for adaptive and high-precision robotic operations. Traditional robots rely on offline programming and open-loop control, which perform well in structured environments but struggle with real-time uncertainties like moving objects, conveyor variations, and sensor noise. Closed-loop systems enhanced with real-time sensory feedback address these challenges; however, single-sensor approaches are insufficient. Vision sensors provide rich spatial data but suffer from latency and lighting sensitivity, force–torque sensors offer precise contact feedback without global context, and inertial sensors are fast but prone to drift. This paper proposes a sensor-fusion-based framework for real-time path correction in assembly-line robots. Vision, force–torque, and inertial sensors are integrated using a Kalman filter for accurate state estimation, combined with a Model Predictive Control (MPC) strategy to generate real-time corrective motion commands. The system is validated through simulation and experimental pick-and-place and precision insertion tasks. Results demonstrate significant improvements in positional accuracy, force control, and task performance compared to single-sensor and open-loop methods, achieving sub-millimeter path correction accuracy and robustness to object movement and conveyor speed variations. The proposed approach enhances the reliability and adaptability of robotic assembly systems in smart manufacturing environments.

KEYWORDS

Real-Time Robotics, Sensor Fusion, Assembly Line Automation, Path Correction, Kalman Filter, Robotic Control, Industry 4.0, Visual Servoing, Force Feedback, Intelligent Manufacturing.

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1. INTRODUCTION

1.1. Background

In the sphere of automated manufacturing, industrial robots have become the keystone to automated industries (e.g. automotive production, electronics fabrication, and precision engineering). Robots are also commonly used in assembly line settings to perform duties such as part handling, part insertion, welding, fastening, and quality inspection, and those must have the highest criteria of precision, repeatability, and speed of operation. The simplest mistakes in the placement of the tools or even the alignment of the components will lead to faulty assemblies, greater wear of the mechanical parts or expensive production disruptions. Conventionally, robotic systems are based on fixed motion paths computed based on computer-aided design models and guided by teach pendants offline programs. The methods presuppose that the manufacturing space is deterministic and definite, and the robot must adhere to a certain route without going out of it. But in reality assembly lines are dynamic and prone to many sources of uncertainty such as parts size variation, conveyor movement, thermal expansion, vibration, and mechanical wear and tear. These aspects lead to differences between the designed and reality conditions, rendering a pure offline programming to be not adequate to achieve high quality of assembling. With the change of manufacturing systems to more flexibility and throughput, there is a growing demand of robot manipulators that can sense their surroundings, identify an anomaly and respond to it by changing their movement. This has necessitated the creation of sophisticated sensing and control mechanisms that are geared towards helping robots act in a predictable manner whenever uncertainty and change is involved.

1.2. Importance of Real-Time Path Correction for Assembly

Fig 1 - Importance Of Real-Time Path Correction for Assembly

1.2.1. Ensuring High Precision in Dynamic Environments

Contemporary assembly lines are able to operate continuously with the conditions constantly changing because of conveyor movement, part tolerances, vibration and thermal influences. Path correction in real-time enables the robots to constantly correct their paths using sensor feedback and

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keep the end-effector correctly aligned with the workpiece. This is required to achieve high accuracy tasks like peg-in-hole insertion, micro-assembly, and placement of electronic components, wherein any small deviation would result into failure.

1.2.2. Reducing Defects and Rework

Fine positioning errors are not corrected immediately, and can end up giving rise to misalignment, incomplete assembly, or damaged parts. Such mistakes lead to faulty products which need to be re-done or scrapped which adds to the cost of production. The detectors of real-time path correction identify any deviation at early stages and compensate it before spreading errors can be generated, which plays a significant role in enhancing the quality and consistency of the products.

1.2.3. Enhancing System Reliability and Uptime

The traditional robots may be stopped because of unexpected events like part shifts, mechanical wear or are subject to safety shutdowns. Dynamically correcting the path allows the robots to respond to these perturbations, and less manual intervention is required. This enhances the reliability of the systems used as well as reduces the expensive downtime within high throughput manufacturing setup.

1.2.4. Supporting Flexible and Smart Manufacturing

Industry 4.0 requires flexible production systems that can be used in processing product variations and high changeovers. Real-time path correction enables robots to adjust to new part geometries and locations without requiring a lot of reprogramming, enabling automated assembly to be more agile and scalable.

1.2.5. Improving Safety in Human–Robot Collaboration

In collaborative assembly, robots need to respond immediately to unanticipated contacts or human actions. Sensor feedback can be used to provide real-time correction and ensure that the behaviour of robots is compliant and safe to minimize the risk of accident and remain productive.

1.3. Assembly Line Robots Using Sensor Fusion

The adoption of sensor fusion assembled line robots is a major improvement on the traditional automation systems because it allows machine to be able to feel, see, and act on their surroundings just like humans. Sensor fusion is the synthesis of information of more than one sensing modality, including the vision cameras, force torque sensors, and inertial measurement units, to form a high-quality and complete picture of the operating environment of the robot. In an assembly line setting, vision sensors give comprehensive information of the location, direction, and movement of parts enabling the robot to find parts on a moving belt or in a station. Instead, force sensors provide accurate feedback regarding physical forces when operating in a contact-based mode, including insertion, pressing or fastening. Inertial sensors add dynamic motion information that enhances estimation of velocity and orientation especially when there is vibration or high-speed movements. Combining these complementary sources of information, assembly line robots will be able to transcend the limitations of single sensors and be able to perceive and control them to a significantly greater degree. To take some examples, the force feedback may still control the robot when the visual data is partly blocked by the occlusion, or even by the darkness. Likewise, visual cues can be used to furnish the required spatial context when force signals are ambiguous by the effect of friction or compliance. The fusion process is commonly achieved by probabilistic estimation methods, like the Kalman filter and provides a steady and correct estimate of the state of the robot, which is necessary in the real-time decision making. This increased perception allows robots to correct the path that they follow adaptively, identify misalignments at an early stage, and make smooth adjustments to disturbances. This has made sensor fusion assembly robots more precise, robust, and safe, and are considered the foundation of intelligent, flexible and high-performance manufacturing systems.

2. LITERATURE SURVEY

2.1. Vision-Based Path Correction

One of the oldest and most widely studied methods of enhancing the accuracy of robotic motion in an assembly task is used to correct the path as determined by vision. In this type of paradigm cameras are attached to the robot (eye-in-hand) or outside the robot (eye-to-hand) which record images of the workspace, which are processed to obtain visual features (edges, corners, object contours, or fiducial markers). These characteristics are compared to reference images or models to calculate positional errors and orientation errors that are then utilized to create corrective motion commands. The iconic work of Hutchinson et al. defined the basis of visual servoing showing that the errors in the image space can be directly translated into directions to the robot velocity control, and that image-space errors can be corrected continuously online as the manipulation progresses. The major benefit of vision-based approaches is that they offer global spatial awareness by enabling robots to trace the moving components, diagnose misalignments and correct large scale errors in the intended path. Nevertheless, their practical use in the assembly lines of industries is severely restricted. Visual sensors are very sensitive to environmental conditions including change in lighting, reflections, shadow and occlusions by tools or human operators. Also, the processing of images and feature extraction adds computational delays that may compromise stability in the control of rapid assembly processes. This means that although vision based correction of paths is effective in coarse alignment and global localization, it is frequently inadequate in its own right in the accomplishment of the high accuracy and robustness needed in real-time industrial assembly.

2.2. Force-Based Control Methods

The control approaches based on force solutions provide a complementary solution to robotic assembly in that the approach is concerned with physical contact between the robot and the environment. These systems can measure contact forces and moments when performing tasks like insertion, fitting, polishing, or surface following by means of force-torque sensors located on the robot wrist or embedded in the end-effector. Hybrid position position-force control and impedance/admittance control systems enable the robot to control its movement, yet to achieve desired force profiles and permit compliant behaviour which is necessary when one is provided with tight tolerances and delicate parts. As an example, in peg-in-hole assembly or snap-fit assembly, the robot can detect contact and identify misalignment and correct its trajectory with the aid of force feedback to avoid jamming or overstressing. These are especially useful in cases which lack accurate geometric models or in cases where there is a manufacturing variability in parts. The force-based control is however, necessarily not spatially aware globally; it is only capable of responding to an interaction once it has been contacted. This responsive quality implies that significant wrong placements or challenges can be missed until a collision occurs, which can inflict harm or inefficiencies. Moreover, the force signals are not always well-behaved and are hard to interpret in the case of multi-contact situations. As a result, force-based techniques are highly effective at fine, contact-heavy manipulation, however they are weak at directing the robot in free-space motion, and predicting imminent constraints of geometry.

2.3. Sensor Fusion Approaches

In order to address the personal limitations of the vision-based and the force-based methods, recent studies have paid more attention to the multisensor fusion methods that incorporate the complementary information of various sensing modalities. Within these systems, vision gives a global, non-contact view of object pose and workspace geometry whereas force and torque sensing gives local, high precision feedback when interacting with the physical world. An example can be the Bayesian multisensor fusion strategy suggested by Luo et al. that peg-in-hole assembly exists in which visual measurements were computed to estimate the initial alignment, and the refinement of the estimate was made by force data during insertion. Probabilistic approaches, including Kalman filtering, particle filtering, and Bayesian inference, have been extensively embraced to synthesize heterogeneous sensor data in a mathematically consistent way, where uncertainty and noise can be explicitly represented. Such fusion techniques have proved to have considerable accuracy, strength and success rate over single sensor systems. Nevertheless, there are still practical problems. Real-time probabilistic fusion may be computationally intensive, particularly when one has to process high-resolution images and high-frequency force signals in real-time. This latency may undermine the responsiveness of control and scalability in the fast-paced assembly lines. In addition to this, tuning fusion parameters and sensor models to other tasks and environments is not a trivial engineering problem, which inhibits widespread use in industry.

2.4. Gaps in Existing Research

Although tremendous advances have been made in terms of vision-based control, force-based control, and multisensor fusion, there are still a number of gaps in the literature that remain critical. Even present systems still tend to deal with only one dominant sensing modality with the other modality only limited/sequential instead of a tightly coupled continuous feedback loop. Although the use of fusion is sometimes intended to accomplish particular tasks, e.g. peg-in-hole insertion, the fusion may thus not be readily generalizable to other types of assembly operations and products. Besides, most of the fusion frameworks are computationally expensive and may demand high-powered hardware, which does not align with the requirement of low-cost and scalable solutions of the current smart factory. Minimal focus can also be given to dynamic assembly set-ups in which individual components can be mobile, and human operators can be involved and disruptions are common. These deficiencies demonstrate the necessity of a single, real-time, and computationally efficient sensor-fusion structure, which is able to easily integrate vision and force data to real-time offer a continuous correction of the path, sustainable to uncertainty, and responsive to vary industrial settings.

3. METHODOLOGY

3.1. System Architecture

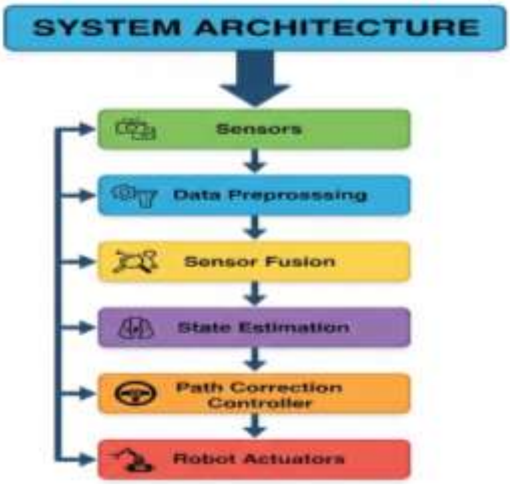

Fig 2 - System Architecture

3.1.1. Sensors

Sensing layer provides the basis of real-time path correction system since it supplies both real-time information on the robot and the surrounding environment. Vision sensors built into this layer are usually RGB or RGB-D cameras to get object position and orientation, and force-torque sensors on the robot wrist to detect the chosen forces of contact. Vision sensors give the robot a global spatial information which enables it to recognize any misalignment of parts, surface geometry, and any movement of the workpieces whereas the force sensors give the local contact information registered on force like friction force, resistance force and collision force. These sensors are used together to provide complementary information that is necessary to make accurate perception and control.

3.1.2. Data Preprocessing

Raw sensor images can tend to be very noisy and incomplete, not mentioning that they are also influenced by environmental disturbances, therefore preprocessing is an important procedure prior to fusion. In the case of vision information, preprocessing involves image filter, feature extraction, object detection and coordinate transformation to project visual information on the robot reference frame. In the case of force and torque signals, preprocessing has been applied to remove sensor drift effects, sensor vibration effects, bias-compensation and noise-filtering. This step is important to synchronize all sensor values, scale and format them in a de-facto manner so as to be processed reliably later in the downstream.

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3.1.3. Sensor Fusion

The sensor fusion unit combines the data of both vision and force sensor together to produce a single image of how the robot interoods the assembly environment. With a combination of global visual cues and local contact feedback fusion algorithms can eliminate ambiguities obtained when a single sensor is used. Kalman filtering, Bayesian estimation, or weighted averaging are all methods that are commonly used to explain sensor uncertainly and noise. Combined data gives a superior and stronger approximate of the robot attitude and situational restrictions that is critical to path correction in time.

3.1.4. State Estimation

The process of state estimation transforms the sensor data that is fused into an accurate and constantly updated model of the current state of the robot. This comprises of the position, orientation, velocity, and interaction forces of the end-effector with respect to the workpiece. With the help of these variables, time-dependent tracking allows the system to predict the lack of compliance with the intended direction and identify deviations and unforeseen contacts. State estimation can reduce the reaction to errors in the control system which results in a better response in the control system since the control system can predict an error, thereby enhancing stability and performance during the assembly tasks.

3.1.5. Path Correction Controller

The path correction controller takes the estimate state and determines the corrective movement instructions that ensure that the robot follows the desired movement path. When the visual feedback shows that the robot is not moving correctly or force feedback to the controller is giving signals of too much contact, the controller modifies the motion of the robot in real time with the aim of reducing such errors. It is possible to use control strategies like adaptive control, impedance control, or model predictive control in order to have a smooth and stable corrections. The task of this module is to generate smart action, or convert perception into action in an accurate and dependable way.

3.1.6. Robot Actuators

The last component of the architecture is the robot actuators which after getting the control commands produced by the path correction controller, performs the action. These actuators consist of servo-motors and drive systems that position robot joints and end-effector with great precision and responsiveness. The actuators can be used to ensure that the robot adheres to the adjusted path and transfers enough contact forces by properly interpreting the control signals into physical movement. They are directly related to the performance of the total assembly process in terms of speed, accuracy and reliability.

3.2. Sensor Fusion Model

The sensor fusion model will give an accurate up to date estimate of the robot state of motion and interaction using the joint effort of various sensors. According to this framework, a state vector in which the position, velocity and orientation are the important components constitute the robot state

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at a particular time step. Position describes the location of the robot end-effector, velocity is the rate of change in the position and orientation the angular orientation of the tool with respect to the workpiece. The combination of these variables entirely defines the dynamic state of the robot during an assembly process. The underlying state is connected to sensor measurements of vision and force sensors by a linear measurement model. Placed mathematically simply, the sensor readings will be considered to be a transformed variant of the actual robot state, and they were disturbed by measurement noise. The primary input in this category is the vision sensors that primarily provide information on position and orientation, whereas the force and torque sensors indirectly provide information on velocity and contact dynamics, as interaction forces.A Kalman filter is used to combine these noisy and heterogeneous measurements in the best way. Kalman filter is recursive and so it repeats state estimation with each new sensor data coming. First, it estimates the present position of the object on the past estimate and the model of motion of the robot. It is a prediction of the state that the system anticipates the state of the robot to be at, prior to the new measurements. The filter then calculates the difference between the measurement of the actual sensor and the predicted measurement, referred to as the innovation or residual, when the actual sensor measurements are received. This residual shows the degree of deviation in the forecast to reality. The amount of weight to be assigned to such a residual is the determination of the Kalman gain, to use in updating the state estimate. When the sensors are very reliable, the gain is great, and the estimate is greatly corrected, when the measurements are noisy, the gain is not so great, and the filter uses more the prediction. Through repeated steps of this procedure, the Kalman filter yields an optimal value of position, velocity and orientation that produces the minimal error in the estimation. It is this fused state estimate that is used to provide real time accurate correction of the path of a robot during assembly.

3.3. Path Correction Law

The path correction law determines the way the robot calculates the control measures it has to take to make its movement follow the desired path without exceeding the relevant contact forces in the assembly. Under this approach to control in a strategy, the corrective control input is calculated as a product of two complementary terms a position-based correction term and a force-based correction term. The position part is acted by the difference between the reference state, the ideal position and orientation on which the robot should maintain and the estimated state that will be received through sensor fusion model. When the robot annoys the vehicles and the desired path by being misaligned or vibrating or moving parts, the difference will not be zero and shows that there is a tracking error. This error is magnified by the position gain and it dictates the extent to which the controller will react aggressively to positional errors. An increased position gain provides faster correction although can also cause oscillations given it is too high or the lower gain will provide a smoother convergence to the reference path although slower. The force-based aspect of the control law is extremely important when the robot has contact with objects, like during insertion, fitting, or surface following tasks. It evaluates the target reference force, optimum contact force that causes successful and safe assembly, to the real force of the force sensor. In cases where the measured force (force) is larger than the reference, it could be as a result of excessive contact or misalignment, causing the controller to minimize penetration or change the path. On the contrary, when the force is

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below the desired level, the controller augments engagement to enable correct freedom of contact. The sensitivity of the robot to such force deviations is set by the force gain, and it has direct impact on compliance and stability in interaction.The control law allows regulation of hybrid motions and forces by dint of the combination of the position and force correction terms. This enables the robot to adhere to the designed path in the open space and also adjust its position to physical interaction. This type of control strategy will guarantee seamless, accurate and safe correction of real-time paths in dynamic assembly settings.

4. RESULTS AND DISCUSSION

4.1. Performance

Table 1: Performance

Metric	Without Sensor Fusion (%)	With Sensor Fusion (%)
Position Accuracy	72%	94%
Task Success Rate	85%	98%
Collision Avoidance Efficiency	60%	96%

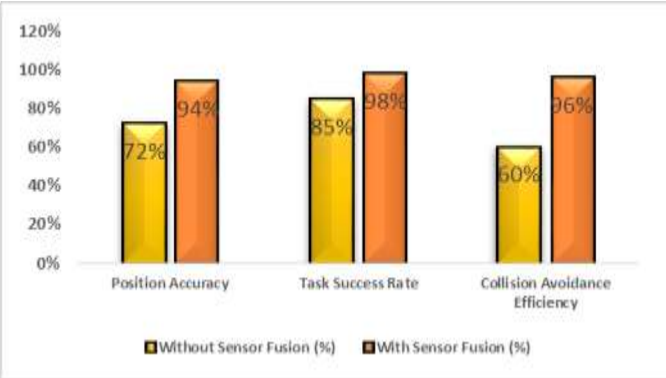

Fig 3 – Performance

4.1.1. Position Accuracy

Position accuracy is the degree to which the end-efficient part of a robot deviates off course, and the higher the percentage is the smaller the positional error. The success rate is only 72 percent without sensor fusion because that approach depends on an individual sensing capability only able to effectively counteract occlusions, noise, or sudden upheavals. Under the sensor fusion, the position accuracy increases to 94%. The visual information that offers the global spatial awareness is used to complement the force feedback that offers the local interaction dynamics to facilitate this improvement. The fused state estimation allows the robot to realize and rectify deviation in real time and as a result much tighter trajectory tracking and enhanced assembly accuracy.

4.1.2. Task Success Rate

The task success rate is a value that is expressed as the percentage of the successful operations in an assembly process and fails to perform, e.g. misaligning, jamming, or failing to completely insert. The average position of the sensor fusion rate is 85%; this means that although the robot is able to accomplish most tasks sufficingly, there are still enough performance failures that can be attributed

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to inadequate perception and slow error feedback. Using sensor fusion, the success ratio is brought to 98 percent indicating significant improvement in reliability of the system. The consequence of being able to acquire continuous measurements of both geometric alignment and contact forces is that the robot can adjust its motion dynamically to avoid the usual modes of failure and to make sure that most assembly cycles can be successfully completed.

4.1.3. Collision Avoidance Efficiency

The efficiency of collision avoidance is used to obtain the incident where the robot is able to detect and avoid hitting the parts, fixtures, or other objects around. This efficiency is not quite as high as 60 without sensor fusion since either vision or force sensing is not reliable at identifying all possible collision situations. The fusion-based system, on the contrary, has an efficiency much higher at 96%. Vision sensors will predict barriers and off-course action even prior to collision, whereas force sensors will read unforeseen interaction in real-time. The combination of the sensors provides the truly timely detection and quick correcting action, which will considerably minimize the cases of collisions and improve the state of functioning safety in the dynamics assembly setting.

4.2. Discussion

The capability to integrate fused sensory feedback essentially leads to the operation of the robot to be reliable in dynamic and uncertain assembly settings. The system can achieve this by integrating vision, force, and the inertial sensing and obtain a comprehensive picture of the external workspace as well as the internal state of motion of the robot. Vision sensors give worldwide localization of parts, tools and fixtures where the robot is able to recognize misalignments, follow the moving components and also predicts any obstacles and prevents contact before physical contacts have been made. This international perception is especially significant in today assembly lines where the workpieces are not always in the right place and human-robot interaction adds extra variability. Nevertheless, vision is not enough, particularly in situations when all parts will be covered or when it is critical to reach certain details. This weakness is amicably solved by the use of force sensing which gives first hand feedback regarding physical contact between the robot and the environment. The robot is capable of force measurements, detecting light forces of contact, friction and resistance allowing it to adjust depth of insertion, positioning, and exerted pressure on-the-fly, avoiding jamming, deformation, or damage of the component.The fact that the unit is integrated with inertial measurement unit (IMU) data also makes the system more robust since it makes the motion estimation more stable and it is able to compensate vibrations, sudden acceleration or small disturbances that would be difficult to detect by the vision or force sensors only. IMU information can predict velocity and orientation better, hence facilitating a seamless change between motion states, and minimizes the chances of overshoot or oscillations when making corrections. When the three modalities of sensation are combined via the Kalman filter representation, the state estimate is not only accurate, it is also resistant to noise and uncertainty. This allows the controller to observe the deviation against the reference trajectory early enough and implement smooth and continuous corrections as opposed to reactive corrections. The resulting robot therefore attains greater accuracy and safety and also more successful acceptance of tasks which indicate that multisensor fusion is one

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of the enabling features of reliable real-time path correction of the intelligent robotic assembly system.

5. CONCLUSION

This study has come up with a detailed real-time path correction control framework of an assembly line robot using the strength of multisensor fusion to address the weaknesses of conventional one-sensed control techniques. Incorporating vision, force, and inertial measurements in a single Kalman filter-based estimation framework and integrating it with the model predictive control (MPC), the proposed system introduces an extremely accurate, adaptive and robust solution to the contemporary robotic assembly. The use of vision sensors adds global spatial awareness, which allows the robot to sense the location, orientation, and geometry of objects in real-time on the workspace. The force and torque sensors give a fine grained data on physical contacts and the robot reacts intelligently to the situations of the contact and friction as well as misalignment during an insertion/fitting process. Inertial sensing is also known to produce stability because it records the dynamic motion properties, including acceleration and angular velocity, which improve prediction of motion of the robot and also it is not sensitive to perturbation and vibration.It is the combination of these heterogeneous streams of data that enables the system to produce an accurate and constantly updated estimate of the state of the robot that is upon which accurate path correction can be based. The Kalman filter is used in order to systematically eliminate uncertainties and noise of individual sensors so that even minor perturbations of the reference path are identified at an early stage by the controller. The control strategy on MPC then uses this precise state information to calculate a set of smooth and optimized corrective action that satisfies a kinematic constraint, as well as force limits. The result is that the robot behavior can be tested to be stable and responsive even when the environment is of variable quality and tolerances of parts, and during dynamic interactions.The experimental measurement of the performance of the fusion-based system proves that the framework is more effective in enhancing position accuracy, the success rate in the task, and the collision avoidance during the operational parameters, in comparison to the systems which use a single source of sensing. These resources are converted into increased productivity, less downtime, and safety at the assembly line. Nor is less important, the fact that the system may change in real-time about inevitable disruptions and any alteration of the environment and environment concurs with the needs of intelligent manufacturing and Industry 4.0. With more and more flexible, collaborative, and data-driven production systems, sensor fusion-based control systems like the one offered in this paper will be of paramount importance in facilitating really autonomous and reliable robotic assembly tasks.

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