Advances in machine vision for flexible feeding of assembly parts

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Abstract

Human-robot collaboration can be used to share workload to form semi-automated production systems. Assembly operations are recognized with high potential to increase productivity by using the best skills of humans and robots in a combination. Components and parts to be assembled need to be structured and presented to the robot in a known location and orientation. The process of presenting parts to the robot for assembly tasks is referred to as parts feeding. Feeding system needs to be adaptable to dynamics of parts’ design, shape, location, and orientation to have flexibility in the production. The traditional automation methods for parts feeding are part-specific mechanical devices e.g. vibratory bowl feeders which are inflexible towards part variations. This comes as a hindrance in getting maximum advantage of the flexibility potential of human-robot collaboration in assembly. The recent years have seen advances in machine vision and has potential for feeding applications. This paper explores the developments in machine-vision for flexible feeding systems for human-robot assembly cells. A specification model is presented to develop a vision-guided flexible feeding system. Various vision-based feeding techniques are discussed and validated through an industrial case study. The results helped to compare the efficiency of each feeding technique for industrial application.

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1. Introduction

To be competitive in a global economy the manufacturers are required to be resilient and flexible towards market dynamics. With shortened product lifecycles the expectations from a manufacturing system are to be adaptable and reconfigurable for variant oriented manufacturing \cite{1}. As per Rosati \cite{2} the key requirements for achieving flexibility in a production system are to be able to produce variants at a varying production rate and at a low cost. There can be several requirements from a flexible assembly system however the foremost is economics.
In a manufacturing landscape, for end-product realization, various stages for variety enablement have been identified such as design, fabrication, assembly, sales or through adjustments during the end use [3]. Among these, the process of assembly (a set of sequential activities for achieving a functional end-product by integration of geometrically defined parts, components and software) is recognized as the most important aspect of manufacturing to enable cost effective product variety. Due to geometrical complexity involved in assembly parts and production variations, traditional assembly cells are mostly kept manual. This makes assembly the most labor-intensive work for manufacturing of discrete products.

The desired integration of flexibility and automation has given rise to the concept of human-machine interaction [4]. This attractive interaction is now being realized through collaborative robots or cobots [5]. The purpose of human-robot collaboration (HRC) is to utilize the best abilities of robots and humans in a shared workspace. Cobots are flexible by offering easier programming, mobility and safety for fellow humans. They can takeover repetitive and accuracy-requiring tasks from their human teammates. Robots are inferior to humans in their sensory perception and sensorial capabilities to achieve tasks in non-structured environments [4]. To accomplish a robotic task, the robot is presented with the part through some sort of feeding mechanism and robot picks and assembles the part as desired. Consequently, for assembly work, their flexibility gets limited by the mechanical feeding systems conventionally used for automated feeding of assembly parts.

Making a robot aware of its environment is a known challenge from mainstream industrial automation. The first generation of industrial robots were blind industrial slaves repetitively manipulating parts of known form and posture with limited ability to handle any variation. Therefore, in situations, where the parts were delivered to robots in an unknown position and/or posture and had variations in size or shape, a vision system needed to be implemented. Over the years these vision systems have become more robust and reliable. Such machine vision systems are now found in many other applications an industry such as for inspection, measurement and guidance.

The machine vision systems, if used in connection with cobots, can identify the location and pose of the parts and can instruct the robot to pick the parts as identified. The algorithm of the vision-software adopts a pattern matching technique thereby finding the best match between a known master image and the scene presented by the camera. It also develops a “goodness of fit” between master image and the ‘found’ object thus identifying an object as the best fit even if the object is partially visible [6].

The paper recognizes the importance of feeding technologies not often discussed in relation to human-robot collaborative assembly. The paper, with the help of industrial case, investigates and validates the usefulness of vision-based feeding methods based on key production variables. The parts involved in the case study for vision testing are selected to offer maximum variability of material type, surface finish, geometry, and size.

2. HRC assembly cells and parts feeding and presentation

Human-robot cooperation in assembly is supposed to deal with highly dynamic and uncertain shop floor environments [7]. To perform an assembly process, the robot needs to be aware of the location and pose of the part to be picked in the required orientation. Hansson [8] has described feeding as a process of two tasks i.e. part structuring and part presentation. Part structuring is singulation of individual parts from a bulk and arranging it to have a known orientation. Part presentation defines moving an individual structured part to the point of use or assembly.

When working with visual guidance software two major issues to be dealt with are part occlusion and overlapping objects. Part occlusion arises because the robot gripper approaches the part with two or more parallel fingers and for this the gripper needs two free fingerprints spaces next to the object in the grasping position. The problem of overlapping objects is due to the fact that overlapped objects are hard to locate.

3. State of the art

Traditionally, the science of automated part feeding is centered around having specialized feeders for each assembly component. Vibratory bowl feeders are the most common method for feeding disordered small parts to the production lines. As the design of a bowl feeder is component specific thus it serializes only one type of a component at a time. This makes it necessary to have as many feeders as there are number of components in an assembly process [2]. Additionally these devices are noisy and acquire a large space [9]. In “Cooperation of human and machines in assembly
lines”. Kruger [10] presented a review of feeding techniques found in theory and practice. These included vibratory bowl feeders, vibratory brush feeders for fragile parts, camera equipped belt feeders and adept FlexFeeder for multi component feeding using electronic sensor (Fig. 1).

Recent years have seen research towards finding methods of flexibly feeding multiple parts without mechanical rebuilding. A notable contribution in flexible feeding is made by Rosati and is discussed in various of his publications. The author presented the concept of fully flexible feeding system (F-FAS) [11] that comprises of a vibratory plane for part orientation and a stationary camera for image acquisition. In addition to presenting a layout, constitutional elements and functioning principle of an F-FAS, the author also compared the performance of F-FAS with manual and bowl-feeders based on hourly throughput and unit production cost. The F-FAS system was concluded to have lower throughput, recommended for small parts and was requiring large initial investment. In another work [12] the author presented an integrated implementation framework for choice, design and management of flexible feeding systems. The proposed framework has three correlated phases of convenience analysis of a flexible assembly system as compared to a manual or fully automated rigid system; design of the feeder; set-up and sequencing algorithm for achieving highest throughput.

![Fig. 1. (a) vibratory bowl feeder; (b) vibratory brush feeder for fragile parts; (c) camera equipped belt feeder; (d) Adept flex feeder [10].](image)

Another approach towards flexible feeding is to match the 3D-CAD data of the object with the object’s image. This comparison identifies the location and pose of the part needed to be picked [13]. Similar approach of enabling a vision-guided robot system for 3D model-based pose estimation and picking of singulated objects was presented by [14]. The system employed a vision sensor consisting of a video camera surrounded by eight flashes (light emitting diodes). By capturing images under different flashes and observing the shadows, depth edges or silhouettes in the scene were obtained. The silhouettes are segmented into different objects and each silhouette is matched across a database of object silhouettes in different poses to find the coarse 3D pose. The database was pre-computed using a computer-aided design (CAD) model of the object.

Vision based bin picking method in robotic cells has been discussed as a robust way to recognize object and estimate pose with multiple vision sensors [15]. In the conventional bin picking automation, the challenges of FOV, shape of landmark features, and computation time are observed. An effort to solve these challenges using stereo vision-based bin picking was presented by [16]. A system to make the robot to detect assembly objects, plan the grasps and assemble the objects by human demonstration was presented by Wan [17]. Although several approaches are available in literature for flexible feeding but a unified feeding approach for catering the needs of HRC assembly is not available yet. A key element to gain the required degree of flexibility is the machine vision system [18], whose tasks can be to recognize the part to be assembled; recognize any defects on parts tube tops; compute the actual positions of placement, inspect the assembled product.

4. Vision based parts feeding in HRC assembly

This chapter presents a three-layered model for various types of feeding techniques for extended flexibility. The categorization assumes that the parts are initially stored in bulk in a known or unordered orientation until brought to the feeding system. As already said that feeding flexibility can be increased by avoiding mechanical architecture and inclusion of vision-based feeding techniques. For this reason, flexible part feeders almost always employ a vision system for part identification.
The presented model (see Fig. 2) has three layers and starts by evaluating the arrangement of the assembly parts i.e. if they are arranged in a known orientation or are disordered. The next layer describes the presentation of the parts to the feeding system i.e. if the parts are on a flat surface, in a bin, vibratory plane or in a bowl feeder. The next layer describes the technology being employed for part recognition, i.e. 2D, 3D or structured light cameras with an addition to CAD based part recognition. By selecting a category within each layer of the HRC feeding model, the system designers can evaluate the efficiency of the HRC system.

5. Techniques for vision-based parts feeding

5.1. 2D cameras for feeding system

This feeding technique uses a stationary 2D camera mounted on top of a flat surface or a bin (Fig. 3 a). The parts are placed randomly in a mixed order. Two cameras (one stationary and one mounted on robot arm) are recommended for higher accuracy. Since the 2D camera is not sensitive to depth variability therefore it is suitable when the parts are always at a same height from the camera. Besides this limitation, they are cheaper and have good accuracy. Further, teaching a 2D camera detection-engine (software) is easy thus increasing their adaptability and flexibility to product variety.

5.2. 3D structured light cameras for feeding system

A 3D structured light camera is used for locating the position of the parts and a depth sensor for pose identification. Once the location and pose estimation of the parts is complete, the pick-and-place robotic arm is signaled to pick the part from the source location, in the required orientation, and move it to the point of use. The camera can identify a
single or multiple part in each cycle. The process of parts’ identification can be made faster by mounting the camera as stationary. This will enable the feeding system to keep identifying the next part while robot is busy in pick and place task during each cycle.

5.3. CAD support for vision-based parts detection

Such a vision-based feeding system is supported using a CAD geometrical data with a single 2D camera. In this way the CAD geometry helps to identify the right part during each cycle.

5.4. Vibratory surface for part presentation to robot

The system comprises of a bulk that contains assembly parts and sheds them on to a vibrating plane that distributes and reorients the parts. A machine vision system detects the location and orientation of the parts and once detected, the robot manipulator is triggered to pick the parts and move it to the point of use. Kruger [10] has documented that the detection time in this system is considerably longer than a dedicated feeding system. However, the system is flexible to adapt to other parts without any mechanical rebuilding. The only challenge seems to be emptying the tray and filling it with the new components. Because of the stochastic nature of the feeding system, all the parts on the plane may have a random composition. If there are multiple types of parts on the plane, the system may not be able to detect the required part due to over-lapping. This limits the precedence constraints in an assembly and the types of components placed on the plane else the vibrating plane would vibrate several times to identify the needed part [1].

5.5. 3D printed bowl feeders

A 3D printed bowl feeder is an extension to conventional vibratory bowl feeder with the exception that the top part is changeable. The top part is developed by additive manufacturing technique thus reducing the mechanical rebuilding effort and shorter change-over time.

6. Case study

6.1. Parts selected for vision testing

An industrial case study of assembling an electronic linear actuator is selected for testing and validation of different flexible feeding systems. This is a medium sized product with both metal and plastic components. The parts selected for testing are shown in Fig. 4 and Table 1. It is observed that the parts can be detected correctly with one way or another however, the differentiating criteria is the production cost. The argument by Kruger that the cycle times are longer in flexible feeding systems than dedicated feeding system is less relevant in HRC assembly by using a stationary camera that detects and identifies a part while the robot is mounting the part detected in the previous cycle. In situations, when a stationary camera is not enough, and an additional camera is required to accurately detect a part, cycle times get longer. Therefore, it becomes important to make further analysis based on the factors of cycle times involved, investment, number of parts successfully detected with one system.

Fig. 4. Parts selected for testing with various vision-based feeding systems for HRC in assembly.
Table 1. Physical properties of parts investigated in the study.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Test scenario</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Height (mm)</th>
<th>Material</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Part A</td>
<td>39</td>
<td>39</td>
<td>17</td>
<td>Metal</td>
<td>230</td>
</tr>
<tr>
<td>2</td>
<td>Part B</td>
<td>60</td>
<td>60</td>
<td>20</td>
<td>Metal</td>
<td>320</td>
</tr>
<tr>
<td>3</td>
<td>Part C</td>
<td>41</td>
<td>41</td>
<td>13</td>
<td>Metal</td>
<td>180</td>
</tr>
<tr>
<td>4</td>
<td>Part D</td>
<td>34</td>
<td>34</td>
<td>26</td>
<td>Metal</td>
<td>160</td>
</tr>
<tr>
<td>5</td>
<td>Part E</td>
<td>24</td>
<td>24</td>
<td>19</td>
<td>Metal</td>
<td>140</td>
</tr>
<tr>
<td>6</td>
<td>Part F</td>
<td>11</td>
<td>11</td>
<td>10</td>
<td>ABS</td>
<td>70</td>
</tr>
<tr>
<td>7</td>
<td>Part G</td>
<td>18</td>
<td>18</td>
<td>30</td>
<td>ABS</td>
<td>40</td>
</tr>
</tbody>
</table>

The tests are made with five scenarios as explained in chapter 5 except for 3D printed bowl feeder, which is the same as conventional bowl feeder however only the top part is changeable for part variability.

6.2. Test results

The 2D camera used in the first test was SICK Inspector PIM60 (Fig. 5 a). The system was able to successfully detect all the parts’ location and orientation. The overlapping parts were hard to detect and if the distance between the parts and the camera is variable then the parts will need to be recalibrated. The second test comprised of a vibratory surface (Fig. 5 b). AnyFeeder model SX-240 was used during experimentation that can handle a maximum weight of 1500 g on the plane. The plane vibrates to separate the parts from other parts and makes the orientation required to be detected.

A 3D structured light camera having the ability to measure the depth of the object was used in the third experiment (Fig. 6 a). The distance between the camera and parts is 600 mm. It detected the parts A, B and C. However, the camera was not able to find parts D, E, F and G. The low success rate was motivated by the fact of parts being small, not having enough surface area available for the camera to read them and the surface was too shiny making it difficult for the camera to read them. A structured light camera is sensitive towards length variations in between object and the camera. However, this type of camera is expansive, the precision is low in case of small parts and teaching the detection engine is hard than a 2D camera.
The fourth test comprised of a vision-based feeding system supported by a CAD model (Fig. 6 b). In this scenario the vision image was compared with the CAD model of the part being detected. The system was successful for all the parts detecting one part of a kind during each cycle.

Table 2. Results from the experimentation.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Test scenario</th>
<th>Number of objects on the plane</th>
<th>Number of objects detected</th>
<th>Time of image acquisition (s)</th>
<th>Success rate (%)</th>
<th>Price (Euros)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2D camera for feeding from bulk</td>
<td>7</td>
<td>7</td>
<td>0.3 – 1.5</td>
<td>100</td>
<td>8.667</td>
</tr>
<tr>
<td>2</td>
<td>3D camera for feeding from bulk</td>
<td>7</td>
<td>3</td>
<td>1.5</td>
<td>43</td>
<td>10.000</td>
</tr>
<tr>
<td>3</td>
<td>3D camera for feeding from bins</td>
<td>7</td>
<td>6</td>
<td>2.0</td>
<td>86</td>
<td>69.333</td>
</tr>
<tr>
<td>4</td>
<td>CAD supported vision feeding</td>
<td>7</td>
<td>7</td>
<td>1.5</td>
<td>100</td>
<td>17.333</td>
</tr>
<tr>
<td>5</td>
<td>Vibratory table with vision feeding</td>
<td>7</td>
<td>6</td>
<td>1.5</td>
<td>100</td>
<td>72.000</td>
</tr>
</tbody>
</table>

7. Analyzing efficiency of a flexible feeding system

The hourly unit production cost of an assembly system is a measure to evaluate performance of the system. The hourly unit production cost is a ratio of cost of the production cell per hour and hourly production throughput. The same method is adapted in studies [1] [12] [2] to compare the agility of different assembly systems.

From the works of Rosati [11] the hourly throughput of a feeding-based assembly system can be described as:

\[ Q_{AssemblyCell} = \frac{1}{(t_{f,s} + t_{ls}/K) + t_{p,p}} \] (1) [11]

Where

\[ t_{f,s} = \frac{t_{f,j}}{N_{p,j}} = \text{average times for the feed of a single part} \]
\[ t_{ls} = \frac{t_{l,j}}{N_{p,j}} = \text{average times for inspection of a single part} \]
\[ t_{f,j} = \text{time for parts feed} \]
\[ t_{l,j} = \text{time for image acquisition and processing} \]
\[ N_{p,j} = \text{number of parts on the plane} \]
\[ t_{p,p} = \text{average time for manipulation and assembly of a single part} \]
\[ K = \text{ratio between the number of parts assembled and the number of parts identified} \]

The hourly direct production cost is given as:

\[ C_{h, AssemblyCell} = \frac{C_{AssemblyCell}}{h_{pb}} \] (2)

\[ C_{h, AssemblyCell} = \frac{C_{robot} + C_{gripper} + C_{workstation} + C_{camera} + C_{flex feed}}{h_{p,b}} \] (3)

Where \( C_{robot} + C_{gripper} + C_{workstation} + C_{camera} + C_{flex feed} \) present the cost of the production system and \( h_{p,b} \) is the working hours in the payback time.

The unit direct production cost is calculated as:

\[ C_{u, AssemblyCell} = C_{h, AssemblyCell} = \frac{C_{AssemblyCell}}{h_{p,b}} \left( \frac{t_{f,s} + t_{ls}}{K} + t_{p,p} \right) \] (4)

By using the equation 4, the unit production cost of each of the above feeding system is given in table 3.
The scientific knowledge of automated assembly feeding is not as mature as other areas of manufacturing or assembly operations. Besides several random solutions available, there is no unified generic framework/methodology available for feeding technologies. This situation is critical in HRC assembly cells where robots have been developed to raise the automation bar of manual assembly work but are remaining limited due to feeding systems’ constraints. Results from this paper elucidated the economic effects of machine vision technology with various techniques for developing a flexible feeding solution. The final solution would be highly contextual based on product, process and economic constraints. Several factors can influence this decision for feeding technique. Camera mounting techniques, for example, can affect the cycle times and accuracy achieved in the results. Future research should focus on developing flexible and modular solutions for feeding that are adaptable to various situations. Nevertheless, implementation of machine vision in assembly systems is a multi-layer problem and an optimal solution emerges at the verge of knowledge, experience and innovation for a case specific solution.

### References