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# Designing of Delta Manipulator as Human-Robot Interaction for Collaborative Mobile Robot

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**Abstract:** This research aims to develop an adaptable and advanced human-robot interaction system for collaborative mobile robots. A delta manipulator with a series elastic actuator is designed as a collaborative medium between humans and mobile robots. The design of the delta manipulator as a human-robot interaction interface and its kinematics are presented. Three control strategies for translational motion and two control strategies for rotational motion are studied and discussed based on their advantages and disadvantages, depending on specific application requirements. This design approach enables the creation of a comprehensive controller system that can effectively command the mobile robot to perform a wide range of movements and maneuvers, enhancing its overall performance and versatility. The resulting system efficiently accomplishes complex tasks in various scenarios, making it a valuable tool for a range of applications.

**Keywords: Autonomous mobile robot (AMR), Series-elastic actuators, Force-transfer controller, Holonomic mobile robot, Collaborative robot**

## 1. INTRODUCTION

In recent years, the use of mobile robot has become increasingly prevalent across a wide range of industries. Autonomous mobile robots (AMRs) are designed to perform tasks autonomously, without human intervention, using a combination of sensors, navigation systems, and control algorithms. They can perform a variety of tasks, especially material handling, transportation, which are most use cases in industrial. However, using mobile robot still requires skilled labor to control and program the robot to perform a variety task. To overcome this limitation, the Collaborative robots (Cobot) are new trend in industrial as they are designed to work alongside humans, enabling direct physical interaction and collaboration in shared workspaces.

The primary objective of this study is to make a significant contribution to the development of advanced and flexible control systems for collaborative mobile robots, especially in the context of human-robot collaboration for transportation tasks. The focus is on enhancing the capabilities of these robots to work alongside humans, enabling efficient and effective cooperation in various transportation scenarios. In order that the human can interact with mobile robot collaboratively, the human-robot interaction mechanism needs to be designed properly. The work in [1] presents the design considerations for the manipulator of mobile robot to achieve collaborative behaviors. It is discussed in [2], that the direct physical interaction required less time, provided more accuracy and less workload for users compared to other contactless interactions, namely the person following approach, and pointing control. The natural way for human to interact with the mobile robot physically is by utilizing force sensing and movement tracking. In this work, we design the delta manipulator with series-elastic actuators as human-robot interaction for control the motion of mobile robot. This design approach enabled us to create a comprehensive controller system that can effectively command the mobile robot to perform a wide range of movements and maneuvers, enhancing its overall performance and versatility. The resulting system can efficiently accomplish complex tasks in various scenarios, making it a valuable tool for a range of applications.

This paper is organized as follows: after the introduction, we provide a detailed description of the design and implementation of our human-robot interface mechanism, highlighting its key features and capabilities in section 2. Then, we present the control strategy to convert the force and motion from human to command the motion of the mobile robot. These are translational and rotational motion, which are discussed in section 3 and section 4 respectively. Finally, we conclude by summarizing the main findings of our research and highlighting its potential applications.

## 2. DESIGN OF HUMAN INTERFACE FOR COLLABORATIVE MOBILE ROBOT

The aim of this work is to design a collaborative medium between human and the mobile robot. It



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needs to interact with humans and convert the force or motion from human to control signal for the motion of the mobile robot. A Series-elastic actuators (SEA) is known as an appropriate solution for force control [3]. By using a series elastic element, the controller can measure the force being applied to the object which is interacting with and adjust its force accordingly. As the main task of the AMR, is moving in plane, the delta parallel-liked is designed as manipulator, simultaneously by integrating the series-elastic actuator to the manipulator, it can be used as the collaborative medium that can interact with the humans. This design builds on the advantages of Delta manipulator to offer new possibilities for collaboration and interaction between humans and robots in a range of settings. With the delta parallel manipulator with SEA, the operator can command the motion of the AMR by applying physical move to the manipulator, which is more intuitive, more user friendly and easier for the robot operator compared to another type of control mechanisms.

### 2.1 Series-elastic actuator power transmission joint.

The series-elastic actuator for the delta manipulator is realized by designing the power transmission of the joint as shown in Fig.1. The SEA power transmission consists of two parts: a yoke and a proximal link, which are connected by a spring. The yoke is attached directly to a DC motor, which transmits torque through the spring to the proximal link as shown in Fig.2. Overall, for the delta manipulator, we have three arms ($i = 1,2,3$) and therefore three such transmission joints, which lay in triangle form as shown in Fig.3

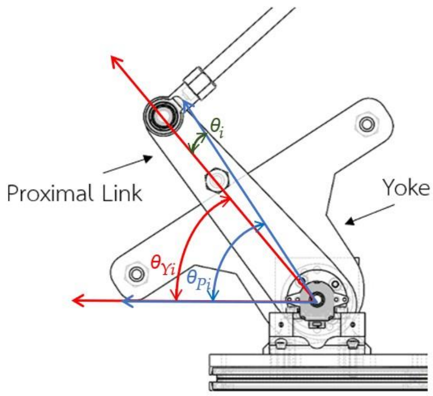


*Figure 1 Power transmission joint assembly, consisting of a yoke and a proximal link.*

In turn, when some force or movement is exerted on the delta manipulator, the movement or the force can be obtained by the difference between the yoke angle ($\theta_{Yi}$) and the proximal-link angle ($\theta_{Pi}$). To obtain the angle information, an absolute encoder is installed on each link. At the end, the movement at the end effector of the manipulator can be calculated from the data from six encoders.

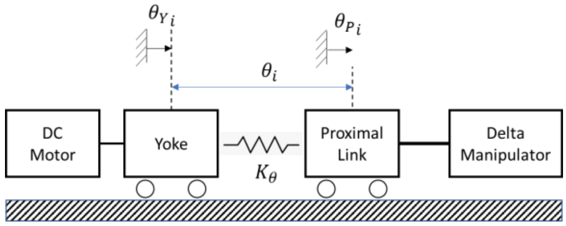


*Figure 2 Schematic diagram of Series-elastic actuator (SEA) power transmission joint.*

### 2.2 Kinematics of Delta manipulator

As illustrated in Fig.3, the revolute-input delta manipulator is composed of three identical legs in parallel between the fixed base and the moving end-effector platform. The revolute joints are fixed at the base platform with the radius $\boldsymbol{f}$. In this work, our SEA-power transmission joint is used as the actuating joint, which drives the link (length $\boldsymbol{r_f}$) which is coupled to an end-effector platform (radius e) via the other link with the length of $\boldsymbol{r_e}$ with universal joints at each end. These two links serve as the leg of the delta manipulator. The delta-style manipulator implements a parallelogram architecture to restrain the orientation of the end-effector platform to remain parallel to the base platform.

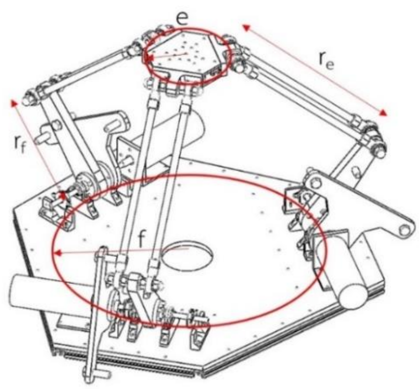


*Figure 3 SEA-Delta Manipulator*

The inverse position kinematics for a delta manipulator with three rotary actuators is the mapping from the end-effector coordinates in task space $[x_e, y_e, z_e] \in \mathbb{R}^{3\times1}$ to joint angles $[\theta_1, \theta_2, \theta_3] \in \mathbb{R}^{3\times1}$. It is discussed in [4], [5] and [6] that the joint angles can be computed by the equation:

$$\theta_i = \arccos\left(\frac{-(r_e^2 - z_i^2) + r_f^2 + (x_i + e - f)^2 + y_i^2}{2r_f\sqrt{(x_i + e - f)^2 + y_i^2}}\right) - \arctan\left(\frac{y_i}{x_i + e - f}\right) \quad (1)$$

On the other hand, like most of parallel robots' architecture, the forward position kinematics of the delta manipulator could not be easily computed. But for the translational-only motion of the 3-DoF Delta



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manipulator, there is an analytical solution for which the correct solution set is efficiently chosen. Williams et al. [7] proposed Three-Spheres Intersection Algorithm for computing the forward kinematic for delta manipulator. It described by the intersection point of three spheres of radius $r_e$ whose origins lie at the distal ends of the base link. Figure 4 shows the geometrical relation of the first arm Delta manipulator and the sphere.

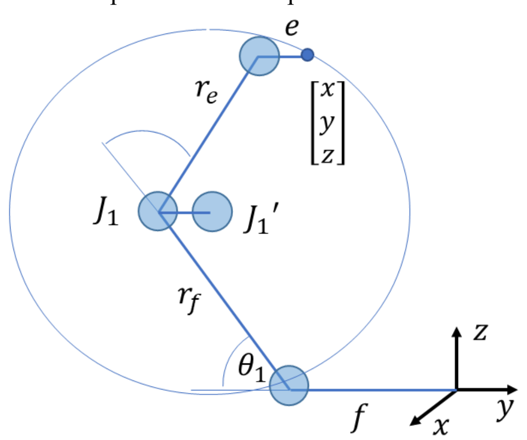


*Figure 4 Geometrical relation of the 1st arm Delta Manipulator for forward kinematic*

From figure 4, the coordinate of the 1st sphere center is:

$$J_1' = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = \begin{bmatrix} 0 \\ -(f - e + r_f \cos(\theta_1)) \\ -r_f \sin(\theta_1) \end{bmatrix} \quad (2)$$

The coordinate of the 2nd and 3rd sphere center can be derived similarly with different of the angle of 120° as follows:

$$J_2' = \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = \begin{bmatrix} (f - e + r_f \cos(\theta_2)) \cos(30°) \\ (f - e + r_f \cos(\theta_2)) \sin(30°) \\ -r_f \sin(\theta_2) \end{bmatrix} \quad (3)$$

$$J_3' = \begin{bmatrix} x_3 \\ y_3 \\ z_3 \end{bmatrix} = \begin{bmatrix} -(f - e + r_f \cos(\theta_3))\cos(30°) \\ (f - e + r_f \cos(\theta_3))\sin(30°) \\ -r_f \sin(\theta_3) \end{bmatrix} \quad (4)$$

To find the intersection of these three spheres is to solve these equations:

$$\begin{aligned} (x_e - x_1)^2 + (y_e - y_1)^2 + (z_e - z_1)^2 = r_e^2 \\ (x_e - x_2)^2 + (y_e - y_2)^2 + (z_e - z_2)^2 = r_e^2 \\ (x_e - x_3)^2 + (y_e - y_3)^2 + (z_e - z_3)^2 = r_e^2 \end{aligned} \quad (5)$$

The solution of equation (5) is

$$x_e = \frac{a_1 z_0 + b_1}{d_{nm}} \quad (6)$$

$$y_e = \frac{a_2 z_0 + b_2}{d_{nm}}$$

$$z_e = -\frac{b + \sqrt{d}}{2a}$$

The summary of equations for forward position kinematics and the calculation of the parameters can be found in [4] and in Appendix A. For more details and the derivation of the three-sphere algorithm, the reader refers to [5] and [6].

When the Delta manipulator is mounted on the mobile robot as shown in figure 5, the force or motion acting on the delta manipulator results the position change of the end effector coordinate $[\boldsymbol{\Delta x_e}, \boldsymbol{\Delta y_e}, \boldsymbol{\Delta z_e}]$. The position change can be calculated from the yoke angle $(\boldsymbol{\theta_{Yi}})$ and the proximal-link angle $(\boldsymbol{\theta_{Pi}})$ measured by encoders using the forward kinematics described above. This position change of the end-effector will be converted into a set of motion instructions, which are then sent to the robot as moving command to enable collaboration between the two systems. This approach allows for seamless interaction and coordination between the Delta manipulator and the mobile robot, providing greater flexibility and adaptability in a range of settings.

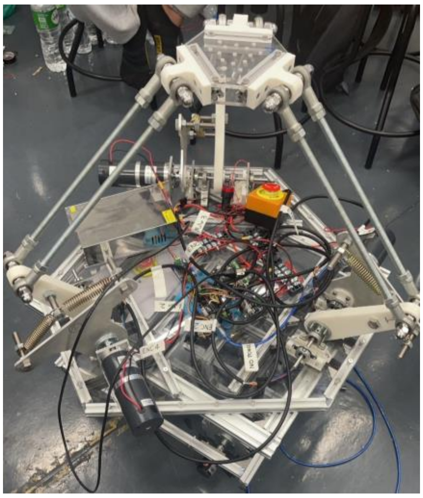

*Figure 5 The holonomic AMR with SEA delta manipulator*

## 3. CONTROL STRATEGIES FOR TRANSLATIONAL MOTION

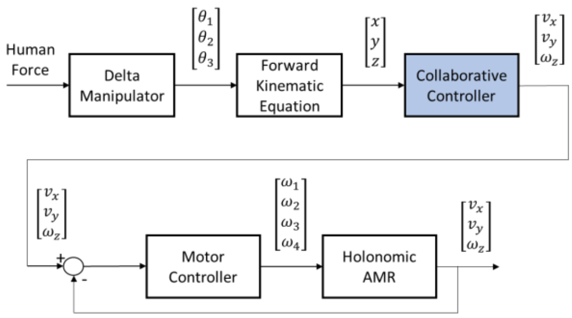


*Figure 6 Overview of control system of the collaborative mobile robot*

The overview of the control system of the collaborative mobile robot is presented in figure 6. As our mobile robot is holonomic, the robot has three degrees of freedom, which are moving in x-direction, moving in y-direction and rotation about z-axis. The moving command of the mobile robots



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are also the velocity in x-direction ($v_x$), the velocity in y-direction ($v_y$) and the angular velocity. ($\omega_z$), respectively. The task of the collaborative controller is to convert the actuated position change of the end-effector by human push and pull into the moving command of the mobile robot, which are the moving velocities of the robot. In order to design the collaborative behavior between the human and the mobile robot, three control strategies are tested for control the motion of the mobile robot in simulation and real application.

### 3.1 Control strategy with P-controller behavior

The first control strategy is the P-Controller behavior. The position changes in x- and y-direction are converted directly to the velocity of mobile robot in x- and y-direction respectively as in the following equations.

$$\begin{aligned} v_x &= K_P x \\ v_y &= K_P y \end{aligned} \tag{7}$$

Figure 7 illustrates the velocity command resulted from the P-controller behavior type. With this controller, the mobile robot will move as long as the user applies force to the delta manipulator Users have to push the manipulator continuously in order to keep the mobile robot moving. Moreover, due to the presence of an elastic element in the manipulator, there is an overshoot behavior observed after the user releases the manipulator, as shown in Figure 7. This overshoot signal results in a swing motion of the mobile robot, as the velocity command alternates between positive and negative values.

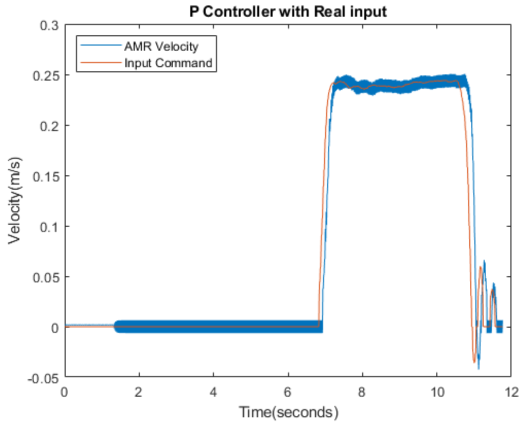


*Figure 7 Velocity command for mobile robot with P-Controller behavior*

### 3.2 Control strategy with PI-controller behavior

The second control strategy is to use the position change of the delta manipulator end-effector to change the velocity of the mobile robot, so that the user can release the manipulator and the mobile robot is still moving with constant velocity. This behavior can be realized by using the PI-Controller behavior, which relation defined by the following equations.

$$\begin{aligned} v_x &= K_P x + K_I \int x(\tau) d\tau \\ v_y &= K_P y + K_I \int y(\tau) d\tau \end{aligned} \tag{8}$$

Figure 8 presents the velocity command resulting from the PI-controller. Compared to the P-controller, the swing behavior by the PI-controller type has less effect, as the velocity alternates in the positive value. It can be observed from Figure 8 that the mobile robot continues to move even after users release the manipulator, thereby enabling collaboration between humans and mobile robots. However, it may be difficult for users to bring the velocity of the mobile robot back to zero to stop the robot.

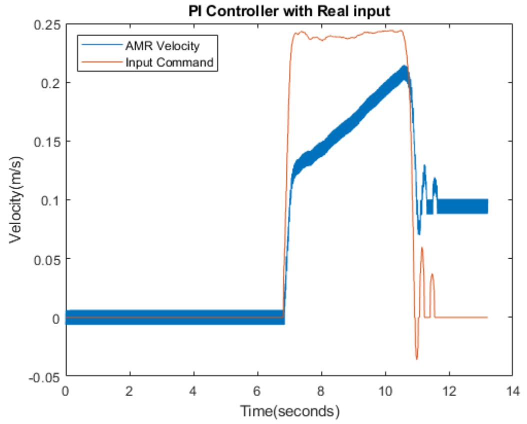


*Figure 8 Velocity command for mobile robot with PI-Controller behavior*

### 3.3 Control strategy with switched PI-controller behavior

To solve the difficulty of the stopping, the PI-controller from the previous section has been modified to allow the mobile robot to slow down on its own when no force is applied to the manipulator. This has been achieved by incorporating a condition in the controller program, as shown in the following equation..

$$\begin{aligned} v_x &= K_P x + K_I^1 \int x(\tau) d\tau && \text{for } |x| > e_{tol} \\ v_x &= -K_I^2 \int x(\tau) d\tau && \text{for } |x| < e_{tol} \\ v_y &= K_P y + K_I^1 \int y(\tau) d\tau && \text{for } |y| > e_{tol} \\ v_y &= -K_I^2 \int y(\tau) d\tau && \text{for } |y| < e_{tol} \end{aligned} \tag{9}$$

where $e_{tol}$ is the defined tolerance of the position change. The velocity command generated by the switched PI-controller for the mobile robot is depicted in Figure 9. Similar to the PI-controller behavior in the previous section, the collaborative behavior is preserved. However, with the implemented condition, the user can now stop the mobile robot by releasing the manipulator and waiting for it to slow down by itself. This type of controller enables a novel collaborative action between humans and mobile robots to control the movement.



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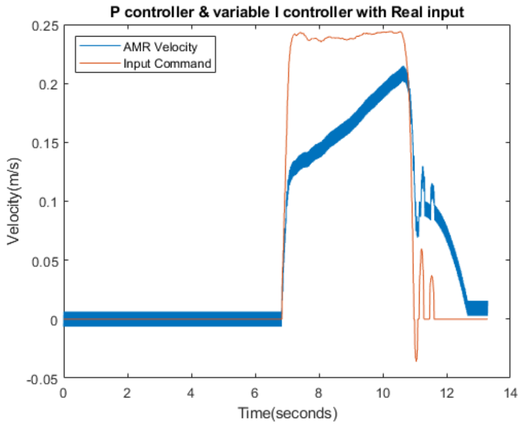


*Figure 9 PI Controller + decay with real input*

The collaborative controller converts the force and motion from the human to the translational movement command for mobile robot. This process enables the mobile robot to move alongside humans in a natural manner. Through extensive testing and analysis, we determined that control strategy with switched PI-controller behavior was the best choice for our system compared to the other. This control strategy enables our mobile robot to move smoothly and naturally, improving its overall performance and making it a more effective tool in transportation applications. The resulting system is a significant step forward in the development of advanced and adaptable control systems for group of mobile robots and has important implications for future research and development in this area.

## 4. CONTROL STRATEGIES FOR ROTATIONAL MOTION

In the previous section, we discussed the realization of translational motion control. However, the holonomic mobile robot is also capable of rotating about the z-axis to change its orientation. To achieve this rotation motion using the delta manipulator as a medium for human-robot interaction, we propose two control strategies. These control strategies aim to change the orientation of the mobile robot in a controlled manner.

### 4.1 Change orientation by using position change in Z-axis

As the position change in x- and y-axis is applied for control the translational motion, where the position change in the x- and y-axes was utilized. However, the position change in the z-axis remained free and could be utilized as an input command to rotate the mobile robot. When the mobile robot is stationary, pressing the end-effector of the delta manipulator will cause the mobile robot to rotate clockwise, and lifting the end-effector will cause it to rotate counterclockwise. The collaborative controller for rotation can be implemented using the following equation.

$$\omega_z = K_P z \tag{10}$$

### 4.2 Change orientation of mobile robot by using the orientation of position change vector

The second control strategy for rotating the mobile robot is using orientation of position change vector $[\Delta x_e \quad \Delta y_e]^T$. In normal state, the mobile robot will slide in x- or y-axis as discussed in section 3. But if the position change vector remains constant for a specific time, the collaborative controller will control the orientation of the mobile robot to the angle of

$$\varphi = \text{atan2}(\Delta y_e, \Delta x_e) \tag{11}$$

Figure 10 shows an example of this control strategy by holding command in y-axis direction. The command for orientation of mobile robot is then $\varphi = -90°$. In this case, the mobile robot moves sliding in y-direction firstly, and then simultaneously change the orientation as shown in figure 10.

Two control strategies for changing the orientation of mobile robot using input mapping are proposed and discussed in this section. The first control strategy suggests using the position change of the end-effector in z-axis as an input command is simple solution to change the orientation of the mobile robot. But this option will be complicated in the future as this delta manipulator will be used to hold some weight for transportation.

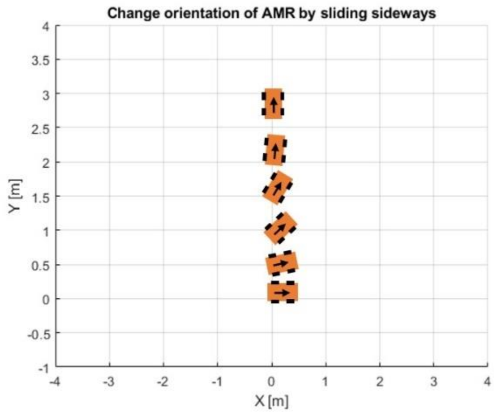


*Figure 10 Change orientation of mobile robot by using the orientation of position change vector*

The second strategy proposes changing the orientation of the mobile robot by using the orientation of position change vector $[\Delta x_e \quad \Delta y_e]^T$. This control strategy will rotate the mobile robot while performing a sliding action. This approach is more complicated compared to the first strategy as it is difficult to program the controller when the mobile robot needs to change its orientation. However, this approach results in a more capable mobile robot that can move in the desired orientation.

The results of this study demonstrate that both strategies have their advantages and disadvantages,



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and their effectiveness may depend on the specific application requirements. If the application demands fast and straightforward orientation changes, the z-axis command may be more suitable. Conversely, if the application requires the mobile robot to move in multiple orientations, changing the orientation during a sliding action may be a better approach, despite its control complexity.

## 5. CONCLUSION AND FUTURE WORKS

In conclusion, this study aimed to create a natural human-robot interface for collaborative mobile robots for transportation applications. By using a series elastic actuator (SEA) and designing a switched PI-controller with collaborative behavior, the resulting system improved the mobile robot's overall performance and demonstrated the potential for advanced and adaptable control systems in transportation. Additionally, two control strategies were proposed for changing the mobile robot's orientation using input mapping. The Z-axis command offers a simple solution for fast orientation changes, while changing orientation using the orientation of position change vector offers a more capable mobile robot that can move in multiple orientations, despite its added complexity. This study contributes to the ongoing development of control systems for AMRs and highlights the importance of considering application requirements in determining the optimal strategy for enhancing mobile robot capabilities.

In future work, we plan to further develop the human-robot interface to enable the mobile robot to collaborate with other mobile robots to complete tasks. Designing a collaborative medium for a group of mobile robots is a challenging task that requires further investigation.

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## APPENDIX A
## FORWARD KINEMATICS EQUATION OF DELTA MANIPULATOR

For the revolute-input delta manipulator with three identical legs, which consists of two links of length $r_f$ and $r_e$, arranged in parallel between the fixed base with a radius $f$ and the moving end-effector platform with a radius $e$, the forward kinematic position is the mapping from the joint angles $[\theta_1, \theta_2, \theta_3] \in \mathbb{R}^{3\times1}$ to the end-effector coordinates in task space $[x_e, y_e, z_e] \in \mathbb{R}^{3\times1}$. This can be achieved using the following equations:[4]

$$
\begin{aligned}
t &= \frac{1}{2}(f-e)\tan(30°))\\
y_1 &= -(t + r_f\cos(\theta_1))\\
z_1 &= -r_f\sin(\theta_1)\\
y_2 &= \big(t + r_f\cos(\theta_2)\big)\sin(30°)\\
x_2 &= y_2\tan(60°)\\
z_2 &= -r_f\sin(\theta_2)\\
y_3 &= \big(t + r_f\cos(\theta_3)\big)\sin(30°)\\
x_3 &= -y_3\tan(60°)\\
z_3 &= -r_f\sin(\theta_3)\\
d_{nm} &= (y_2 - y_1)x_3 - (y_3 - y_1)x_2\\
w_1 &= y_1^2 + z_1^2\\
w_2 &= x_2^2 + y_2^2 + z_2^2\\
w_3 &= x_3^2 + y_3^2 + z_3^2\\
a_1 &= (z_2 - z_1)(y_3 - y_1) - (z_3 - z_1)(y_2 - y_1)\\
b_1 &= -\frac{1}{2}\big((w_2 - w_1)(y_3 - y_1) - (w_3 - w_1)(y_2 - y_1)\big)\\
a_2 &= -(z_2 - z_1)x_3 + (z_3 - z_1)x_2\\
b_2 &= \frac{1}{2}\big((w_2 - w_1)x_3 - (w_3 - w_1)x_2\big)\\
a &= a_1^2 + a_2^2 + d_{nm}^2\\
b &= 2(a_1b_1 + a_2(b_2 - y_1d_{nm}) - z_1d_{nm}^2)\\
c &= (b_2 - y_1d_{nm})^2 + b_1^2 + d_{nm}^2(z_1^2 - r_e^2)\\
d &= b^2 - 4ac\\
z &= -\frac{b+\sqrt{d}}{2a}, x = \frac{a_1z_0 + b_1}{d_{nm}}, y = \frac{a_2z_0 + b_2}{d_{nm}}
\end{aligned}
$$



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