A Novel Approach For Collision Avoidance In Collaborative Robotics Application

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Abstract

Ina this research, 3D robotic vision is implemented for pick and place tasks which uses a real-time collision avoidance algorithm that incorporates obstacle recognition and avoidance in collaborative robots. In conventional method of pick and place operation by collaborative robot (cobot), if in case any obstacle comes in between predefined path then cobot abort its operation and stops at same position. To continue pick and place operation operator need to remove obstacle and restart then operation. Due to this operational cycle time will increase, efficiency of cobot reduced. To overcome this problem we have implemented 3D vision system with machine learning algorithm in cobot. For safe human-robot collaboration, 3D vision technology has been implemented for obstacle detection and avoidance in pick-and-place operations. The Cognex IS2800 smart camera is used to take standard and depth images in a designated workspace. Object recognition is done using a deep neural network (DNN) along with point cloud segmentation, 3D object-pose estimation, and accurately identifying obstacle locations. A machine learning-based algorithm is used for collision avoidance based on obstacle coordinates received from the camera module. Due to the machine learning algorithm, the cobot can dynamically modify its trajectory, guaranteeing safe operation during the pick-and-place operation. This paper demonstrates the algorithm's performance under different operating conditions which results into optimize cycle time, avoid collision with obstacle and efficiency increased. By using proposed methodology will be able to achieve 84% of original cycle time with obstacle detection vision system and machine learning algorithm. The Techman TM5 6-DOF robotic arm is used for the demonstration of practical experimentation of the proposed method in detecting obstacles and avoiding collisions during pick-and-place operation.

Keywords: Collaborative Robot; Collision Avoidance; Machine Learning; 3D Vision Camera; Path Optimization.

1. Introduction

In recent years, the robotics field has mainly focused on the potential and challenges of collaborative robotics. This will help to work collaboratively with humans during working together, which results in humans adapting 100% this technology with the speed, repeatability, and payload capacity of cobots. By adding these features in cobot the cobot will work on complex tasks more efficiently. Multiple researchers have explored this field which helps to interface with humans. Collaborative robots have features that enable humans to work together in a safe environment, which is not possible in industrial robots, and due to this, they help humans work safely. In the case of high-collaboration scenarios, the workflow is significantly disturbed due to the collision between the robotic arm and the human worker which results in the stopping of the cobot or aborting its operations which impacts on production cycle. To avoid such type of scenarios and to enhance efficiency it is preferable to proactively avoid collision by dynamically adjusting its path in real time. To achieve this we can integrate the vision camera scanner or sensors-based systems, along with an advanced control system that gives continuous trajectory re-planning and updates. Modern collaborative robots (Cobot) are integrated with environmental perception capabilities which allow them to adjust their behaviors in real-time. In the conventional method if the robotic arm makes contact with the robot force sensor detects the interaction which results in the robot stopping and ensuring safety. However, this safety mechanism has limitations on performance such as reduced speed which increases the cycle time of the systems. To reduce these challenges an advanced approach is being developed to predict collision between human and cobot, enabling proactive feedback to enhance safety [26]. The critical challenge for achieving both safety and efficiency is difficult as cobots operate in a dynamic unstructured and populated environment.

Planning and reactive controls are the two main ways to avoid collision. Wherein planning enables the creation of an ideal path from known conditions whereas reactive control makes sure the robot can instantly adjust to dynamic changes. However, treating these methods separately introduces limitations. One commonly used approach is the “elastic band” method, which was initially inspired by image processing techniques involving the snake algorithm method. To allow robots to dynamically adjust its path in the dynamic environment this method is used for smoothing and optimization [23].

Robotic vision is a crucial task in the manufacturing industry to detect during pick and place tasks. The general collaborative robot arm is facing challenges for pick and place operation based on vision guidance systems. To enhance the vision method we can incorporate a depth camera or smart camera which helps to recognize objects and their positional coordinates accurately [22]. Also, this 3D camera will help to get real-time environmental monitoring which is critical for safe robot operation. To ensure safety collaborative robots are integrated with external sensors to monitor the environment and detect obstacles. To assess and optimize 3D human pose, a neural model integrated with a cobot can be used [25]. By using 3D sensing technology collaborative robots continuously track obstacles and dynamically adjust their path to avoid collision between obstacles and robotic arms.

To optimize the path and enhance the robot's flexibility and intelligence we have proposed a method that uses Cognex smart 3D camera for real-time obstacle detection. To classify and respond to different obstacle movement speeds we have introduced a machine learning logic. To avoid obstacles in pre-defined workspace by robotic arm and reach its destination Rapidly-exploring Random Tree (RRT) algorithm is implemented which allows robots to navigate complex environments.

The paper is organized as follows. Section 2 provides an overview of the existing work done related to collision avoidance on collaborative robot i.e. literature review. In section 3 is explained about proposed methodology which includes material used and software used to implement machine learning algorithm etc. Section 4 shows results analysis and discussion. Finally, in Section 5 we present conclusions and propose some future scope.

2. Literature Review

The growth of smart manufacturing is mainly driven by intelligent automation and robotics technology. Collaborative robots (cobots) are widely used in different applications across various industries. The safety specifications for industrial collaborative robots and their operating system were introduced in 2016 by the International Organisation Standardization (ISO) i.e. ISO/TS 15066. This standardization enables humans and Cobot can work safely in a common workspace [5]. Due to these guidelines, many organizations have invested in research work in developing collaborative robots, Such as Universal Robots, KUKA Robotics, and Techman Robot which has developed cobots along with the built-in feature of the vision camera system. These advancement enables to shape the future of working in human and cobot in the same workspace to strengthen operation capabilities in the industry [24].

Planning and reactive controls are the two main ways to avoid collision [1]. However increasing robot safety often means a compromise in their performance, which requires designers to find the balance between safety and performance [2]. Currently, collaborative robots have features of the force sensor, which helps to detect external force or human interference and stop immediately or abort their task to ensure human safety [2]. These features limit the performance of the collaborative robots such as speed, load, and so on. In the conventional method, robotic manipulators for industrial applications are designed for specific tasks with static environments that involve collision-free trajectories [3]. Additionally, safety features need to be built in Cobot’s to ensure human safety while working in a common workspace. Specifically in unstructured and dynamic environments [4]. The collision avoidance ability of the robot is determined by the motion control, which detects collision avoidance strategy [6]. To ensure human safety an effective method is proposed for avoiding collision between humans and cobots using a timely feedback system. All such algorithms however follow the same philosophy that is repulsive terms linked to obstacles and attractive terms linked to the final destination [7]. Experimental results show that, the advantages of power and force over speed and separation monitoring both in terms of psychological impact and cycle time [8]. Artificial intelligence-based framework software Media Pipe is used to inform temporal data, for example, video and audio. This software is a machine-learning solution that can be used to detect body position [9]. As an extension of this research work, the online computation of a safety zone is defined to ensure a safe working environment for human collaborators [10]. However the results show, that adapting to a dynamic environment for a robot is more challenging and it limits its functionality. The proposed framework in this research uses reinforcement learning to adapt to a dynamic environment still the robot finds it difficult to adapt completely unpredictable and unstructured scenarios [11].

1. These methods require a dedicated set with built-in sensors, for collision avoidance which increases its cost [12]’

2. Due to a lack of independent intelligence, the efficiency of the collision avoidance method is low i. e. the human body as a moving obstacle [13-16].
3. In dual path planning model the distance is main constraint for two different paths [17].
4. Rather current collaborative robots are advanced and more expensive and tend to adopt post-collision detection which increases human risk factors. To address these types of issues we are implementing an active collision avoidance method using machine learning [20].

Table 1. Literature Review

Sr. No.	Title	Year of Publication	Publisher	Author	Method	Observation
1.	Hybrid Path Planning Model for Multiple Robots Considering Obstacle Avoidance.	2022	IEEE	Tianrui et al.	Improved Swarm Algorithm	This method has limitations of the repulsive field function model abort the robot's functioning, which increases its cycle time[21].
2.	Dynamic Collision and Deadlock Avoidance for Multiple Robotic Manipulators.	2022	IEEE	Nigoragafur et al.	novel motion control Algorithm	This method is only used to avoid collision between different robotic arms. It is not integrated with unpredictable human motion [3].
3.	A Control Architecture for Safe Trajectory Generation in Human-Robot Collaborative Settings.	2024	IEEE	Jozsef Palmieri et al.	Safety Planner Algorithm	This method is only integrated with human motion tracking system which limits its capacity to perform in dynamic scenarios [4].
4.	3D collision avoidance strategy and performance evaluation for human-robot collaborative systems.	2023	ELSEVIER	Giovanni Boschetti et al.	Augmented reality	To ensure the safety in collaborative workspace this method uses the speed separation monitoring system which reduces the speed of Cobot as per the distance of the operator[18].
5.	Using Elastic Bands for Collision Avoidance in Collaborative Robotics.	2022	IEEE	Tomás Kot et al.	Elastic Band Algorithm	This method uses control points to create a new trajectory to avoid collision which limits the

						smoothness and adaptability of the trajectory [1].
6.	Collision Avoidance Algorithm for Collaborative Robotics	2016	Int. J. of Automation Technology	Stefano Mauro et al.	Artificial Potential Techniq ue	This method uses a potential field technique to avoid collision which pushes the robot to reach its destination [7].
7.	Collision detection for collaborative assembly operations on high-payload robots	2024	ELSEVIER	Konstant inos Katsamp iris-Salgado et al.	F/T Sensor	This method is only used for robots with large payload capacity to ensure collision avoidance [8].
8.	Experimental implementatio n of skeleton tracking for collision avoidance in collaborative robotics	2024	Springer	Matteo Forlini et al.	Machine Learning	This method is only designed for tracking the human skeleton i.e., it only identifies human movement and avoids collision with it [9].
9.	Robust safety zones for manipulators with uncertain dynamics in collaborative robotics	2024	Taylor and Francis	Lorenzo Scalera et al.	Speed and Separati on monitori ng	This method uses the technique SSM i.e. it reduces the speed of Cobot to avoid collision [10].
10.	Digital Twin-Driven Reinforcemen t Learning for Obstacle Avoidance in Robot Manipulators: A Self-Improving Online Training Framework	2024		Yuzhu Sun et al.	Digital Twin	This method uses reinforcement learning which limits Cobot flexibility in dynamic environment [11].

Although different researchers work in this domain however there are some limitations and gaps they are as follows:

1. The limitations of the repulsive field function model abort the robot's functioning, which increases its cycle time.

2. It is not integrated with systems for tracking human motion or with human-robot task allocation strategies, limiting its ability to execute complex operations in dynamic collaborative environments.
3. It can only work for collision avoidance between multiple robotic manipulators.
4. Some methods was only designed to detect human skeleton and its movements
Accurately.

3. Materials and Methods

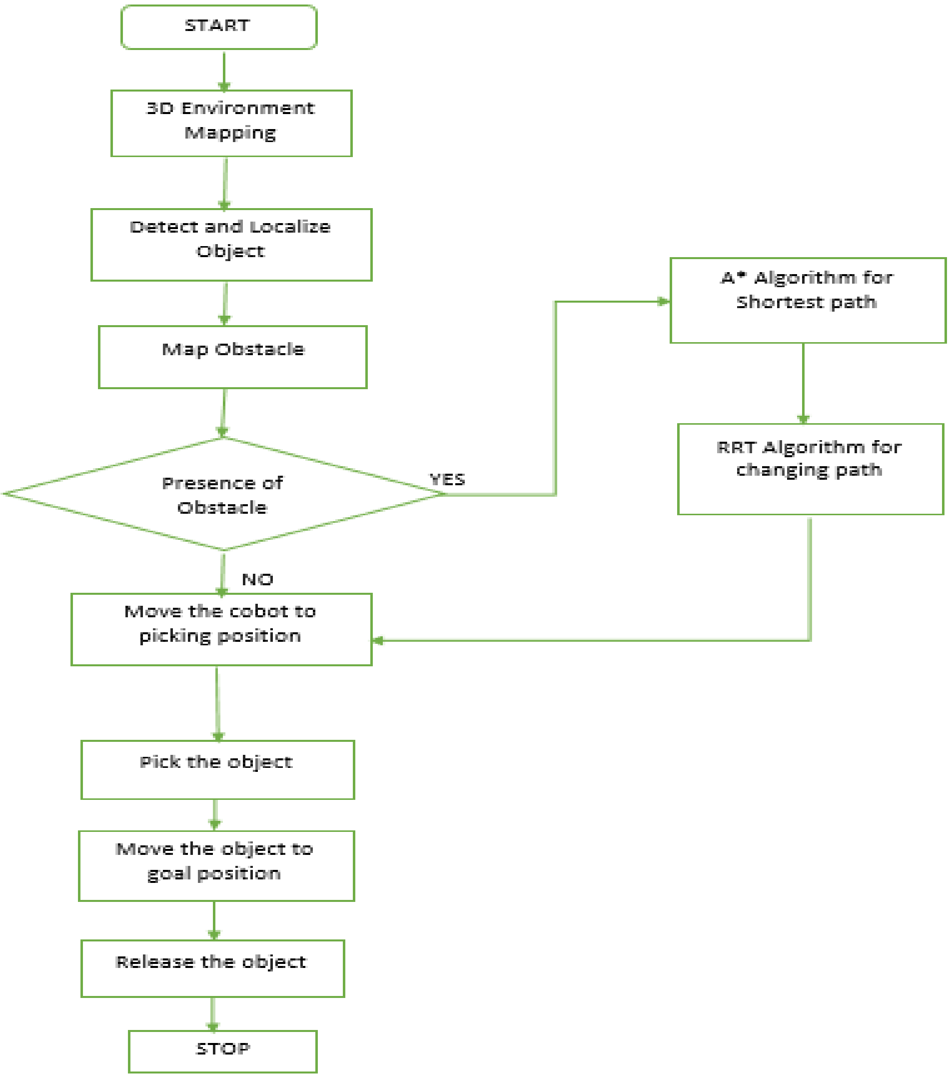

Figure 1. Proposed methodology for collision detection and avoidance in cobot

The system methodology in fig. 1 shows the flow chart of obstacle detection and collision avoidance to ensure safe pick-and-place operation for a collaborative robot. The Cognex IS2800 smart camera is used to monitor the environment where Cobot is performing pick-and-place operations. The captured RGB and depth images of the workspace use a Deep Neural Network-based object detector to identify obstacles, and then their pose and scenes are localized using the Cognex IS2800 smart camera. Next, the scene's point cloud is transformed from the Cognex smart camera. A CAD model database determines the pose of the obstacle then the point cloud corresponding to the obstacle is segmented. Based on the estimated pose, an online pick-and-place motion planner generates the Cobot's path using the Rapidly-exploring Random Tree (RRT) algorithm to reach the destination i.e., the placing point. Throughout the execution of the operation, the workspace is continuously monitored by the Cognex smart camera. If any people or obstacle is not detected by an environment tracking and obstacle detection module then Cobot executes a pick-and-place operation using a predefined path in system.

3.1. Hardware used

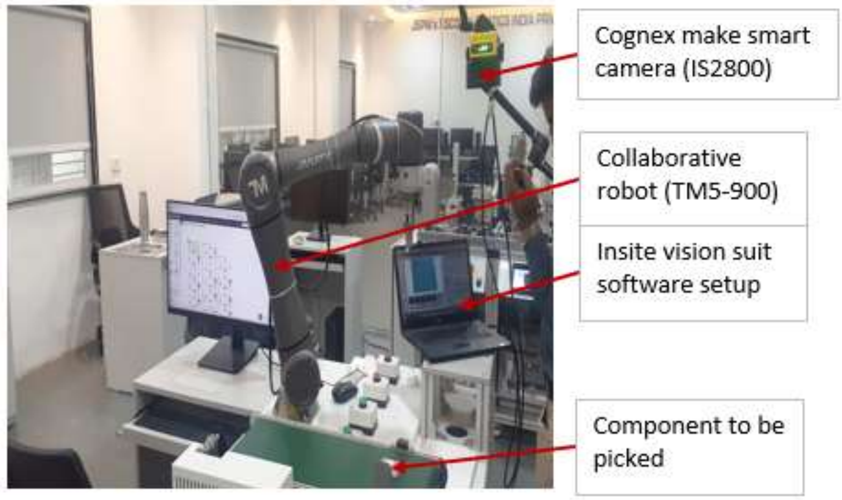

Figure 2. Experimental Set-up used to test the Collision Avoidance System

3.1.1. TM5-900

Figure 3. Techman make collaborative robot (TM5-900)

Table 2. Specification of TM5-900

Weight	Maximum Payload	Reach	Degree of freedom	I/O	Communication	Programming Environment
22.6 kg	4 Kg	946 mm	6 rotating joint	Digital In: 16/ Digital Out: 16 Analog In: 2/ Analog Out: 1	RS-232, Ethernet, Modbus, PROFINET	TMflow

3.1.2. GRIPPER

Figure 4. Pneumatic Parallel Gripper used to hold component

1. Type - Parallel Gripper
2. Model No. - AG1P01020B
3. Bore Diameter - 20mm
4. Outer Gripping Force - 42N
5. Inner Gripping Force - 66N
6. Weight - 0.27kg

3.1.3. Cognex IS2800 Smart camera

Figure 5. Cognex make (IS2800) Smart camera

1. Image Sensor - 1 /2.8" CMOS monochrome and colour
2. Image Resolution Options - 1.6 MP (1440x1080)
3. Discrete output - 2 opt-isolated
4. Communications - Ethernet interface
5. Protocols - TCP/IP, PROFINET, Ethernet/IP™, SLMP, OPC/UA, FTP
6. Software - In-Sight Vision Suite
7. Working distance - maximum 500mm

3.1.4. GigE Ethernet

Figure 6. Communication cable-GigE Ethernet

1. Speed - up to 1000 Mbps at a bandwidth of 100 MHz
2. Maximum length - 550 m for 50 μm/500 MHz×km multi-mode fiber
3. Optical power specifications of SX interface - Minimum output power = −9.5 dBm.

Minimum receive sensitivity = −17 dBm.

3.2. Software used

A variety of software tools were employed to enable the communication between different hardware components, robot control, and overall system management. Our existing operational environment—with Kinect sensors i.e. Cognex smart camera and an industrial Techman cobot—Robot Operating System (ROS) and RoboDK were chosen as the primary control architectures due to their strong compatibility within the robotics domain. TMflow is Techman make software used programme a normal pick-and-place operation. In-sight vision suite software enables the platform for obstacle detection and new trajectory optimization python programming.

3.2.1. ROS Setup

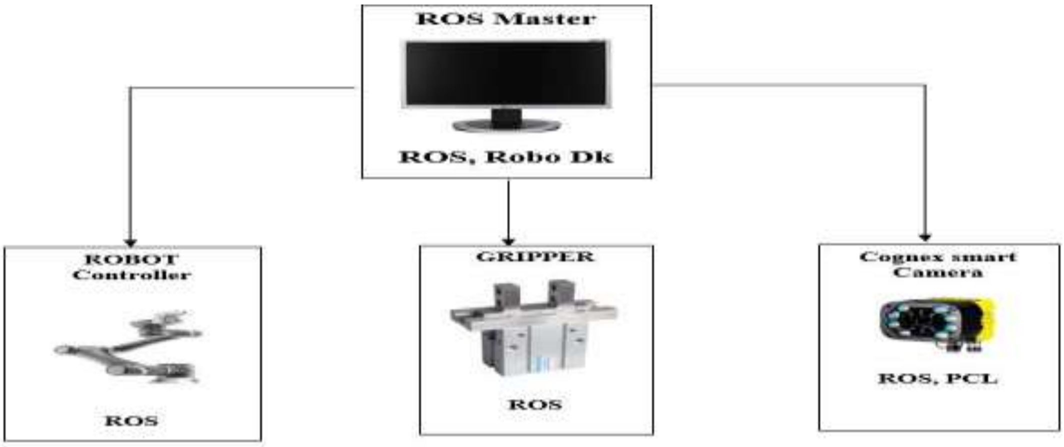

Figure 7. ROS Network Architecture.

To enable seamless communication among various hardware and software components used in the experimental setup ROS acts as a backbone of the system. The robot operating system manages the data exchange from the Kinect sensor i.e. Cognex smart camera, processes segmentation information, and directs control commands to the cobot. To provide seamless data transfer between the perception modules and the robot control systems in real-time sensor integration and inter-process communication are possible due ROS.

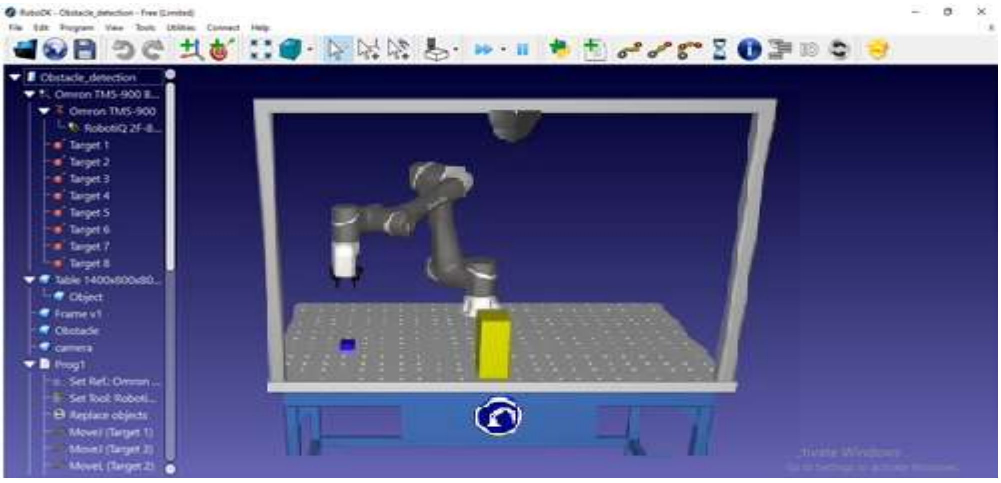

Figure 8. Simulation of pick and place operation of TM5-900

RoboDK supports to ROS system by providing tools for offline simulation, path planning, and optimization of robot trajectories. It helps to optimize and refine the robot movement before installation on actual projects which ensures the safe and efficient operations of cobot. RoboDK provides a virtual platform for testing the experimental setup and improving accordingly. RoboDK is compatible with industrial robots which helps simulation results into real-world operations.

System Integration:

a. To achieve a unified control framework for collision avoidance in pick and place operation both ROS and RoboDK are interfaced along with vision software through Ethernet communication protocol.

b. Data of Cognex make smart camera and segmentation: Gathered information from a smart camera is processed through ROS to enable accurate segmentation of information. I.e. Obstacles and other elements in the workspace.

c. Robot control: The control commands received from ROS to the cobot are processed through the vision system while RoboDK assists in generating and simulating collision-free trajectories using a machine learning algorithm.

d. Overall system coordination: The ROS and RoboDK software enables hardware components to work together seamlessly, which results in increasing performance, safety improvement, and more efficient operation of collaborative robots.

This integrated approach not only streamlines the system's functionality but also provides the flexibility needed to adapt to various operational scenarios in smart manufacturing.

Figure 9. Programming logic of Pick and Place Operation using TMflow software

TMflow software is used to program robot motion and logic configuration. It allows users to manage and set robot parameters and process logic in graphical flow chart form. We used this software to program the pick and place activity of cobot. For more details refer above figure wherein a graphical representation of the program is prepared in TMflow software.

3.2.2. in-sight vision suite

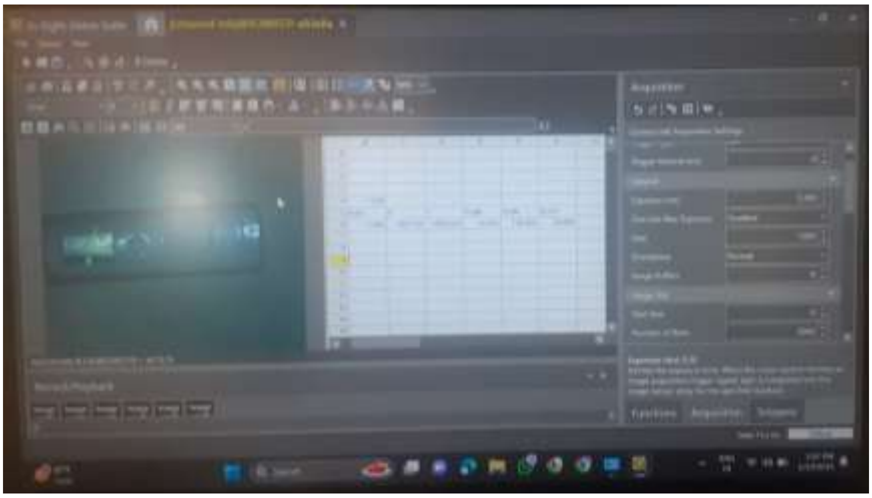

Figure 10. Obstacle detection using in-sight vision suite software

The In-sight 2800 vision system is used to detect obstacle positions in the pre-defined workspace. This system is designed to inspect different applications through image processing, deep learning algorithms, and conventional techniques. In this project, we have integrated this vision system with a cobot to detect obstacles in a pre-defined workspace through a machine-learning algorithm. After completion of obstacle detection, the vision system provides obstacle positional coordinates to the Cobot controller and accordingly, the cobot utilizes these coordinates to avoid the obstacle in a pre-defined pick and place program. While avoiding obstacles the cobot will identify a new path and reach the destination point without colliding with obstacles. For details refer above actual image of the In-sight 2800 vision system, refer following backend program of the vision camera for obstacle detection and new path generation of the cobot.

Machine learning methodology is as follow-

1. Model Design

a. Obstacle detection- In this we have used DNN for obstacle detection. The input from smart camera is bounded by boxes. The 3D obstacle mapping is done by Point cloud Library (PCL).

b. Collision Avoidance- The RRT algorithm is used along with Deep Q-Networks to detect current robot pose, position if obstacle and speed of cobot. The decision model avoid the collision and reward safe trajectory.

2. Training Process

a. Data Preparation- We have collected datasets such as human-robot interaction scenarios, various types of obstacle different operating conditions.

b. Simulation Environments- we have used RoboDk software to simulate camera input, robot dynamics, obstacle interaction as discussed in section 3.2.1

3. System Integration

a. ROS-Based Architecture- The smart camera publish a data the machine learning model gives the obstacle position to cobot RRT algorithm will generates collision free path by avoiding obstacle.

b. Real- Time inference Optimization- We have used Vision Suite software for edge deployment and NVIDIA jetson deploy model.

```
if gripper_position == 2:
  rospy.loginfo("workpiece attatched")

  lefty_robot.group.attach_object('workpiece')

 #print "============ Press `Enter` when the workpiece is physically attatched..."
 #raw_input()
  pub_create_octomap.publish(1)
  rospy.wait_for_message("octomap_created", Bool, timeout=None)
  rospy.sleep(1)

  lefty_robot.go_to_pose_goal(workpiece_com.x, workpiece_com.y,workpiece_com.z+0.1, workpiece_dirvec.x, workpiece_



  lefty_robot.go_to_pose_goal(5.42, 9.23-0.13, 0.86+0.05, 0, 0, 1, 0)
 #print( "============ Press `ENTER` to release workpiece")
 #raw_input()
```

Figure 11. Python programming for obstacle detection and new path generation

4. Results and Discussion

We have considered following parameters to do the experimental setup and result analysis:

Collaborative robot model- Techman TM5-900

Cobot speed during operation- 300 mm/sec.

Horizontal distance between component pickup and placement point- 600 mm.

Vertical distance of component from Cobot's home position- 200 mm.

Component gripping time- 2 Sec.

Component ungripp time- 2 Sec.

Proposed cad model layout during operation-

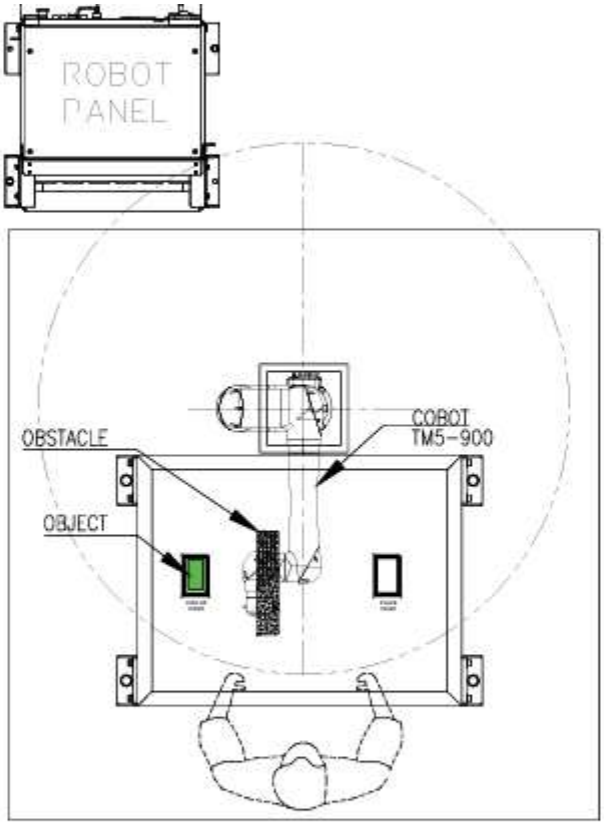

Figure 12. Proposed cad model layout

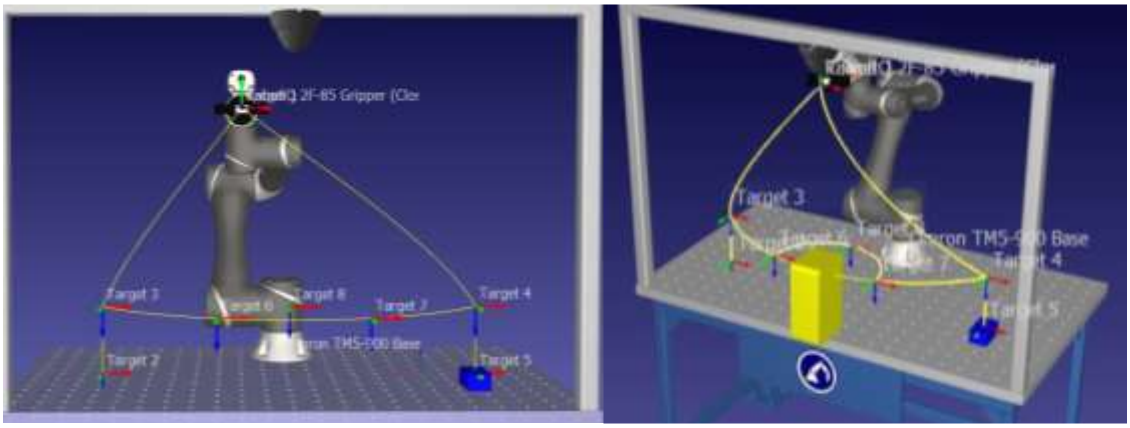

Figure 13. Trajectory visualization before and after obstacle detection

Table 3. Result of experimental setup

Operating conditions	**Speed**	**Cycle time**
Without Obstacle	300 mm/sec.	10.66 Sec.
With Obstacle	300 mm/sec.	15.50 Sec. with cobot stops at obstacle and operator interference to remove obstacle.
Obstacle and cobot integrated with vision system.	300 mm/sec.	12.66 Sec.

With reference to above Table 3 and provided different input conditions, after implementation of 3D vision camera we achieved optimized cycle time compared to without camera and obstacle conditions.

5. Conclusions

This paper presents research focused on a real-time collision avoidance algorithm used in pick-and-place operations for 3D robotic vision. The deep learning-based object detection is integrated with point cloud segmentation for improving the collaborative robot's ability to dynamically detect and avoid obstacles and enhance 3D object-pose estimation. RGB and depth images are captured using the Cognex IS2800 Smart Camera enabling real-time environmental sensing. A deep neural network (DNN) processes this information for object classification. The position of obstacles is estimated by the system with the help of a Cognex smart camera.

The integration of machine learning techniques for real-time decision-making is a key aspect of this research, which ensured the adaptability of cobot to dynamic environments, the system enables collision-free pick-and-place operations with the help of rapid obstacle detection and trajectory re-planning. The algorithm proposed in the paper calculates optimal paths effectively. Also, the movement speed and location of obstacles are considered. The study demonstrated the incorporation of artificial intelligence into robot control resulting in enhanced safety as well as operational efficiency, minimized unplanned stoppages reducing cycle time.

The algorithm was validated experimentally with the help of a 6-DOF Techman TM5 robotic arm. The results demonstrated the successful obstacle detection along with modified trajectories in real time which ensured uninterrupted operation. The developed system has improved collision avoidance by allowing predictive adjustments based on environmental changes when compared to the traditional reactive control approaches. By using proposed methodology will be able to achieve 84% of original cycle time with obstacle detection vision system and machine learning algorithm. The research also highlighted the advantages of integration of advanced control strategies for path planning such as the Rapidly-exploring Random Tree (RRT) algorithm

A few challenges remain after all the advancements. The highly unpredictable scenarios where obstacles demonstrate erratic movements may compromise the system's effectiveness. The scope of improvement may contain enhanced adaptability with the help of advanced tools like reinforcement learning techniques and improving system robustness in unstructured environments. Also, to optimize efficiency, the algorithm's capability to handle multi-robot collaboration can be further expanded.

On the whole, a robust and intelligent collision avoidance system capable of significantly improving the safety and performance of collaborative robots was presented in this study. The proposed approach sets the foundation for safer and more efficient human-robot collaboration in industrial automation by integrating advanced vision-based detection, machine learning, and real-time path planning.

Author Contributions

Rabiya Mulla: Writing – original draft, Supervision. Bhagavat Jadhav: Conceptualization, Supervision. Rakib Nadaf: Writing- review and editing. Hrutik Gaikwad: Supervision and writing review.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Funding

This research received no grant from any funding agencies.

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