Safe and Automated Assembly Process using Vision assisted Robot Manipulator

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Abstract

Many manufacturing industries especially small and medium size (SMEs) industries are reluctant to automatize their production using robots. This is due to the fact that mostly industrial robots are not properly equipped to recognize their surrounding and take intelligent decisions regarding path planning especially for low volume, flexible production with versatile production lines. The proposed idea is that a robot manipulator performing assembly or disassembly tasks should be able to predict potential collisions even with unknown obstacles and must be able to prevent i.e. react automatically for safe detour around obstacle. Currently, industrial robots have tactile sensing abilities, which detect collisions after a real contact but the existing proposals for its avoidance are either computationally expensive, need prior information about the obstacles or not very well adapted to the safety standards. Therefore, this paper introduces a ToF sensor based information collection and intelligent decision methodology in order to localize the un-known, un-programmed obstacles and propose a safe peg-in-hole automated assembly process. In the case of collisions, the proposed method will provide various solutions and decides for the best solution according to the scenario on-hand. The proposed solution is quick and robust and currently applied for static environment, whereas dynamic obstacles will be treated in future.

Keywords: Assembly process; Peg-in-hole process; Industrial Robot; Path Planning; Robot vision.

1. Introduction

Manufacturing industries are shifting towards automated assembling processes using state-of-the-art robot in order to increase the company output. Robot manipulators are the perfect option for enhancing production automation, which complements human strengths in assembly and manufacturing processes by handling high repeatability, position precision, high payload and fatigue. For instance, an assembly process can be automatized using manipulator robot e.g. KUKA-DLR Lightweight (LWR) [1] with forced control strategy [2]. The peg insertion industrial process is a good example of assembly process, which can be automatized using robot in order to increase the mass production. On one hand, enhancing automation increases mass production of a company but at the same time increases the robot controller intelligence requirement issues related to collisions. Industrial robots need automatic intelligent solution to detect the risk of expected collisions and plan a rapid change to the already planned trajectory in order to avoid colliding with other machinery, working parts and humans. The robot controller might therefore need some intelligence to predict the risky situation on-hand and decide for a better solution to the problem. The proposed solution should not only help robot to detect a harmful situation but also to provide a solution to detour the harmful obstacle.

The rest of the paper is organized as follows. The detailed problematic is discussed next, following the state-of-the-art. The proposed path planning approach is presented in section 2. Section 3 discusses the validation results on a Peg-in-hole scenario demonstrated in the laboratory context. The final conclusions are drawn in the end of the paper.
### Nomenclature

<table>
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>LWR</td>
<td>Lightweight Robot</td>
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<tr>
<td>Robo-MAPPS</td>
<td>Robot Manipulator-robot Automatic Path Planning System</td>
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<tr>
<td>MLI</td>
<td>Modulated Intensity Light</td>
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<td>FRI</td>
<td>Fast Research Interface</td>
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<td>ToF</td>
<td>Time of Flight</td>
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### 1.1. Problematic

The general problematic is therefore an automatic collision detection and avoidance system for general robot assisted assembly process. As a general practice, during an assembly tasks such as peg-in-hole process, if the powertrain is misplaced or any unknown obstacle is present which was not taken into account in the previously programmed robot trajectory e.g. a machine extra part, a human etc., the robot is able to stop moving after exerting a defined force but currently not able to automatically detour the unknown obstacle especially during machining and assembling processes. This causes a potential risk of collision, which implies an expected damage to the machinery, production part, manipulator itself [3] or any nearby human, which might be annoying if not harmful. Therefore such unwanted scenarios and contacts need to be avoided automatically by the robot controller.

Some of industrial robots are equipped with force control sensors attached to it in order to stop its movement after exerting a specified amount of force on the obstacle. But exertion of such a force may also not be an option for certain processes such as fragile processes e.g. food packaging, glass picking and placing etc. The problem becomes more serious when humans are involved in the collision scenario [4]. In practice, these forces are limited after contact detection to avoid harming humans during collaborative works but the continuous exertion of safe force on human may also create problems by annoying worker with continuous touching at the shop-floor production. The contact issue is also very much important for a human-robot-collaborative environments [5] where several legal requirements need to be considered [6].

Industrial robots are used for mass production because of their fatigue-proof ability and complementing human skills, therefore a contact with obstacle and interruption during production may be highly undesirable for industries that demand automation [7, 8]. An automatic path generation method is therefore necessary to avoid any known and unknown obstacles in the vicinity of the robot during production/assembly processes.

The dynamic aspects such as velocity and acceleration are difficult to take into account in offline programming [9, 10] of the robots and also for ‘teach and replay methods’, but they are extremely important to be taken into account in order to program for the real environment. A part from dynamic aspects integration into the offline systems, some other important issues, which may cause collisions in the real robot assisted scenario are highlighted below [9]:

- Mostly industrial robots are designed for better repeatability than accuracy.

### 1.2. Existing proposals

Safe path planning with collision detection and avoidance is a hot topic of research treated by many researchers. Several methods are developed in this regard, for example, gesture and voice command based contactless collaboration [11, 12] by a direct communication between a human and robot. A human should understand a risky scenario and command a robot highly in-advance to stop before any harm, which demands an extra energy from the human to concentrate on the collision itself and not concentrating on the production. This process will take advantage of the robot force but will not use the complementary skills of human for productive collaboration.

In robotics, the circular fields [13], elastic strips [14] and artificial potential field [15] are the most important collision detection and avoidance strategies but the drawback of the method lies in the robot may be getting stuck in the local minima and the path generation process relatively slow. Siciliano et. al. has also investigated [16] safe path planning solutions, especially in dynamic changing scenarios but existing proposal lacks a successful method that can take into account the aspects of unknown obstacles and generate automatic solutions for its avoidance. The reason behind this is that a standard safe and robust sensor technology suited for manufacturing environment is still missing, and also computation time is an important issue for such solution proposals.

So far vision based techniques are considered as the important tools for optimizing the robot path in a collision scenario e.g. during welding process [17, 18, 19]. Some stationary surveillance zones can be defined using optical vision systems [20], where obstacles are detected when entered, and robots motion can be stopped. The 2D vision systems are a good solution for environment prediction but they are not good when exposed to external lights, changing illuminations and occlusions in the scenario.

For the first time a depth information based collision detection and avoidance has been used [21] for Human Robot Interaction, where the physical interaction between human and robot such as predefined gestures or voice commands are used. The depth information extraction sensor technology gives a wide application to predict the 3D environment with less computation and equipment but not fully utilized yet for automatic collision avoidance scenarios.

The Time-of-Flight (ToF) depth sensor solutions [22, 23] are currently in investigation, with having advantages over conventional 2D vision systems such as they are not affected by the light intensity differences and provide additional depth information of the environment. ToF sensors can rapidly capture the 2.5D information from the scene, which can be used for decision process to detect and localize different objects in the scene. For instance, a solution [24] proposed...
with two Kinect camera sensors with very less occlusions operated with infrared illumination of the scene and triangulation method can observe the distances to the obstacles. The solution proposed reduces the speed of robot when reaching an obstacle but automatic collision avoidance solutions are not implemented yet.

A solution is therefore necessary, which takes into account the 3D information of the assembly process, detect potential collisions and provide rapid decision to detour the obstacle. The main objective of proposed solution will be a safe human-robot-collaborative assembly process with initial application to known and unknown static obstacles. The solution proposed will be applied to peg-in-hole assembly process as an initial application.

2. Robot Manipulator Automatic Path Planning System (Robo-MAPPS) Approach

The Manipulator-robot Automatic Path Planning System (Robo-MAPPS) approach generates an alternative path for robot when potential collisions are expected with obstacle in a partially unknown environment. The major important steps during this path planning process includes the “obstacles detection and localization” using 3D vision sensor, “collision detection” by verifying the already programmed trajectory and “collision avoidance” by taking a safe detour automatically using a best direction selection strategy as detailed in the flowchart in Fig. 1. A peg-in-hole process using robot will automate the assembling process where a robot e.g. KUKA-DLR has to insert pegs/cylinders inside different holes as shown in Fig. 2, and unknown, un-programmed object or nearby human may act as an obstacle. Initially a tip point of the peg or TCP point of the robot is considered for path generation, whereas path in focus is a pre-programmed transversal path between three peg insertion points shown with obstacle on the second location. Real information about the scene are collected using ToF, 3D-MLI sensor [23], with a resolution of 56*61 Pixels, installed on the table.

2.1. Obstacles detection and localization

Information data about different objects in the scene are collected using vision sensor, potential obstacles are localized for collision in the assembly environment with the help of 3D point clouds with depth information. A subtraction matrix is calculated from the initial scene information and the updated scene information which gives the location for new, displaced or unknown obstacles.

Initial status of the scene where no obstacle are present with 3D coordinates (x y z) information about depth of objects in the scene is shown in Fig. 3 (a), taken from MLI sensor. This reference image is used to compare for detecting the new (available) obstacles. The actual scene information are detected by a fresh 3D image from the scene using 3D MLI sensor. The actual information is then compared with the reference image, which gives the presence of an unknown static obstacle as shown in Fig. 3 (b) or (c).

Fig. 1. Flowchart Robo-MAPPS.
2.2. Collision detection

When potential threats are present, the obstacle present are localized in the scene, the proposed method then generate the already planned trajectory in order to see for any overlap between the planned path and the obstacles. The already planned path is generated on the subtraction matrix, which gives a clear indication of where the obstacles are actually present in the 3D environment. In the presence of obstacles in the initial path, a potential collision is detected (Fig. 3 (d)).

2.3. Collision Avoidance

A diversion strategy is adapted to prevent the moment of robot to the risked workstation and a detour is advised while keeping in mind the original location of the obstacle. The localized obstacle is therefore avoided by choosing a best diversion strategy among the two proposed diversion direction solutions by Robo-MAPPS approach such as “above the obstacle” & “in-front of the obstacle” as shown in Fig. 4. These secure points are generated once the obstacle positions are calculated.

Once secure points are generated using the two proposed solutions i.e. above and in-front, then a secure position is selected for each solution among the various possibilities because row of secure points exists in each case. The selection of secure point in each case is subjected to minimizing the distance criteria:

\[
\begin{align*}
\min D_{ij}^n &= \sqrt{\sum_{l=1}^{n} (x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2} \\
&\quad (1)
\end{align*}
\]

\[\begin{align*}
D \Rightarrow \text{Total distance} &; \ x, y, z \Rightarrow \text{Coordinates values} \\
n \Rightarrow \text{The total number of straight trajectories e.g.} &; n = 2; \text{for two trajectories i.e.}
\end{align*}\]

& satisfying the collision free next trajectory i.e.

\[
\sum_{i=1}^{2} C_j + \sum_{i=1}^{2} C_i \neq 1; \text{ (1 → Collision value) (2)}
\]

After selecting a feasible secure position using the above criteria the onward path is verified using the same procedure as discussed previously. The safe path obtained is finally improved by removing the unnecessary trajectory points for both solutions obtained in order to get two improved safe paths for the robot. The proposed method generated two different safe trajectories for the same collision problem because of the proposed secure points above and in-front of the obstacle. Both safe paths obtained in the previous step are safe but the robot controller should be intelligent enough to decide which one to choose. The best path is then selected using the following criteria:

- Minimum trajectory length,
- Time to reach the final point, proportional to the length of path,
- Minimize the number of axis of robot in movement and also keep in mind the robot accessibility limitations.

Finally the selected best path is applied back to the robot using Fast Research Interface (FRI) [25].

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Fig. 2. Peg-in-hole process using Kuka-DLR Robot (Experimental setup).

Fig. 3. Depth information matrices from the scene (from 3D-MLI sensor) of Fig. 02; a) Initial scenario; b) obstacle above the second station; c) two obstacles, one above and one in-front of the second station; d) Collision with the obstacle above the second station

Fig. 4. Secure points generation above and in-front of the obstacle.
3. Validation and Discussions

The approach presented in the previous section is applied to a peg-in-hole scenario carried out by a KUKA-DLR Lightweight robot in laboratory setup. The objective of the experiment was safe and automatic path planning for a peg-in-hole process by detecting and avoiding collisions with unknown, un-programmed obstacle. Fig. 5 shows the detailed experiment and the two solutions obtained for avoiding collisions. Two kind of images are shown for each status of the robot i.e. one real picture of the scenario using 2D camera and second (blue), a 3D depth information image taken from 3D MLI sensor installed on the scenario.

In Fig. 5 (a, b, c), a Peg-in-hole scenario is shown where the robot has to insert three pegs at three different holes with initially pre-defined programmed trajectory starting from “a” to “b” and then to “c”. In Fig. 5 (d, e) an unknown un-programmed obstacle is placed for the sake of experiment, which is not programmed initially and it might cause collision with the robot at station 2 as shown in Fig. 5 (d). The proposed vision based system observes the scene and detects the expected collision before it happens and decides for detouring the obstacle far before the robot starts moving towards this station for example when robot is at first station as shown in Fig. 5 (e).

The vision assisted Robo-MAPPS approach detects this obstacle, localizes its position and generates safe trajectory for the robot “above the obstacle” and “in-front of the obstacle” as shown in the second and third row of the Fig. 5. In the second row of Fig. 5 (f, g, h, i, & j), one can see the sequential detour of robot above the obstacle. The same process is repeated for detouring the obstacle in-front as shown in Fig. 5 (k, l, m, n, and & o). The proposed approach therefore generate two solutions for the same collision problem.

The two solutions presented above are then compared in Table. 1 for the criteria discussed previously and the resulted best solution is selected, which is then applied on the robot for the collision problem described. The criteria application to both solutions indicates that solution 02 is the best option for the current scenario on hand and robot has to move in-front of the obstacle to generate a safe detour around the obstacle.

<table>
<thead>
<tr>
<th>Safe path planning</th>
<th>Solution # 01</th>
<th>Solution # 02</th>
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<tbody>
<tr>
<td>Above</td>
<td>Length of path</td>
<td>78cm</td>
</tr>
<tr>
<td></td>
<td>Time to achieve</td>
<td>3.9sec</td>
</tr>
<tr>
<td>In-front</td>
<td>Robot Accessibility</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 1. Analysis of safe path planning solutions (Robot speed = 0.2m/sec).

Fig. 5. Path planning application with peg-in-hole process scenario: a) Peg-in-hole scenario, first station; b) Second hole station; c) Third hole station; d) Collision with an unknown, un-programmed obstacle at second station; e) decision point before collision; f, g, h, i, j) Detouring the obstacle according to solution 01, above the obstacle; k, l, m, n, o) Detouring the obstacle according to solution 02, in-front of the obstacle.
The overall safe trajectory generation process takes only one second for both trajectories generation and the final best solution availability to the controller of the robot. The two solutions proposed are currently not optimal and a more optimal solution might exist but the method proposed is intelligent enough to generate a best automatic trajectory for unknown un-programmed obstacle in short span of time.

The solution proposed were only investigated using the Tool Center Point (TCP) trajectory of the robot using Cartesian impedance control strategy, and therefore the rest of the robot joints are not investigated for collisions. A solution to this regard may be the best trajectory should be followed by each and every joint of the robot to ensure safe movement around the obstacle at a well-defined security margin, which was defined manually here. Another solution could be to investigate the developed solution scenarios for joint control strategy, which will program each joint to a secure position in the case of collisions. Nevertheless, the solution proposed in this paper is intelligent enough to generate safe paths for robot assisted assembly process in static environment, which will be extended to dynamic obstacle scenarios in future, e.g. for human-robot-collaborative flexible assembly process.

Conclusions

A robot manipulator automatic path planning strategy based on 3D-ToF sensor is presented for peg-in-hole assembly process. The method proposed not only detect potential risk of collisions with unknown un-programmed obstacles using the environment map but also take an intelligent rapid decision to generate two solution proposal for collision avoidance and finally select the best trajectory among the two, for automatically detouring the obstacle. The proposed approach generate safe detour trajectory in assembly process in less than one second, which will be further optimized for dynamic scenario in future.

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