Abstract

Highly accurate sensor based robot movements are demanded in many light assembly applications. In our study the goal is to implement a vision sensor in the gripper frame of a robotic manipulator to investigate how to achieve high accurate but at the same time flexible movements. Our sensor comprises two cameras and a suitable lighting. The 3D coordinates of the objects close to the grasping point are extracted based on the normal stereo disparity calculations. The recent results of our experiments shows that we are able to achieve the accuracy of about 20 micrometers in the area of 90 x 70 mm$^2$ and that our control method is capable of driving the robotic manipulator according to this accuracy. In this paper we describe our control method and the performance of the sensor as well as the preliminary results of our studies.

1 Introduction

The demand for high accuracy movements of a robotic manipulator has become one of the most important issues among light assembly applications, which is the fastest growing area of robotic automation. An accurate movement can be accomplished by a stiff mechanical structure of a manipulator and using proper conventional control facilities. However, this might be too expensive and inflexible a solution in many cases due to the varying environmental conditions in the assembly site. This means that there is a rapidly growing need for sensor based control of robotic manipulators to achieve the highly accurate movements in the real assembly site.

The goal in our study is to achieve high accuracy movements of the robotic manipulator by an accurate visual sensor installed in the gripper. The visual sensor extracts 3D coordinates of the objects in the manipulation environment close to the grasping point. The sensor comprises two cameras and suitable lighting. The 3D coordinates are calculated based on the method of normal stereo disparity.

1. Dynamic position-based look-and-move control structure

The control structure of our system is the well-known dynamic position-based look-and-move [1] [3], which is shown in Fig. 1.

The visual control of robots is a subject largely investigated recently. In the literature the term visual servoing has also been used to mean basically the same thing. There are a number of studies and applications reported in [3]. The visual servoing has been used in applications like screwdriver placement, floppy disk insertion and six degree-of-freedom relative positioning by using fixed stereo vision [4].
The aim of this paper is to show briefly the control structure based on the visual guidance of the robotic manipulator and to describe the experimental setup as well as to present the recent results of our studies.

2 Description of the Method

2.1 Control Structure

A dynamic position-based look-and-move control structure (see Fig. 1) is applied to movement control of the visual sensor integrated in the robot gripper. In our case the open-loop fashioned control structure demands accurate movements of the robot.

The camera position respect to the robot base frame is calibrated by moving the camera above the known object. The orientation of the camera is determined with extrinsic camera calibration, when the X-Y plane of the robot and the reference object are parallel.

At the ‘look’ phase the images are captured and the 3D position difference between the target object and the fingers of the gripper is calculated. At the ‘move’ phase the differences are added to the current position of the robot and the movement is performed.

2.2 Visual Sensor Integrated to the Gripper

Our visual sensor comprises two compact cameras and LED type lighting which are integrated to the gripper. The gripper is linear and air-operated having machined fingers. (Fig. 2.).

The finger tips and the target object are visible to both the cameras. This is an advantage, because the exact pose of the target object can be determined after picking. In this case, the mechanical inaccuracy of the gripper does not affect the performance of the system.

The tilt angles of the cameras are about 23 degrees. The length of the fingers is 100 mm and the distance between the cameras is 150 mm (Fig. 2.). The relative position and orientation of the cameras is assumed to stay constant during the operation.

Figure 2. A schematic drawing of the visual gripper

The method of the 3D measurement is as follows. First, the intrinsic camera calibration parameters are solved for both the cameras and then the poses of the cameras respect to the world frame are solved with extrinsic camera calibration [2]. The position and orientation of the camera 2 frame respect to camera 1 frame are calculated by using the well-known homogenous matrix transformations.

The 3D coordinate values of the object point P are determined by using the 3D lines of sight. The intersection point of these lines produces the coordinates of the point P. Due to the image distortions and errors in determination of the camera poses there is no actual intersection point. Therefore the least squares (LS) fitted intersection point is used as the coordinates of the point P.

The performance of the visual sensor is crucial in order to achieve the accurate movements of visual guided robot. The correct camera calibration and successful feature extraction are key issues in achieving the goal.

Figure 3. The geometry of the 3D sensor
3 Experiments

3.1 Experimental Setup

The experimental setup consists of a SCARA type of a robot, two analog JAI microhead cameras with 7.5 mm focal length and PC. Image capturing was performed with Integral Technologies Flash Bus frame grabber. The image processing and robot control algorithm were run in PC. The robot motion controller and the PC communicates via serial port.

The camera calibration was performed with a flat reference object. It is a glasslike SiO$_2$-plate painted with chromium. It has 9 x 7 white circular dots on black background with a center-to-center distance of 10 mm and 6 mm diameter of each dot. The center-to-center accuracy and the accuracy of diameter of the dots are better than 0,5 $\mu$m. The flatness of the reference object is better than 5 $\mu$m. A diffuse back lighting system based on red LEDs was used to illuminate the reference object in these early experiments of ours.

A wooden gripper model was manufactured. The model contains adjustable clamps for the cameras and a stick describing the fingers.

3.2 Robot Movement

In order to achieve high accurate robot movements which are commanded by the vision sensor, the movement itself should be accurate relative to the robot base inside a specified region. For that reason, there was a need to compensate the robot X-Y plane inaccuracies. That was possible due to the high repeatability of the robot.

The compensation was carried out by the aid of the calibrated camera attached to robot end-effector, which was moved above our reference object. The accuracy of the camera and reference object based movement determination is better than 5 $\mu$m. The X-Y plane accuracy compensation test requires parallelism of the reference object and the robot X-Y plane. This was ensured with Keyence laser distance sensor with accuracy better than 30 $\mu$m.

3.3 Performance of the Visual Sensor

The performance of the visual sensor was tested by using the reference object as the actual object to be measured. The object was measured at three separate height levels, called zero, bottom and top level respectively. The distance between each of the separate levels was 2 mm. A manual coordinate meter with the accuracy of 2 $\mu$m was used to measure the height. Three tests were performed:

a) Height level test. The 3D coordinates were measured at each level. The height differences between two levels were calculated from the measured coordinates. These differences were compared to the known ones and the deviations between them were examined.

b) Dimension measurement test. All the possible dimensions in 3D at each height level from the object were measured. The deviations between the known and the measured dimensions were studied.

c) Flatness test. A LS plane was fitted to the 3D coordinates measured at each height level and the deviations of these coordinates from the corresponding LS plane were examined.

3.4 Control Method Verification

The wooden model of the gripper was manufactured to perform the tests needed for verification of the control method. The purpose of this gripper model was to test the functionality of the control method. In our tests a nut was attached to wooden fingers. The goal of the control task was to position one of the nut corners exactly above the centre of a metal ring while it was moved randomly from place to place inside the robot calibration area so that the ring was visible to both the cameras.

Figure 4. The first camera view of the nut and the metal ring
In Fig. 4 and Fig. 5 the corner of the nut and the center of the metal ring (marked with a dot) are extracted from the images.

4 Results

4.1 Robot Movement

The accuracy of the robot movement after the compensation is shown in Fig. 6.

![Figure 6. Results of the robot accuracy compensation](image)

Fig. 6 comprises 40 specified destination positions where the movement accuracy after compensation is determined. The positioning error at each destination position is marked with the square. The positioning error is calculated as a dimension between the destination and the reached position in 2D.

4.2 Performance of the Visual Sensor

The results of the height level test are shown in Table 1, where the markings "Bottom–Zero", "Zero-Top" and "Bottom-Top" describe the height level changes between the corresponding levels respectively. It can be seen from the results that there is no significant difference in the accuracy between the plane levels.

<table>
<thead>
<tr>
<th></th>
<th>Bottom - Zero</th>
<th>Zero-Top</th>
<th>Bottom-Top</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>2.014</td>
<td>2.007</td>
<td>4.020</td>
</tr>
<tr>
<td>Min</td>
<td>1.981</td>
<td>1.998</td>
<td>3.977</td>
</tr>
<tr>
<td>Mean</td>
<td>1.996</td>
<td>1.994</td>
<td>3.990</td>
</tr>
<tr>
<td>Std</td>
<td>0.005</td>
<td>0.004</td>
<td>0.006</td>
</tr>
<tr>
<td>Range</td>
<td>0.033</td>
<td>0.022</td>
<td>0.045</td>
</tr>
</tbody>
</table>

The results of the dimension measurement test are shown in Table 2, where the marking "Top", "Zero" and "Bottom" describe the level where the dimensions are measured correspondingly. It can be seen from the results that there is no significant difference in the accuracy of dimension measurements at each separate level.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Std</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>0.014</td>
<td>-0.009</td>
<td>0.001</td>
<td>0.003</td>
<td>0.023</td>
</tr>
<tr>
<td>Zero</td>
<td>0.011</td>
<td>-0.008</td>
<td>0.002</td>
<td>0.003</td>
<td>0.018</td>
</tr>
<tr>
<td>Bottom</td>
<td>0.009</td>
<td>-0.009</td>
<td>0.000</td>
<td>0.003</td>
<td>0.019</td>
</tr>
</tbody>
</table>

The results of the flatness measurement test at the "Zero" level are shown in Fig. 7.

![Figure 7. Results of the flatness test at the zero level](image)
The points marked with crosses describe the deviations from the LS plane. A error surface is fitted to 3D coordinates. The text "Base" in the figure means the distance between the origins of the two camera poses and "Img. dist." is the orthogonal imaging distance, which is the distance between the center of the baseline and the measured object as orthogonal to measured object. The accuracy figures of the flatness are: stdev 0.005 mm, max 0.019 mm, min -0.010 mm. There are no significant differences in the other two levels in the flatness examination.

It can be concluded from the results described above that our sensor is capable of measuring 3D coordinates within accuracy which is better than 23 micrometers (range).

4.3 Control Method Verification

The early experiments with the wooden model of the gripper show that our control method works properly. When the metal ring was randomly moved in X, Y and Z directions in the robot calibration area, the corner of the nut was successfully positioned above the center of the metal ring (see Fig. 4 and Fig. 5) with the accuracy better than 0.5 mm.

5 Summary and Conclusion

Our goal is to integrate an accurate visual sensor to a linear air operated gripper. The visual sensor comprises two compact analog video cameras and LED type lighting. The 3D coordinates of the objects are extracted based on the normal stereo disparity calculations. This 3D information is used to command the robot movement. The recent preliminary results of our experiments show that we are able to measure 3D object features within the accuracy of about 20 micrometers in the area of 90 x 70 mm² and that our control algorithm functions properly. The performance of the functionality was verified with our test where a wooden model of the gripper was used.

Our current results are promising in the way to achieve our final goal, which is to be able to realise the gripper with the integrated vision sensor. Our purpose is that the robot pick and place movements can be controlled based on the sensor measurements within the accuracy which will be better than 20 micrometers.

Acknowledgements

This study is a part of the Accurate optical 3-D measurement system for light assembly applications project. The project is financially supported by the Technology Development Centre of Finland (TEKES) and the companies involved in the study. Their support is gratefully acknowledged.

The authors are grateful to Mr. J. Sipola for making the programs for this study experiments.

References


