DESIGN AND ANALYSIS OF TWO-LINK DISCRETE FLEXIBLE MANIPULATOR

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Abstract. Proposed two-link flexible manipulators suit the requirement of larger work volume than the traditional flexible manipulators and handle high payloads equal to that of rigid manipulators. The simulation was performed on the Computer-Aided Design (CAD) model of the Motoman HC-10DT, a Human-Collaborative robot. During the analysis, one link of the manipulator was modified as a flexible manipulator for which static and modal analysis was done and compared the results with the actual link of the robot to validate the proposed design. The kinematic analysis was also done to find the reach of the modified robot. Total deformation on both the flexible manipulator and the actual link of the robot was 0.2mm but the maximum von Mises stress acting on the flexible manipulator was 2.97% lesser than that of the rigid link of the robot. Eventually, the safety factor of the flexible manipulator was higher compared to the rigid link. The factor of safety of the upper link is 1.41 and the lower link is 1.51 whereas the actual link of the robot has the safety factor of 1.30.

Keywords: Flexible manipulator, Design, CAD model, kinematic analysis.

1. Introduction
Robots are present in the industries for more than fifty years. Initially, they were very gigantic and operated in metal cages or any other protective safer surroundings. Evolution and some applications of the industrial robot are detailed in [1]. Primarily, they were used for spray painting and spot welding on auto assembly lines. The major aspect to be considered is the safety of human beings in the proximity of robots. This resulted in very strict protocols and the requirement of ultra-careful safety facilities such as metal cages. These restrictions prohibited the usage of robots to work in collaboration with humans in some applications where humans and robots can operate the same item in the same period. After numerous research like integrating sensors to a conventional industrial robot [50] fortunately, with the arrival of collaborative robots (or cobots), the association between robots and humans [2] is possible nowadays. The present trade demands large-scale customization, and lower lead period, therefore requiring flexible assembly lines. These requirements are remarkably popular in small and medium-sized enterprises (SMEs). Cobots will be able to solve the current issues in manufacturing sectors and assembly lines, as they can physically interrelate with humans in a shared workspace; besides, they can be effortlessly reprogrammed even by non-professionals [3]. Cobots have another advantage of controlling its functions remotely.
To upgrade the production rate in industries, it is necessary to minimize the heaviness of the robots and/or to maximize their working speed. Because of these motives, it is advisable to use flexible manipulators in robots. Flexible manipulators have advantages like larger work volume, higher operational speed, better maneuverability, better transportability, and safer operation. There are two types of flexible manipulators being used in robots. They are discrete flexible arm and continuum flexible arm. Discrete robot arms are made up of a series of small rigid links that are joined using discrete joints. If the number of rigid links increases the degree of freedom of the arm also increases which, in turn, helps the arm to move around in the desired trajectory and the motion of such robots is highly predictable. Contrastingly, continuum arms have a smoother trajectory by elastic deformations. Though the body of continuum arms is very lighter than their discrete equivalents, their motion is more uncertain [4]. The design of discrete and continuum manipulators was inspired by nature. Many organisms like monkeys, Climbing morning glory vine, Octopus, Stingray, Komodo dragon, giraffe, brittle star, basket star use the same mechanism as that of discrete and continuum manipulators for their survival [5]. The use of flexible discrete manipulators in cobots increases its efficiency in terms of production and safety. This proves that the flexible manipulator can find its application in a variety of sectors, like construction and maintenance of buildings, space applications, and agricultural applications [46]. To design a flexible arm effectively, either premeditated for a particular task or a variety of tasks, numerous factors are to be reviewed. This comprises the flexibility and strength of the manipulator, payload capacity, topmost acceleration, and speed specification, and also a worthy actuator for controlling the movement that is intended [6].

This research concerns the novel design of a flexible discrete manipulator for cobots that can be used in integration with the existing rigid manipulator. In particular, the research was done for the human-collaborative robots used for assembly, machine tending, material handling, pick and place processes. But the design is applicable for all the general applications of both industrial robots and cobots.

2. Earlier research work on the flexible manipulator

Owing to the effectiveness of this topic, scientists around the world are now working on optimizing the design and motion planning of flexible manipulators. Some investigations regarding the flexible manipulators are briefed in the following. Details about the various factors to be considered in control of weightless robots used for terrestrial and space applications have been discussed in [7]. Researchers have worked on the manipulators with larger work volume, which is used for the working in storage tanks [8]. Many have researched the contouring and collision control of robots with flexible manipulators [10], [9]. Key topics to be considered in the control and dynamic behavior of robots with flexible manipulators have been elaborated in [11]. Set of researchers have successfully modeled and studied the control of a robot comprising rigid and flexible arms [12]. Further, researchers have done similar work with slight variations [13]. Two-link manipulators were practically experimented by many researchers [14], [15], [16], [11], [18], [19], [20], [21]. Research has been done to find the frictional forces acting in a planar two-link flexible manipulator with help of innovative identification techniques [19].

Few people have experimentally analyzed the association of robots and humans in surgeries [22]. Control aspects such as feed-forward control, modal reference adaptive control, regular PID control, and self-tuning control of flexible manipulators were also studied in the past. [23], [24], [25] deals with computed torque control of two-link flexible manipulators and [26], [27], [28] deals with adaptive control of the same. Interestingly, [29] has brought up a unique controlling scheme using quasi-static deflection compensation with the help of neural networking for the motion control of two-link flexible manipulators. Researchers even analyzed the hybrid force and position control [30], [31]. Studies on the implementation of the PD controller of flexible robots are also studied [32], [33]. Still many research on flexible manipulators can be found in [34].
3. Design approach

It is evident from above that much research has been carried out only regarding the materials, motion planning, mathematical modelling, and vibration controls of flexible manipulators. But some of the main drawbacks of the existing flexible manipulators that have not been addressed to date is its low payload-carrying capacity and its use in combination with the rigid manipulators of industrial robots and cobots. The use of flexible and very lightweight materials makes it impossible to work with heavy payloads. Considering the requirement of such a lightweight flexible manipulator with high load carrying capacity and easy integration with industrial robots and cobots a novel design of a manipulator is proposed by referring [35]. The proposed design of the manipulator is discretized into two links that are made up of a rigid material such as metals. These links can have rotary or linear motion depending on the type of joint placed in between them which is operated with the help of a Permanent Magnet Synchronous Motor (PMSM) [36] [37].

The motors used to control the motion of the cobot must have enough strength to counter the labourer’s pushing forces and the inertial forces of the payload. But, high power motors may not be safe to use. However, the proposed design employs joints that provide mechanical constraints. These constraints can steadily be calibrated with the help of computer control. Thus, the motion of the cobots is essentially smooth and does not require powerful motors [38]. This manipulator will act as a single rigid entity unless the motor is operated to make the manipulator flexible. Figure 1 depicts the rigid manipulator and Figure 2 shows the flexible movement of the same manipulator.

![Figure 1. Rigid state of the manipulator.](image1)

![Figure 2. Flexible state of the manipulator](image2)

4. Experimental procedure

In the need of verifying the novel design, the proposed design was enforced in the CAD model of Yaskawa’s Human-Collaborative robot called MotomanHC-10DT [17]. Figure 3 shows the proposed design used in HC-10DT. The actual upper arm of the robot was replaced with the discrete flexible manipulator of two links joined by a revolute joint. The link above the revolute joint is called the upper arm and the one below the revolute joint is named lower arm. The dimensions of each link of the manipulator are dependent on the application of the robot. In case of the requirement of a translation motion of the flexible manipulator, the revolute joint can be altered with the prismatic joint similarly. But this paper focuses only on revolute joints as it is the favourable joint for the HC-10DT
cobot due to its applications. A separate space is allotted on the side of the lower arm to mount the PMSM and other mechanisms [47] required for the actuation of the joint. These two links make a flexible manipulator. The PMSM can be operated only when the arm is required to act as a flexible manipulator. Else, it remains as the traditional rigid manipulator. In the view of light-weighting the manipulator, cast aluminium alloy called A356 [39] was used for analysis purposes.

![Modified HC-10DT robot.](image)

5. Result and discussion
To validate the novel design, the actual rigid and the modified flexible arms of the HC-10DT human-collaborative robot were subjected to various static analysis to find the von Mises stress, total deformation, natural frequency, and Factor of Safety of both the arms and the results were compared [40]. As stated earlier, the material was chosen as T6 heat-treated A356 because of its high strength to weight ratio and other improved mechanical properties. Notable properties of Aluminium A356 are listed in Table 1. The automatic mesh was generated for the rigid link, upper arm, and lower arm are designated in Figures 4, 5, and 6 respectively, and used for further analysis. For all the analyses, the end opposite of the revolute joint is fixed in both the links. The torque acting on the upper and lower arms of the flexible manipulator is calculated as 168 Nm and 260 Nm respectively and 253 Nm acts in its rigid equivalence as shown in Figures 7, 8, and 9 respectively. The analysis results of the flexible manipulator and rigid manipulator are mentioned in Table 2. It is apparent from Table 1 and 2 that the von Mises stress acting on both the arms of the flexible manipulator is not greater than 36.91% of the yield strength of Aluminium A356 but the maximum von Mises stress acting on the actual arm is 39.88% of the yield strength of Aluminium A356. Eventually, the factor of safety of both the arms of the flexible manipulator is greater than that of the actual arm of the robot.

Resonance has become a salient point to be considered in any mechanical model. If any external frequency equals the natural frequency of a system it leads to disasters or system collapse, such an external frequency which causes failures is called resonance frequency. In absence of any external
forces, a system tends to vibrate at a particular frequency which is termed as the natural frequency of that system. The modal analysis helps in understanding the characteristics of mode shapes and natural frequencies in the real world [41]. With the same fixed constraints as mentioned above, nine natural frequencies and mode shapes of the flexible and rigid manipulators were found using their finite element model. The result of the modal analysis has been listed in Table 3. The design of the flexible manipulator and its static analysis were done in Creo Parametric 4.0 [42] and ANSYS 19.1 [43] respectively.

To check the reach of the modified robot arm, Kinematic analysis was done for the Motoman HC-10DT with a flexible manipulator. Though RoboAnalyzer [48] and MechAnalyzer [49] are one of the best tools to learn kinematics of a robot, Creo Parametric 4.0 [44] was used for this research. Initially, the 4th motor, from the base of the robot, was rotated at an angular velocity of 9.0deg/s for 10 seconds, and the 3rd motor was rotated at the angular velocity of 3.5deg/s for the next 10 seconds. Figure 10 represents the final position of the end effector after the actuation of the links. This is one of the positions that cannot be achieved with the help of a rigid manipulator in that robot. The position is calculated for the base of the robot. Figure 11 shows the graph plotted against the position of end effector versus time.

![Figure 4. Mesh of the rigid arm](image)

![Figure 5. Mesh of the lower arm](image)
Figure 6. Mesh of the upper arm

Table 1. Properties of Aluminium A356

| Properties               | Values |
|--------------------------|--------|
| Density (kg/m³)          | 2670   |
| Poisson's ratio          | 0.33   |
| Elastic Modulus (GPa)    | 72.4   |
| Yield Strength (MPa)     | 165    |
| Tensile Strength (MPa)   | 234    |

Figure 7. Constraints in the Lower arm.
Figure 8. Constraints in Upper arm.

Figure 9. Constraints in Rigid arm

Table 2. Static analysis results

| Results               | Upper arm [Hz] | Lower arm [Hz] | Rigid Equivalence [Hz] |
|-----------------------|----------------|----------------|------------------------|
| von Mises Stress      | 60.9MNm⁻²      | 57.0MNm⁻²      | 65.8MNm⁻²              |
| Total deformation     | 0.21mm         | 0.20mm         | 0.21mm                 |
| Factor of Safety      | 1.41           | 1.51           | 1.30                   |

Table 3. Modal analysis results

| Arms / Modes | Frequencies of the Upper arm [Hz] | Frequencies of the Lower arm [Hz] | Frequencies of the Rigid equivalence [Hz] |
|--------------|-----------------------------------|-----------------------------------|------------------------------------------|
| 1            | 1623.0                            | 1300.1                            | 55.632                                   |
| 2            | 1865.8                            | 1803.9                            | 93.749                                   |
| 3            | 2063.9                            | 1809.8                            | 509.8                                    |
| 4            | 2191.1                            | 1988.0                            | 629.78                                   |
All the results prove that the proposed design is better than the rigid manipulator of the robot under the same conditions. Since the proposed flexible manipulator is made of stiffer material, its
accuracy and repeatability can easily be controlled [45] also it has a longer reach when compared to other flexible manipulators. Importantly, it can also be used along with rigid manipulators. Though there are many advantages, its weight and high-power consumption when compared to traditional flexible manipulators are major disadvantages. This design can be used in any work environment and with all robots which especially demands a flexible manipulator for extended work envelopes and heavy payload carrying capacity.

6. Conclusion

From the simulation results, it is evident that the proposed design functions fairly and better than its rigid counterpart. This research proves that rigid manipulators can also be made flexible by having a joint in it. The proposed design can be utilized in all the robots where the use of actual flexible materials for the manipulators is not feasible. The novel design was implemented in the CAD model of Motoman HC-10DT human-collaborative robot and its Von Mises stress, total deformation, a factor of safety, and natural frequencies of the flexible manipulator and its equivalent rigid manipulator were compared and it was found that upper and lower links of the proposed manipulator have safety factor as 1.41 and 1.51 respectively but the actual rigid link of Motoman HC-10DT cobot had a safety factor of 1.30. The total deformation of the flexible manipulator and the rigid link was 0.2mm. Further research can be carried out in furthermore discretizing the manipulator, finding its dynamic behaviour, and light-weighting the proposed manipulator.

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