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Axis transformation for delta robots with three rotary axes

Overview of delta robots with three rotary axes

ID	Delta_ThreeAxisRotational
Type	Basic transformation
License	SWL-XCx-MOT-KINxLEVEL2xxx-NNNN
Required axes	3 (rotary axes)
Compatible with orientation transformations	Yes

Robot structure

A delta robot with three axes of rotation (called "3-axis delta robot" for the rest of the section) consists of a fixed upper platform, three rotary axes Red1, Red2, Red3 (also called shoulders), three upper arms, three elbows, three lower arms and the movable lower platform. The upper arms are each connected to a rotary axis (shoulder). The elbows are located between the upper and lower arms. The lower, movable platform is connected to the robot via the forearms. The shoulders are at a 120° angle to each other. In a 3-axis delta robot, the three rotary axes Red1, Red2 and Red3 are driven. This allows the lower platform to be positioned in the room. The elbows can swivel freely around two axes. As the lower arms consist of two parallel spokes, the design of the robot ensures that the lower platform is always parallel to the upper platform. This means that it is not possible to change the orientation of the flange on the 3-axis delta robot.

Fig. 85: 3-axis delta robot with rotary axes in the zero position

Robot parameters

Fig. 86: 3-axis delta robot with rotary axes

The following assumptions are made so that the axis transformation can be carried out correctly:

- The rotary axis defined as Rot1 is located opposite the X-axis at a distance l1 from the robot origin. (see Fig. 86)
- The axes Red1, Red2 and Red3 are offset from each other by 120°, with Red2 offset in the negative y-direction (counterclockwise when viewed from above)
- The length l2 is identical for all three arms of the robot
- The length l3 is identical for all three arms of the robot
- In the zero position of the Red1, Red2 and Red3 axes, the upper arms are aligned horizontally (in the same plane as the upper platform)
- In the positive position of the rotary axes Red1, Red2, Red3, the upper arms point downwards. For example, if the axis has a value of 90°, the corresponding upper arm points straight down, opposite the Z-axis

The following parameters are required to configure the 3-axis delta robot:

Parameters	Description	Condition
l1	The radius of the upper platform to which the rotary axes Red1, Red2, Red3 are attached	l1 > 0
l2	The length of the upper arms, between the red1/red2/red3 axis and the elbow	l2 > 0
l3	The length of the forearms, between the elbow and the edge of the lower, movable platform	l3 > 0
l4	The radius of the lower platform	l4 > 0

Additional restriction of the parameters:

l1 ≠ l4 or l2 ≠ l3	This condition has to be met for the axis transformation to work. If the condition is not fulfilled, then : ■ the size of the upper and lower platform is identical ■ the upper arms and forearms are the same length Then the condition is not fulfilled. In this case, the robot has a special structural singularity: As soon as all axis values are less than or equal to 0, the solution of the forward transformation is always the origin of the robot

Solution selection

With the 3-axis delta robot, there are several solutions for both forward and backward transformation.

Forward transformation

For the forward transformation, there are one or two different solutions for a specified axis position:

Fig. 87: Upper solution of the forward transformation for 3-axis delta robots with rotary axes

Fig. 88: Lower solution of the forward transformation for 3-axis delta robots with rotary axes

The position of the elbows is clearly determined by the position of the rotatary axes Red1, Red2, Red3. However, the movable platform could be located either above the elbows (Fig. 87) or below the elbows (Fig. 88).

In the axis transformation, it is assumed that the robot is always in the lower solution (Fig. 88) .

Inverse position kinematics

For the backward transformation, there are up to 2 solutions per arm of the robot for a specified Cartesian position. This results in a maximum of 2^3 = 8 different solutions in which the arms are angled inwards or outwards.

Fig. 89: Solution selection Reverse transformation for 3-axis delta robots with rotary axes

The axis transformation always selects the outer solution for all three arms of the robot. Moving to an inner elbow position is possible, for example, using movement commands in the axis space. If the robot is in this situation, motions in Cartesian space are no longer possible, as these would cause a change to the outer solution.

Singularities of a 3-axis delta robot with rotary axes

With a 3-axis delta robot, singularities occur at the upper and lower edge of the workspace.

Singularities at the lower edge of the workspace

These singularities can also be referred to as elbow singularities. These singularities occur when the shoulder, elbow and connection point to the moving platform are in line for at least one arm of the 3-axis delta robot. In addition to the restrictions in the direction of movement, it would be possible in this singularity for a change from the outer to the inner elbow solution to take place.

Fig. 90: Elbow singularity in the 3-axis delta robot (outstretched arm)

At Fig. 90, the right arm of the 3-axis Delta robot is fully extended. It is no longer possible to move downwards in the direction of the outstretched arm. In addition, an instantaneous upward motion in the direction of the outstretched arm is not possible, as the shoulder of the outstretched arm would have to rotate too quickly.

Singularities at the upper edge of the workspace

The design of the robot must be taken into account for the singularities at the upper edge of the workspace. For 3-axis

delta robots with the property l1 + l2 < l3 + l4, the following singularity can occur at the upper edge of the workspace:

Fig. 91: Singularity at the upper edge of the workspace for short-arm 3-axis delta robots

In this type of singularity, the elbow is completely folded in. The shoulder, elbow and connection point to the moving platform are in line here. In this case, upward movement in the direction of the folded arm is no longer possible. In addition, an instantaneous motion downwards in the direction of the folded arm is not possible, as the shoulder of the folded arm would have to rotate too quickly. In this type of singularity, a change from the outer to the inner elbow solution could occur. For 3-axis delta robots with the property l1 + l2 > l3 + l4, the following singularity can occur at the upper edge of the workspace:

Fig. 92: Singularity at the upper edge of the workspace for long-arm 3-axis delta robots

This singularity occurs when the forearms are positioned in such a way that the elbows can no longer be moved outwards. In this position, it is not possible to predict in which direction the moving platform moves. Transitions from the lower to the upper solution of the forward transformation can therefore occur here. Linear motions can no longer be performed as soon as the robot is in the upper solution.

Axis transformation for delta robots with two rotary axes

Overview of delta robots with two rotary axes

ID	Delta_TwoAxisRotational
Type	Basic transformation
License	SWL-XCx-MOT-KINxLEVEL2xxx-NNNN
Required axes	2 (rotary axes)
Compatible with orientation transformations	Yes

Robot structure

A delta robot with two rotary axes (called "2-axis delta robot" for the rest of the section) consists of a fixed upper platform, two rotary axes Red1 and Red2 (also called shoulders), two upper arms, two elbows, two lower arms and the movable lower platform. The upper arms are each connected to a rotary axis (shoulder). The elbows are located between the upper and lower arms. The lower, movable platform is connected to the robot via the forearms. The shoulders are at a 180° angle to each other. In a 2-axis delta robot, the two rotary axes Red1 and Red2 are driven. This allows the lower platform to be positioned in the X-Z plane. The elbows can pivot freely. A parallel design on the lower arms ensures that the lower platform is always parallel to the upper platform. This means that it is not possible to change the orientation of the flange on the 2-axis delta robot.

Fig. 93: 2-axis delta robot with rotary axes in the zero position

Robot parameters

Fig. 94: 2-axis delta robot with rotary axes

The following assumptions are made so that the axis transformation can be carried out correctly:

- The rotary axis defined as Rot1 is located opposite the x-axis at a distance l1 from the robot origin. (see Fig. 93)
- The Red1 and Red2 axes are offset from each other by 180°, with Red2 pointing in the positive x-direction
- The length l2 is identical for all three arms of the robot
- The length l3 is identical for all three arms of the robot
- In the zero position of the Red1 and Red2 axes, the upper arms are aligned horizontally (in the same plane as the upper platform)
- In the positive position of the rotary axes Red1 and Red2, the upper arms point downwards. For example, if the axis has a value of 90°, the corresponding upper arm points straight down, opposite the Z-axis

The following parameters are required to configure the 2-axis delta robot:

Parameters	Description	Condition

Parameters	Description	Condition
l1	The radius of the upper platform to which the rotary axes Red1, Red2 are attached	l1 ≥ 0
l2	The length of the upper arms, between the red1/red2 axis and the elbow	l2 > 0
l3	The length of the forearms, between the elbow and the edge of the lower, movable platform	l3 > 0
l4	The radius of the lower platform	l4 ≥ 0

Additional restriction of the parameters:

l1 ≠ l4 or l2 ≠ l3

This condition has to be met for the axis transformation to work.

If the condition is not fulfilled, then :

- the size of the upper and lower platform is identical
- the upper arms and forearms are the same length

Then the condition is not fulfilled.

In this case, the robot has a special structural singularity: As soon as all axis values are less than or equal to 0, the solution of the forward transformation is always the origin of the robot

Solution selection

With the 2-axis delta robot, there are several solutions for both forward and backward transformation.

Forward transformation

For the forward transformation, there are one or two different solutions for a specified axis position:

Fig. 95: Upper solution of the forward transformation for 2-axis delta robots with rotary axes

Fig. 96: Lower solution of the forward transformation for 2-axis delta robots with rotary axes

The position of the elbows is clearly determined by the position of the rotary axes Red1 and Red2. However, the movable platform could be located either above the elbows (Fig. 95) or below the elbows (Fig. 96).

In the axis transformation, it is assumed that the robot is always in the lower solution (Fig. 96) .

Inverse position kinematics

For the backward transformation, there are up to 2 solutions per arm of the robot for a specified Cartesian position. This results in a maximum of $2^2 = 4$ different solutions in which the arms are angled inwards or outwards.

Fig. 97: Solution selection Reverse transformation for 2-axis delta robots with rotary axes

The axis transformation always selects the outer solution for both arms of the robot. Moving to an inner elbow position is possible, for example, using movement commands in the axis space. If the robot is in this situation, motions in Cartesian space are no longer possible, as these would cause a change to the outer solution.

Singularities of a 2-axis delta robot with rotary axes

With a 2-axis delta robot, singularities occur at the upper and lower edge of the workspace

Singularities at the lower edge of the workspace

These singularities can also be referred to as elbow singularities. They occur when the shoulder, elbow and connection point to the moving platform are in line for at least one arm of the 2-axis delta robot. In addition to the restrictions in the

motion direction, it would be possible in this singularity for a change from the outer to the inner elbow solution to take place.

Fig. 98: Elbow singularity in the 2-axis delta robot (outstretched arm)

At Fig. 98, the right arm of the 2-axis Delta robot is fully extended. It is no longer possible to move downwards in the direction of the outstretched arm. In addition, an instantaneous motion upwards in the direction of the outstretched arm is not possible, as the shoulder of the outstretched arm would have to rotate too quickly.

Singularities at the upper edge of the workspace

The design of the robot must be taken into account for the singularities at the upper edge of the workspace. For 2-axis delta robots with the property l1 + l2 < l3 + l4, the following singularity can occur at the upper edge of the workspace:

Fig. 99: Singularity at the upper edge of the workspace for short-arm 2-axis delta robots

In this type of singularity, the elbow is completely folded in. The shoulder, elbow and connection point to the moving platform are in line here. In this case, upward movement in the direction of the folded arm is no longer possible. In addition, an instantaneous motion downwards in the direction of the folded arm is not possible, as the shoulder of the folded arm would have to rotate too quickly. In this type of singularity, a change from the outer to the inner elbow solution could occur. For 2-axis delta robots with the property l1 + l2 > l3 + l4, the following singularity can occur at the upper edge of the workspace:

Fig. 100: Singularity at the upper edge of the workspace for long-arm 2-axis delta robots

This singularity occurs when the forearms are positioned in such a way that the elbows can no longer be moved outwards. In this position, it is not possible to predict in which direction the moving platform moves. Transitions from the lower to the upper solution of the forward transformation can therefore occur here. Linear motions can no longer be

performed as soon as the robot is in the upper solution.