Development of a Reconfigurable Four-Bar Mechanism For a Human Robot Collaborative Gripper

Keerthi Sagar*, Vishal Ramadoss*, Michal Jilich, Matteo Zoppi, Dimiter Zlatanov, and Alessandro Zanella

Abstract With the rise of collaborative robots in industries, this paper proposes a human robot collaborative gripper for a windshield assembly and visual inspection application. The collaborative interface which acts as a haptic feedback device is mounted on the gripper using a deployable mechanism. The kinematics of a reconfigurable mechanism are analyzed to illustrate the advantages for using it as an unit mechanism and the concept is extended to a parallelogram based deployable four bar mechanism. A novel threefold reconfigurable four bar mechanism is developed by creating adjacent units orthogonally and the connection between such units are investigated. The proposed mechanism can be deployed and stowed in three directions. Locking of the mechanism is proposed using mechanism singularity. Kinematic simulations are performed to validate the proposed designs and analyses.

Key words: Kinematics, Orthogonal, Deployable Mechanism, Human-Robot Collaboration, Gripper.

1 Introduction

Robots have long been a vital part of the everyday industries and the future of manufacturing portray robots and people working in a cooperative manner to complete collaborative tasks. The collaborative robots (co-bots) are designed to work alongside humans assisting them with various tasks. In this paper, the main collaborative

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application in focus is towards an EU H2020 CoLLaboratE usecase [5], visual inspection and windshield assembly in *Centro Ricerche Fiat, Italy*. Assembly of windshield on the car chassis is usually an automated procedure due to strong tolerances in positioning and safety measures. In the existing workcell setup, the operator picks the windshield using a zero-gravity manipulator and places it on a rotating table for assembling the rear view mirror and sensors on the windshield. The operator also simultaneously checks for visual cracks on the outer surface. After the consequent assembly, a robot picks and places the windshield on the car chassis. With such a layout, the operator has to manually orient the gravity aiding manipulator to place the windshield on the assembly table and make more logistic steps in picking the assembly components from the material handling line. In the proposed collaborative workcell, the robot performs the operation of picking the product variant from the rack and presents it to the operator. The operator performs all the operations directly on the windshield mounted on the robot. The gripper acts as the collaborative interface between the robot and the human operator. The paper is organized as follows: Section 2 provides a brief overview of the collaborative gripper system. The kinematics of the reconfigurable mechanism are formulated in Section 3. The working modes and the singularity analysis of the mechanism are illustrated in the Section 4. Section 5 concludes the paper and presents areas of future work.

2 The Collaborative gripper system

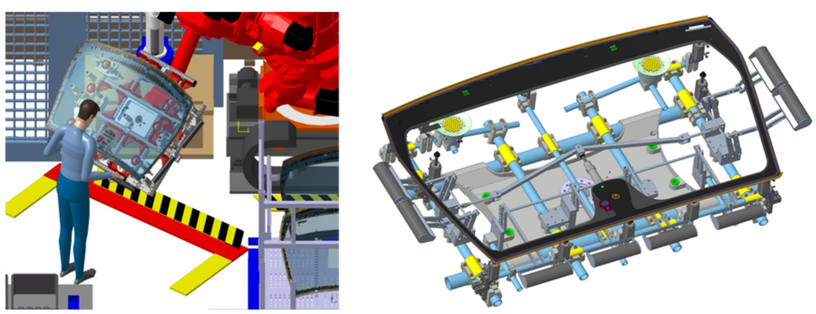


Fig. 1: a) Conceptual design of the collaborative gripper system to place robot skin for human interaction b) The proposed threefold reconfigurable four bar mechanism for the deployment of tactile handles in three different directions

The conceptual design of the collaborative gripper system is shown in Figure 1(a). The gripper is provided with a handle equipped with tactile feedback sensors (robot skin). The operator can use the tactile handle to manipulate (position and orient) the robot and send signals to trigger specific actions of the robot [1] which is illustrated in Figure 1. The tactile handles should be deployed only during the human interaction phase and stay in a retracted position. This is a requirement, since a static structure of the tactile handle can cause interference during picking operation from the rack and assembly on the car chassis. This article focuses on the development of a threefold reconfigurable four bar mechanism for the deployment of tactile handles.

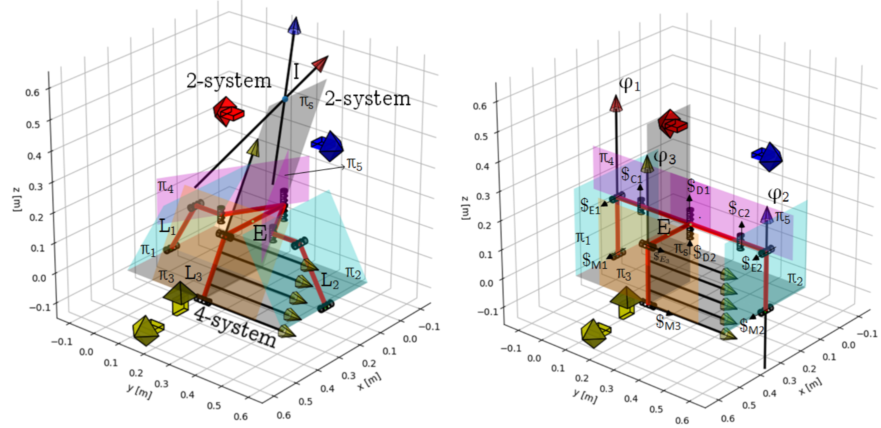
3 The reconfigurable mechanism

The operator has to access the collaborative gripper in three directions. This is elucidated in Figure 1(a). Most of the research that has been made on reconfigurable mechanisms has focused on structures that consist of scissor-like elements (SLEs) [8], Hoeken linkage [4], Sarrus linkage [7] and metamorphic mechanisms [2]. The four bar linkage is more suitable as a unit mechanism as it can achieve the desired behavior for our application with limited number of actuators. First, the desired motion is limited as we require nominal magnification ratio. Second, parallelogram based four bar is stable linkage and can withstand heavy loads. For these reasons, we propose a novel solution by leveraging the principles of reconfigurablity and four bar linkage.

3.1 Motion Analysis of the reconfigurable mechanism

The mobility using Gruebler-Kutzbach [3] criterion was predicted incorrectly. Instead of using the modified GK criterion, the constraint and free motion analysis are investigated through reciprocal screw theory [3]. Because of the symmetry of the structure of the proposed system, the motion of limb 1, in one branch is the same as that of limb 2 in the other branch. What follows will only analyze the proposed mechanism to figure out the mobility. The mechanism has 1 DOF. For modeling purposes, we consider a triangular structure as representation which is actuated by a prismatic joint. The revolute joint at D_1 can be considered as virtually two revolute joints with a point in between for the purpose of analysis, thereby forming symmetrical limbs, which is represented in Figure 2(a). The mechanism is analyzed as a parallel manipulator by considering E as an end-effector, hence forming a three limb architecture.

The limb 1 (L_1) is a 4R chain, 2-system of screws with a constraint force in the direction of line formed by the intersection of two planes π_4 and π_1 and a couple represented by a solid pyramid arrow in red color perpendicular to the screw axis of joint C_1 and E_1. The limb 2 (L_2) is also a 2-system of screws with a constraint force in the direction of line formed by the intersection of two planes π_5 and π_2 and a couple represented by a solid pyramid arrow in blue color, which is perpendicular to the screw axis of joint C_2 and E_2. The limb 3 (L_3) is a RR chain, 4-system with two constraint couples, a constraint force passing through the joint axes and a planar pencil



(a) (b)

Fig. 2: Constraint Analysis using screw theoretic representation

of screws (from which any one of the screws in the set can be a reciprocal screw), all represented in yellow color. We choose the basis of screw system according to the choice of end-effector. The dimension of the constraint wrench system is defined using the formula $dim(U+V) = dim(U) + dim(V) - dim(U \cap V)$. The dimension of the constraint wrench system is 4+2+2-3= 5-system of constraint wrenches, where $dim(U \cap V)$ is three forces (two intersecting forces at point I) and another force parallel to the pencil of screws of M_3E_3, passing through point I. Therefore, dimension of the twist system is 1 with translational degrees of freedom which depends on the configuration and moves in the symmetric plane π_s. M_3E_3, E_3D_1 and the projection of D_1 on the midpoint of M_1M_2 forms a parallelogram that acts like a four-bar linkage as depicted in Fig. 3. Thus, the link E_3D_1 acts as an end-effector for the four bar linkage and thereby 1 DOF translational motion.

3.2 Kinematic Modeling

The kinematics of the reconfigurable mechanism which is shown in Figure 3, is described in this section. Firstly, the position analysis is performed in which the position of E_1, E_2 and E_3 are determined. This is crucial as the path traced by these points determine the folding and unfolding pattern. A_i, B_i and E_i for $i = 1,2,3$ forms a triangle in XZ and YZ planes. $\triangle A_1B_1E_1$ and $\triangle A_2B_2E_2$ are in XZ plane for the configuration shown in the Figure 3. $\triangle C_1D_1C_2$ is in XY plane. l_{ki} for $k,i = 1,2,3$ denote the length of the links for corresponding triangles. M_1, M_2 and M_3 represent the projection of the points E_1, E_2 and E_3 on the XY plane respectively. δ_1, δ_2 and

δ_3 are the corresponding lengths of A_1M_1, A_2M_2 and A_3M_3. A piston is connected between the E_3 and D_1 with a length L. The links are connected using revolute joints for the defined points. The orientation of revolute joints are shown in the figure. θ_1 and θ_2 are angles between π_1(shifted from XZ) and π_2(shifted from XY) plane defined at points B_1 and B_2 rotating in counter-clockwise direction. θ_3 is the angle between YZ and XY plane defined at point B_3. Since E_1 and C_1, E_2 and C_2 are collinear, θ_4 and θ_6 are considered as zero in the mechanism. θ_5 and θ_7 are the angles between YZ and XZ plane defined at points C_1 and C_2.

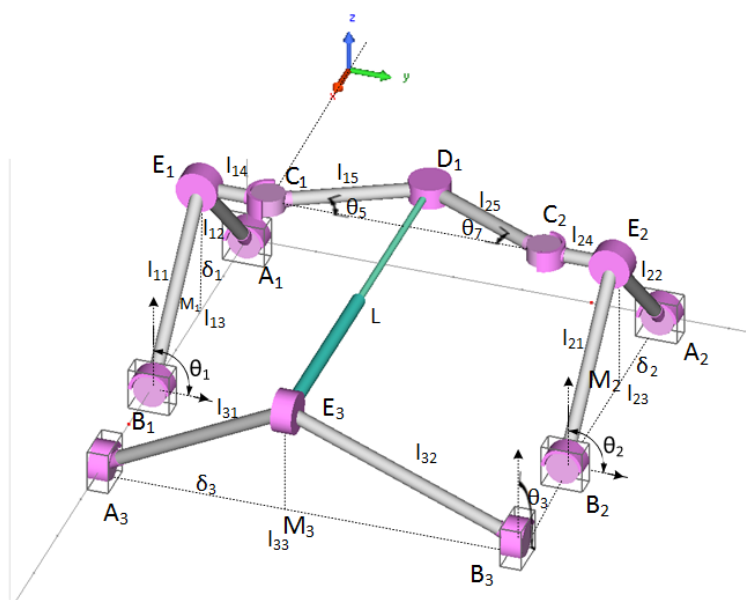


Fig. 3: Reconfigurable mechanism description

The coordinates of A_i are defined as $[x_i, y_i, z_i]$ for $i = 1,2,3$. The coordinates of B_i (for $i = 1,2$) are given below:

$$\begin{aligned} B_1 &= [x_1 + l_{13}, y_1, z_1] \\ B_2 &= [x_2 + l_{23}, y_2, z_2] \end{aligned} \tag{1}$$

The coordinates of E_i (for $i = 1,2$) are given below:

$$\begin{aligned} E_1 &= [x_1 + \delta_1, y_1 + \sqrt{(l_{11}^2 - \delta_1^2)}c\theta_1, z_1 + \sqrt{(l_{11}^2 - \delta_1^2)}s\theta_1] \\ E_2 &= [x_2 + \delta_2, y_2 + \sqrt{(l_{21}^2 - \delta_2^2)}c\theta_2, z_2 + \sqrt{(l_{21}^2 - \delta_2^2)}s\theta_2] \end{aligned} \tag{2}$$

The coordinates of C_1, C_2 and D_1 are:

$$\begin{aligned} C_1 &= E_1 + [0, l_{14}, 0] \\ C_2 &= E_2 + [0, -l_{24}, 0] \\ D_1 &= C_1 + [l_{15}s\theta_5, l_{15}c\theta_5, 0] \end{aligned} \tag{3}$$

where $c(.)$ and $s(.)$ notations are used for cosine and sine of the arguments respectively.

Expanding Equation 3, it is given as:

$$C_1 = [x_1 + \delta_1, y_1 + \sqrt{(l_{11}^2 - \delta_1^2)}c\theta_1 + l_{14}, z_1 + \sqrt{(l_{11}^2 - \delta_1^2)}s\theta_1]$$
$$C_2 = [x_2 + \delta_2, y_2 + \sqrt{(l_{21}^2 - \delta_2^2)}c\theta_2 - l_{24}, z_2 + \sqrt{(l_{21}^2 - \delta_2^2)}s\theta_2]$$
$$D_1 = [x_1 + \delta_1 + l_{15}s\theta_5, y_1 + \sqrt{(l_{11}^2 - \delta_1^2)}c\theta_1 + l_{14} + l_{15}c\theta_5, z_1 + \sqrt{(l_{11}^2 - \delta_1^2)}s\theta_1] \quad (4)$$

The equality constraints are expressed as:

$$E_3[y] = D_1[y] \qquad E_3[z] = D_1[z] \quad (5)$$

which implies that the y- and z-coordinate of points E_3 and D_1 are same. For the x-coordinate of E_3, the distance constraint is defined and is described as:

$$\| D_1 - E_3 \| = L \quad (6)$$

The coordinates E_3 are obtained using the following expression:

$$E_3 = [x_3 + \sqrt{(l_{31}^2 - \delta_3^2)}c\theta_1, y_3 + \delta_3, z_3 + \sqrt{(l_{31}^2 - \delta_3^2)}s\theta_3] \quad (7)$$

where the coordinates of B_3 are given as:

$$B_3 = [x_3, y_3 + l_{33}, z_3] \quad (8)$$

The angle constraints are expressed as:

$$\theta_2 = \pi - \theta_1 \qquad 0^\circ < \theta_1 < 90^\circ \quad (9)$$

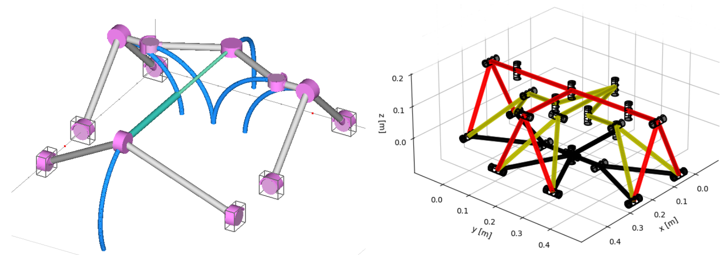
For a given input θ_1, the position analysis was performed and the coordinates, path traced by the points E_1, E_2 and E_3 are simulated respectively.

4 Kinematic Simulation

A mathematical mock-up of the reconfigurable mechanism was programmed and simulated using Python 2.7. The simulations were also validated with the educational tool for kinematic analysis of mechanism, GIM Software [6]. The deployment process is illustrated with different planes shown in Figure 4(b). The results of both simulations are presented in Figure 4.

4.1 Singularity Analysis

The singularity analysis [9] is performed and the singular configurations for proposed mechanism is shown in Figure 6. The fully deployed configuration, shown in Figure 6(a), is a singular configuration as the three lines intersect at a common point in a plane. As shown in Figure 2(b), the constraint forces φ_1, φ_2 and φ_3 present in limbs 1, 2 and 3 becomes parallel to each other, hence are linearly dependent.



(a) (b)

Fig. 4: (a) The path traced by the reconfigurable mechanism (b) Simulation of the deployment process: fully folded state(black color), partially folded state(yellow color) and fully deployed state(red color)

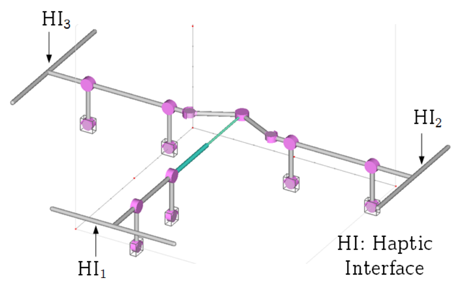
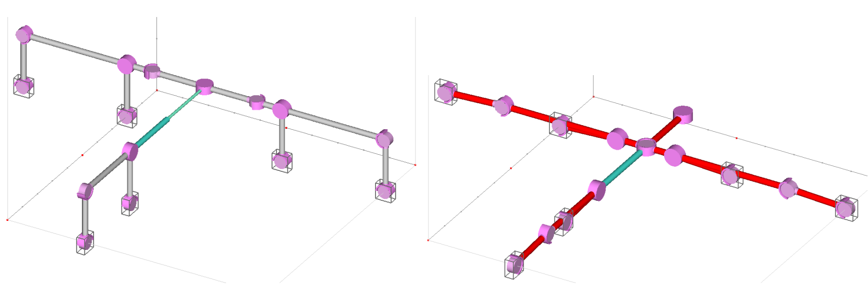


Fig. 5: Reconfigurable mechanism with three orthogonal four bar linkages

The dimension of total constraint wrench systems becomes six and hence results in 0 DOF. This singular configuration of the reconfigurable mechanism based on four bar linkage can be exploited in a way to perform certain tasks such as opposing human operative loads. The singular configuration shown in Figure 6(b) can be avoided by allowing the motion within joint limits.



(a) Fully deployed configuration (b) Fully folded configuration

Fig. 6: Singular configurations of the reconfigurable mechanism

5 Conclusion

This paper introduced a reconfigurable robotic solution for effective mounting of human robot collaborative gripper which the operator utilizes as a tactile handle to manipulate the robot. By developing a novel reconfigurable mechanism based on four bar linkage, we achieve both compact folding and maximum expansion and to withstand external forces applied by the operator. The kinematic model of the reconfigurable unit mechanism is presented and then the working mode is simulated. The deployed and stowed configurations are modeled and analyzed using simulation tools. The kinematic simulations were presented to show the capability and ease of the mechanism that is mounted on the collaborative gripper. The singular configurations were studied by extending the unit mechanism to a four bar based mechanism. Future work includes employing the reconfigurable mechanism in different domains and to explore the possibility of stacking the mechanisms.

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