Underactuated Part Alignment System (UPAS) for Industrial Assembly Applications

Brian J. Slaboch
Department of Mechanical Engineering
Marquette University
Milwaukee, Wisconsin 53233
Email: Brian.Slaboch@Marquette.edu

Philip A. Voglewede*
Department of Mechanical Engineering
Marquette University
Milwaukee, Wisconsin 53233
Email: Philip.Voglewede@marquette.edu

ABSTRACT
This paper introduces the Underactuated Part Alignment System (UPAS) as a cost-effective and flexible approach to aligning parts in the vertical plane prior to an industrial robotic assembly task. The advantage of the UPAS is that it utilizes the degrees of freedom (DOFs) of a SCARA (Selective Compliant Assembly Robot Arm) type robot in conjunction with an external fixed post to achieve the desired part alignment. Additionally, the UPAS is not constrained to work with rigid, polygonal parts. Three path planning techniques will be presented that can be used with the UPAS to achieve the proper part rotation. The results from laboratory testing showed that the UPAS can be used to consistently achieve the desired part rotation to within 5% of the desired value.

1 INTRODUCTION
Four degree of freedom (DOFs) SCARA (Selective Compliant Assembly Robot Arm) type robots are commonly used industrial assembly robots due to their speed, accuracy, and robustness. [1]. The end-effector of the SCARA robot in Fig. 1 allows for translational motion, and it can be rotated about the z-axis (i.e., Schöenflies motion). SCARA type robots work well for industrial assembly tasks that take place along a vertical axis (i.e., the direction of the gravitational force). However, it is often necessary to orient parts along a non-vertical axis. This requires the part to be oriented in the vertical plane prior to assembly. The goal of the Underactuated Part Alignment System (UPAS) is to create a cost-effective and flexible approach to aligning parts in the vertical plane prior to an industrial assembly task.

* Address all correspondence to this author.
1.1 Part Orientation Techniques.

Researchers have developed different methods for orienting parts for assembly. One common approach is to use a vibratory bowl feeder. As parts are fed through the system, parts with the incorrect orientation are rejected. Vibratory bowl feeders are typically costly for flexible industrial assembly tasks because they are usually designed for one specific part. Additionally, vibratory bowl feeders are often responsible for 50% of the failures of assembly tasks [2].

In an effort to circumvent the need for vibratory bowl feeders, researchers have focused on industrial parts feeding by grasping and manipulation. Early end-effector designs mimicked the human hand. Examples of these are the Stanford/JPL hand [7], the Utah/MIT Hand [8], and the Barrett Hand [9]. While these end-effectors have many DOF, they are difficult to use in an industrial setting due to the required computational power and coordination of the DOF.

Much research has also been completed on part manipulation in the horizontal plane. Goldberg et. al [10] showed that a simple parallel gripper can be used to orient parts by using a sequence of normal pushes. A similar approach is taken by Akella [11] et al. in which parts are fed on a conveyor belt and manipulated using a one-joint robot. Lynch et al. [12] showed how to perform part manipulation in the horizontal plane by using a three DOF robot that has a passive revolute joint. Although the work done on manipulation within the horizontal plane is useful, these approaches are generally not applicable to manipulation in the vertical plane due to the effect of gravity.

1.2 Part Orientation in the Vertical Plane.

The work in this paper is primarily motivated by previous work done on part manipulation within the vertical plane. Erdmann [13] implemented a system that used two robots with flat palms to manipulate polygonal parts. Blind et al. [14] created a reconfigurable “pachinko machine” that utilizes a grid of retractable pins in the vertical plane to manipulate a part.

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1For a more comprehensive review of grasping and manipulation research see [3], [4], [5], and [6].
Moll and Erdmann [15] showed how to orient parts by dropping them from various heights onto specifically design surfaces. Other researchers have created robotic grippers that are specifically designed to orient parts in the vertical plane. Carlisle et al. [16] produced a pivoting gripper that uses ball bearings to rotate a polygonal part under the force of gravity. Rao and Goldberg [17] subsequently proved that the pivoting gripper could be used to orient a polygonal part arbitrarily in six DOF using a four DOF SCARA type robot. Ziesmer and Voglewede [18] improved upon this design by creating a metamorphic gripper that uses metamorphic joints that change between fixed joints and spherical joints, and in 2002 Zhang et al. [19] showed that it is possible to orient polygonal parts while grasping them.

Each of the aforementioned vertical plane robotic grippers are advantageous in an industrial setting. The following list outlines the advantages of these grippers:

1. The grippers are underactuated which reduces the overall complexity of the system.
2. Each gripper can provide an additional DOF to a SCARA type robot without adding an additional actuator.
3. Each approach provides a systematic method to achieve the appropriate part manipulation.
4. The need for vibratory bowl feeders may be reduced or eliminated.
5. The grippers are lightweight.
6. The grippers are low cost.

The disadvantage of these robotic grippers is that they are designed to work with rigid, polygonal parts. The UPAS described here has the same advantages of the other vertical plane robotic grippers, but it can also be used with non-rigid or non-polygonal parts. By decoupling the grasping and manipulation process much more flexibility can be added to the overall system. This is an important advantage the the UPAS has over existing designs. Additionally, the UPAS is designed such that simple kinematic algorithms can be used as a guide to help achieve the proper part rotation.

This paper is outlined as follows: In section 2 the general procedure for the UPAS will be explained. This will be followed by a more detailed kinematic analysis of the system in section 3 and a brief dynamic analysis in section 4. The experimental results will be provided in section 5, and in section 6 practical considerations will be discussed.

2 PROPOSED METHOD FOR PART ALIGNMENT

The goal of the UPAS is to create a simple, cost effective system that can be used in an industrial setting. In this system a part is first grasped by a standard binary gripper, and then the entire gripper (along with the part) is rotated by an external force. After part rotation occurs the gripper becomes fixed at the desired angle due to torque resistance that is supplied by a constant torque hinge. For the UPAS the following assumptions are made:

1. A robot producing Schöenflies motion is used for the assembly task (i.e., SCARA).
2. The assembly task requires that the part must be rotated in the vertical plane prior to assembly.
3. A gripper exists that can be used to grasp the part in its initial orientation.

4. The part’s initial position and orientation is known. A vision system may be used for this purpose.

The UPAS in Fig. 2 consists of a four-axis robot\(^2\), a fixed post, and the Underactuated Part Alignment Gripper (UPAG) shown in Fig. 3. The UPAG consists of a base, pivot arm, binary angular gripper, and a constant torque hinge (i.e., friction hinge). The UPAS aligns a part in the vertical plane by completing three tasks:

1. A gripper is used to grasp the part in its initial orientation (Fig. 2a).

2. The UPAG is moved until the pivot arm makes contact with the fixed post. The force on the pivot arm from the fixed post causes the constant torque hinge to rotate (Fig. 2b).

3. The UPAG is moved to a position in which the pivot arm no longer makes contact with the fixed post (Fig. 2c). The resistance torque from the constant torque hinge ensures that the gripper does not rotate due to inertial forces and gravity. The gripper has now been rotated by a desired angle \( \theta_d \) (Fig. 2c).

![Fig. 2. UPAS: The part is grasped in Fig. 2(a). The force from the fixed post causes the pivot arm to rotate in Fig. 2(b). In Fig. 2(c) the gripper has been rotated by an angle \( \theta_d \).](image)

This approach requires careful path planning to ensure that the gripper (and subsequently the grasped part) is rotated to the desired angle \( \theta_d \). The next section contains three different path planning techniques that can be used to rotate a part in the vertical plane.

\(^2\)For testing purposes the end-effector of a six-axis robot was constrained to move with four DOF (three translational and one rotational) to simulate a SCARA robot.
3 Gripper Orientation Techniques

Consider the UPAS schematic in Fig. 4. The fixed post has a radius, \( r \), and the pivot arm has a thickness, \( t \), and a length, \( L \). The distance between the centerline of the positioning hinge and the centerline of the fixed post is \( h \). The center of the constant torque hinge is point \( A \).

The purpose of the UPAS is to rotate the gripper around the \( z \)-axis by a desired angle of rotation \( \theta_d \). Positive rotation is defined by a counterclockwise rotation in the plane. Fig. 4 shows the \( \theta = 0 \) position. A cylindrical fixed post is aligned with the \( z \)-axis. As the UPAG moves in the \( xy \)-plane the pivot arm makes contact with the fixed post, and the force from the fixed post causes the gripper to rotate. To simplify the kinematics, the fixed post of radius \( r \) can be replaced by a circle of radius \( R \) where \( R = r + \frac{t}{2} \). The pivot arm can then replaced by a line as shown in Fig. 5(b).

There are different ways to move the UPAG in the \( xy \)-plane to achieve a desired angle of rotation. However, depending on the assembly application, certain paths are more suitable than others. This section will outline different path planning algorithms that can be used to achieve the the desired angle of rotation, \( \theta_d \). Note that this is a purely kinematic analysis. Frictional forces and the impact between the fixed post and the pivot arm will be ignored.
Fig. 5. Simplified Geometry: The fixed post of radius $r$ can be viewed as a circle of radius $R$ where $R = r + \frac{t}{2}$.

3.1 Straight Line Path Algorithm

One way to achieve the desired angle of rotation is to move the center of the constant torque hinge along a straight line from an initial point $A(x_i, y_i)$ to a point $B(x_f, y_f)$ as shown in Fig. 6.

Figure 7 shows the simplified schematic for the straight line path. The center of the constant torque hinge begins at a known point $A(x_i, y_i)$ and moves to a point $B(x_f, y_f)$ along a straight line of length $d$ that is at an angle $\alpha$ with respect to the vertical. This leads to the following relationship between $A(x_i, y_i)$ and $B(x_f, y_f)$ for the straight line path algorithm:

\begin{align*}
x_f &= x_i + d \sin \alpha \\
y_f &= y_i + d \cos \alpha.
\end{align*}
Fig. 7. Straight Line Path Schematic: The center of the constant torque hinge moves at an angle $\alpha$ with respect to the vertical.

By analyzing the geometry from Fig. 7 the distance, $d$, from $A(x_i, y_i)$ to $B(x_f, y_f)$ in terms of $h$, $R$, $\alpha$, and $\theta_d$ is

$$d = \frac{\sin \theta_d}{\sin(\pi - \alpha - \theta_d)} \left( h - R \tan \frac{\theta_d}{2} \right). \quad (3)$$

Thus, given $A(x_i, y_i)$, $R$, $h$, $\alpha$, and $\theta_d$ a designer can use Eqs. 1 and 2 to calculate $B(x_f, y_f)$ using the straight line path algorithm.

There are three sub-cases of the straight line path algorithm that will be examined in more detail. Each of the three sub-cases correspond to different values of $\alpha$. The first sub-case will be when $\alpha = 90^\circ$. This corresponds to horizontal motion. The second sub-case will correspond to $\alpha = 45^\circ$. This sub-case is used when $90^\circ$ of rotation is desired. The final sub-case will correspond to $\alpha = \frac{\pi}{2} - \theta_d$. This sub-case is useful in minimizing the amount of time required for rotation.

3.1.1 Case 1: Horizontal Line Path Algorithm ($\alpha = 90^\circ$).

The first path that will be examined in detail is the case in which the center of the constant torque hinge is moved along a horizontal line as shown in Fig. 8. It is assumed that the center of the constant torque hinge is moved far enough along the horizontal line that the pivot arm no longer makes contact with the fixed post as shown in Fig. 8(d). One advantage of the horizontal line path is that it is time independent. This path planning algorithm works well in cases where $90^\circ$ of rotation is not desired as will be explained later. The horizontal line path schematic is shown in Fig. 9. By setting $\alpha = 90^\circ$ Eqs. 1 and 2 reduce to

$$x_f = x_i + d \quad (4)$$

$$y_f = y_i. \quad (5)$$
Fig. 8. Horizontal Line Path: The center of the constant torque hinge is moved along a horizontal line.

Fig. 9. Horizontal Line Path Schematic: The center of the constant torque hinge moves from point A to point B along a horizontal line.

where

\[
d = \frac{\sin \theta_d}{\sin \left( \frac{\pi}{2} - \theta_d \right)} \left( h - R \tan \frac{\theta_d}{2} \right). \tag{6}
\]

However, it must be noted that Eqs. 4 and 5 are only valid when the fixed post remains in contact with the pivot arm. From Fig. 9 it can be shown that \( \theta_d \) is dependent on the values of \( L \), \( R \), and \( h \). The values of \( L \) and \( R \) are fixed, but by varying \( h \) different \( \theta_d \) values can be obtained.

\[
\theta_d = \arccos \left( \frac{h - R}{L} \right). \tag{7}
\]

Equation 7 shows that by using the straight line path algorithm there are limits on the value of \( \theta_d \) due to geometrical constraints on \( L \), \( R \), and \( h \). For this specific design the value of \( \theta_d \) is limited to 0.56 rad. (31°) < \( \theta_d \) < 1.29 rad. (74°) for horizontal line path motion. Due to the limitations of the horizontal line path motion another path planning algorithm needs to be developed that allows for an increased range of \( \theta_d \).
3.1.2 Case 2: 90° Rotation Algorithm ($\alpha = 45^\circ$).

Many assembly tasks require the part be rotated 90° from a vertical position to a horizontal position. One possible path to achieve a 90° rotation is to move the center of the constant torque hinge at a 45° angle (with respect to the y-axis) as shown in Figures 10 and 11. Other values of $\alpha$ may also be used, but there are limitations on the value of $\alpha$ due to geometrical constraints. This will be discussed in further detail in the next section.

![Diagram of 45° Angle Path](image)

Fig. 10. 45° Angle Path: The center of the constant torque hinge is moved from an initial point $A$ to a final point $B$ along a 45° line.

![Diagram of 45° Angle Path](image)

Fig. 11. 45° Angle Path: The center of the constant torque hinge moves at a 45° angle with respect to the vertical.

By setting $\alpha = 45^\circ$ Eqs. 1 and 2 reduce to

$$x_f = x_i + \frac{d \sqrt{2}}{2}$$  \hspace{1cm} (8)

$$y_f = y_i + \frac{d \sqrt{2}}{2}$$  \hspace{1cm} (9)

$$d = \frac{\sin \theta_d}{\sin (\theta_d + \frac{\pi}{4})} \left( h - R \tan \left( \frac{\theta_d}{2} \right) \right).$$  \hspace{1cm} (10)

It should be noted that by using Eqs. 8, 9, and 10 any value of $\theta_d$ may be obtained between 0° and 90°. However, substituting
\( \theta_d = 90^\circ \) into Eq. 10 and then placing this result into Eqs. 8 and 9 gives

\[
x_f = x_i + h - R \\
y_f = y_i + h - R.
\] (11) (12)

Equations 11 and 12 show the simplicity of the proposed method. Given the values of \( h \) and \( R \) a designer can quickly program a 90\(^\circ\) rotation. Equations 11 and 12 also show that to use the 90\(^\circ\) rotation algorithm \( h \) must be greater than \( R \). This section presented an algorithm to achieve a rotation from 0\(^\circ\) to 90\(^\circ\). This algorithm works especially well for cases in which 90\(^\circ\) of rotation is desired.

The goal of any assembly task is to complete the task as quickly as possible. The next section will introduce what will be called the shortest distance path algorithm. The goal of this path is to determine the shortest possible distance the UPAG would need to move to achieve the desired angle of rotation, \( \theta_d \).

3.1.3 Case 3: Shortest Distance Path Algorithm \((\alpha = \frac{\pi}{2} - \theta_d)\).

The goal of the path described in this section is to determine the shortest possible distance the UPAG would need to move to achieve the desired angle of rotation, \( \theta_d \). This path is advantageous because minimizing the distance needed to achieve the angle of rotation decreases the cycle time. Consider the fixed solid line that is at an angle of \( \theta_d \) in Fig. 12 and denote it as the line of rotation. This line is offset and tangent to the fixed post. If the constant torque hinge is moved from its initial position to any position on the line of rotation the gripper will be rotated by an angle \( \theta_d \). The quickest way to achieve a rotation of \( \theta_d \) is to move the constant torque hinge from its initial position in a straight line perpendicular to the line of rotation.
Figure 13 shows the schematic for the shortest distance path. From the geometry it can be shown that in the case of the shortest distance path equations

\[ x_f = x_i + d \cos \theta_d \]  
\[ y_f = y_i + d \sin \theta_d. \]  
\[ d = \sin \theta_d \left( h - R \tan \theta_d \right). \]

Additionally, there are physical constraints on the value of \( \alpha \) to ensure that the constant torque hinge does not make contact with the fixed post. From Fig. 14

\[ f = \sqrt{h^2 + R^2}, \]

and

\[ \sin \left( \frac{\alpha_{\text{min}}}{2} \right) = \frac{R}{\sqrt{h^2 + R^2}}, \]
which leads to

$$\alpha_{\text{min}} = 2 \arcsin \frac{R}{h^2 + R^2}$$  \hspace{1cm} (18)

It is critical that \( \alpha > \alpha_{\text{min}} \) to ensure that the positioning hinge does not make contact with the fixed post. In this section the shortest distance path algorithm was presented as a way to rotate the gripper by an amount \( \theta_d \) by moving the UPAG the shortest distance. The advantage of this algorithm is that the time for rotation is minimized, but the disadvantage is that there is a limit on the range of motion for \( \theta_d \).

### 3.2 Discussion of Straight Line Path Algorithms

In section 3.1 three different straight line path algorithms were presented. If possible, the horizontal line path should be the chosen kinematic algorithm. The reason for this is that it requires simple programming and is generally more efficient than either the \( 90^\circ \) rotation path algorithm or the shortest distance path algorithm. The reason for this is that the horizontal line path algorithm is time independent. However, in cases in which \( 90^\circ \) of rotation is necessary the \( 45^\circ \) path should be used. Each of these kinematic algorithms should be used as guidelines to help designers determine approximately where to move the end-effector of the robot to achieve the desired angle of rotation.

### 3.3 Return Path Algorithm

Each of the presented path planning algorithms provided a different way to rotate the gripper to a desired angle \( \theta_d \). However, once the gripper is at a desired angle there needs to be a path planning algorithm used to return the gripper to the \( \theta = 0 \) position. Just as there are numerous ways to achieve the initial gripper rotation, there are an infinite number of return path algorithms that could be used.

The algorithm presented in this section is useful for the situation in which the gripper must be returned to the same height as in the initial position. It is assumed that the gripper is at some angle, \( \theta \), with respect to the \( y \)-axis. Additionally, it is assumed that the initial position occurs when point \( c \) makes contact with the fixed post. Point \( c \) is the point on the pivot arm that is a distance \( h \) from from the center of the constant torque hinge. From the geometry shown in Fig. 15 the following
Fig. 15. Return Path Schematic

Equations can be written for $D(x_2, y_2)$ and $E(x_f, y_f)$:

$$x_2 = x_i + R(1 + \cos \theta) + h\sin \theta$$  \hspace{1cm} (19)

$$y_2 = y_i + h(1 - \cos \theta) + R\sin \theta$$  \hspace{1cm} (20)

$$x_f = x_i + 2R$$  \hspace{1cm} (21)

$$y_f = y_i.$$  \hspace{1cm} (22)

Equations 19-22 show that the return algorithm is a convenient way to return the gripper to the $\theta = 0$ position.

4 DYNAMIC ANALYSIS

The previous section provided the kinematic analysis to be able to rotate the gripper to the desired angle. However, dynamic effects may cause undesired motion. The constant torque hinge must provide enough torque resistance to resist gravity and inertial forces caused by rapid movements of the robot. In this analysis we will ignore any impact that occurs between the fixed post and the pivot arm. Figure 16 shows a schematic of a SCARA type robot with the UPAG attached at point A. Link $l_4$ represents the distance between the center of the constant torque hinge and the center of mass of the UPAG.

Fig. 16. SCARA Robot with UPAG attachment. The center of mass of the UPAS is located at point $d$. 

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The resistance torque of the gripper will be denoted by $\tau$, the mass is $m_4$, the moment of inertia is $I_d$, and $\ddot{x}_A$ and $\ddot{y}_A$ are the linear accelerations of point $A$ in the $x$ and $y$ directions, respectively.

As the pivot arm makes contact with the fixed post the constant torque hinge must supply enough resistance torque to ensure that the gripper does not rotate due to inertial forces. By performing a standard Newton-Euler dynamic analysis\(^3\) it can be found in Eq. 23 that

$$\tau > (m_4 l_4^2 + I_d)\dot{\theta} + m_4 l_4 (\ddot{x}_A \cos \theta + \ddot{y}_A \sin \theta) + m_4 g l_4 \sin \theta.$$  \hspace{1cm} (23)

Equation 23 shows that given the system parameters one can quickly determine the amount of torque necessary to ensure that the gripper will not rotate due to inertial forces during post contact.

In many assembly tasks, however, the end-effector of the robot will be moved relatively slowly through the gripper rotation. Once the gripper is rotated to the desired angle the end-effector will move as quickly as possible in open space to finish the assembly process. The rapid movements that occur in open space could potentially impart unwanted rotation. The necessary resistance torque in free space was determine using Lagrange’s equations of motion. In general the kinetic and potential energy much be found for each link. However, in this particular case the kinetic and potential energy of links one through three can be ignored because the kinetic and potential energy terms are not dependent on either $\theta_4$ or $\dot{\theta}_4$. The resulting equation for $\tau$ is then given in Eq. 24 as

$$\tau = I_d m_4 [(g + \ddot{l}_3) s_4 + c_4 l_1 (\dot{\theta}_1 s_{23} - \dot{\theta}_1^3 c_{23}) + l_2 s_3 (\dot{\theta}_1 + \dot{\theta}_2) - c_3 (\dot{\theta}_1^2 + \dot{\theta}_2^2)] - l_4 s_4 [(\dot{\theta}_1^3 + \dot{\theta}_2^3) + 2 \dot{\theta}_3 (\dot{\theta}_1 + \dot{\theta}_2)] - 2 \dot{\theta}_1 \dot{\theta}_2 (l_2 c_3 + l_4 s_4)].$$ \hspace{1cm} (24)

Equation 24 is important from a design perspective. Given the robot joint angles, velocities, and accelerations it is possible to create a torque profile showing the required resistance torque necessary so that the gripper does not move due to inertial forces and gravity. By using Eq. 24, a designer can select an appropriate constant torque hinge for their particular assembly task.

5 Experimental Testing

The prototype system is shown in Fig. 17 (a). A Schunk PWG-60s angular two finger binary gripper was used in this design, and a Reell constant torque hinge with 1.5 N-m of torque resistance was used. The system has a weight of 4.09 N

\(^3\)See [20] for a more detailed explanation of the dynamic analysis.
Fig. 17. General testing procedure: The center of the constant torque hinge is moved from an initial \(A(x_i, y_i)\) position to a final \(B(x_f, y_f)\) position to achieve the desired rotation \(\theta_d\).

Fig. 18. Generalized testing results: Adding a one second delay reduced the percent error to approximately 5%.

(0.92 lb). A incremental encoder was used to record the angular position of the pivot arm with respect the vertical axis. Five different tests were completed to determine the accuracy and repeatability of the proposed method as shown in Table 1. In each test the speed of the robot was set to 10% of the maximum speed to reduce impact. The center of the constant torque hinge begins an initial point \(A(x_i, y_i)\) as shown in Fig. 17(a). The robot then moves to a point \(B(x_f, y_f)\) (Fig. 17(b)) as
calculated by using an appropriate form of Eqs. 1 and 2. The end-effector then moves into free space as shown in Fig. 17(c). In tests that are noted with “Delay” a one second delay was added after reaching point B.

Figure 18 shows a representative plot of $\theta$ vs. $t$ where $\theta$ is the counterclockwise angle around the $z$-axis, and $t$ is the time. The specific values of $\theta_d$ (desired angle), $\theta_p$ (peak angle), and $\theta_{dm}$ (measured desired angle) for each test are provided in Table 1. For both the 90° rotation testing as well as the shortest distance path testing with no delay there were significant inertial effects that caused a large error. However, by adding a one second delay the percent error drops to a reasonable level of approximately 5%. The most successful test was the horizontal line path testing as a low percent error (4.4%) was achieved with no delay. Each of the different tests was repeated three times. The standard deviation between consistent points on different runs is given in the last column of Table 1. This low standard deviation shows that the tests are repeatable in a controlled setting.

<table>
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<th>Test</th>
<th>$\theta_d$</th>
<th>$\theta_{dm}$</th>
<th>% error ($\theta_{dm}$)</th>
<th>$\theta_p$</th>
<th>% error ($\theta_p$)</th>
<th>$\sigma$</th>
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<td>Horizontal line path test (No Delay)</td>
<td>70.3°</td>
<td>67.2°</td>
<td>4.4%</td>
<td>70.7°</td>
<td>0.56%</td>
<td>0.0587°</td>
</tr>
<tr>
<td>90° rotation algorithm testing (No Delay)</td>
<td>45°</td>
<td>37.8°</td>
<td>16%</td>
<td>39.55°</td>
<td>12.1%</td>
<td>0.035°</td>
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<tr>
<td>90° rotation algorithm testing (Delay)</td>
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<td>42.7°</td>
<td>5.1%</td>
<td>44.45°</td>
<td>1.22%</td>
<td>0.042°</td>
</tr>
<tr>
<td>Shortest distance path algorithm testing (No Delay)</td>
<td>30°</td>
<td>24.32°</td>
<td>18.93%</td>
<td>26.43°</td>
<td>11.9%</td>
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<tr>
<td>Shortest distance path algorithm testing (Delay)</td>
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<td>28.7°</td>
<td>4.33%</td>
<td>30.8°</td>
<td>2.67%</td>
<td>0.049°</td>
</tr>
</tbody>
</table>

6 Practical Considerations

The kinematic algorithms can be used to achieve the desired angle of rotation to approximately 5% of the desired value. For all practical purposes these kinematic algorithms should be used as a guide so that one can determine approximately how to move the end-effector to achieve the desired rotation. From there one can manually adjust the system to account for springback as well as inertial effects. There are too many factors involved in achieving a perfect open loop model, but the kinematic equations are a nice guide. There are also several key issues that must considered prior to using the UPAS system. One area of concern is that forces during assembly may cause the passive joint to rotate. This may be a factor in some assembly operations, and would need to be taken into consideration. Additionally, it should be noted that the system
will only be as accurate as the SCARA robot itself. SCARA robots have built-in compliance that must be considered when using the UPAS system.

7 Conclusion

This paper introduces the Underactuated Part Alignment System (UPAS) as a cost-effective and flexible approach to aligning parts in the vertical plane prior to assembly. The advantage of the UPAS over existing approaches is that rigid, polyhedral parts are not required for operation. Additionally, the path planning algorithms make this system easy to use in an industrial setting. Path planning algorithms were presented that may be used with the UPAS to achieve the desired part alignment. Tests were performed that showed the device works in a laboratory setting. Using only the kinematic equations of the system parts were able to be rotated to within 5% of the desired value. Future work will focus on finding ways to reduce the cycle time and increase the accuracy of the system.

References


