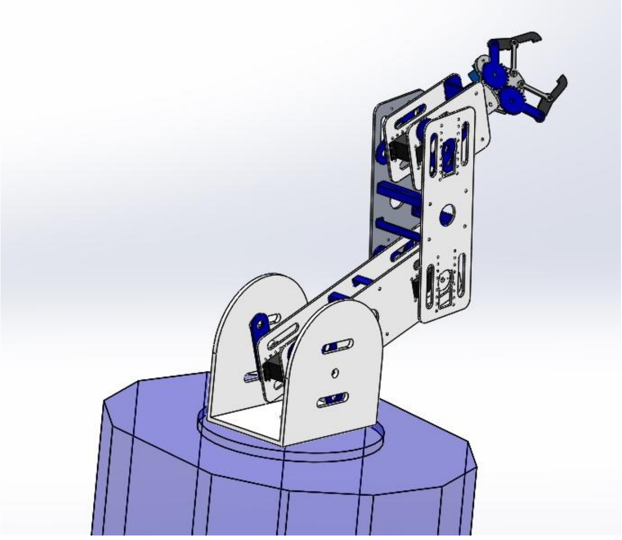
Design and Development of a Self-Adaptive, Reconfigurable and Low-Cost Robotic Arm



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Abstract.

This study presents the design, development and control of a low-cost, self-adaptive robotic arm, which can be easily modified, adding/subtracting different sizes of the links to perform a variety of tasks either for educational or common purposes in daily lives. Therefore, the presented robotic arms have a flexibility to be assembled in different combinations to fulfill various tasks and provide a platform where students could perform kinematics and control studies on it.

Keywords: robotic arm, cost-efficient, low cost, reconfigurable, self-adaptive, manipulator, robot control, easy control with multiple DOF

1 Introduction

As robotic technologies are starting to evolve for common use, the low-cost and efficient products started to be demanded for every aspect of the robotics area including robotic manipulators, which were first started to be used in industrial plants, but now being used in much broader range for daily assistance. (Xie, 2008) These kind of robotic arms generally mounted to a mobile base whether it can be a mobile manipulator base (Korayem *et al.*, 2015) or a wheelchair (Redwan *et al.*, 2006). So in contradiction to the industrial predecessors, the recent evolved versions are much lighter in weight and cheaper in cost.

As the daily use of the robotic arm becomes the topic, for the achievement of low-cost production becomes important. Simpler the design, easier the production replacement of its parts for reconfiguration becomes essential or replace parts. For every application, there may be a specific mechanical structure, allowing it to behave in a most efficient manner. To be more specific, a simple weight lifting operation may need 2DOF (Degrees of Freedom) structure, whilst a medical application of a robotic arm may need to have at least 4 limbs to make it more anthropomorphic. (Jamie *et al.*, 2012) Thus, different kinds of mechanical arms are being designed and produced for different applications based on a task oriented design strategy. While this type of strategies seems effective as it fulfills the defined tasks, it limits the possible marketing demand.

Self-adaptive robots are also a recent topic of study where a robot does not really be limited to the human capabilities but use the advantage of changing its shape and size. In order to achieve this, small robots can merge to form bigger structure in a specific configuration. (Zhang *et al.*, 2009)

This project focuses on designing a low-cost robotic arm which can easily be modified with adding and/or removing links with different sizes to achieve the optimal mechanical structure for various tasks, without changing its manufacturing process. Thanks to this flexibility, it can serve for different tasks in different applications. By this aspect, it would reach to a broader market demand with a lower cost. Also, the easy-to-assemble structure with the compactness of the unassembled parts makes the product easier to store, transport, and replace, which makes it much more available on long-term basis. It is important to emphasize that the structure of the arm is a very common use due to its simplicity and effectiveness. Since the focus of this paper is the configurability and enhanced adaptability of the robotic manipulators, it has been decided to follow the Elfasakhany and his team's method to provide low-cost design and production. (Ashraf *et al.*, 2011)

Another advantage of being interchangeable, low-cost robotic arm, is the educational usage opportunities. A "Lego-like" structure allows an opportunity for a student to work on this robotic arm base by changing sizes of the links, adding and removing the links, attaching cameras and sensors, calculating kinematics and implementing various control algorithms for the arm. Thus, this gadget can be used as an educational toolbox for motion control and motion orientated course laboratories and projects.

2 Methods

2.1 Mechanical Design

The design consists of individual joints formed by two panels of parallel plates connected by beams which has two standard sizes, sorted by long or short beams. Short beam joints have the actuators attached at the ends of the arms, and linked to the long beam joints via the shaft of these actuators. The joints attached together with pins and cable at the ends of each links, the number of joints can be increased or decreased very efficiently in a short time (less than a minute). Since at this point the torque capabilities of each actuator is very important. The panels are designed to support various types of actuators in terms of size and power. When needed, two parallel motors can be attached at the link connections of the robotic arm to provide the high levels of torques.

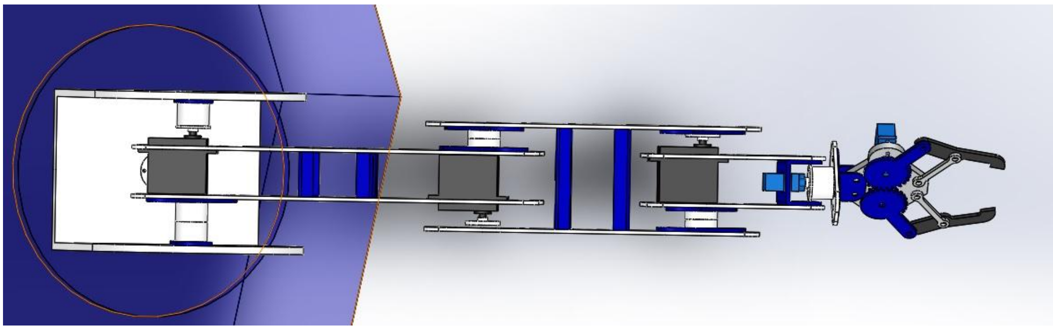


Fig. 1. Top view for the mechanical design. Motors of the arm are shown as black as small motors of the gripper are shown light blue.

Besides, in this platform, each panel has its own wiring in each side, which is open ends. As the links attached to each other, these ends are connected to each other closing that specific circuit. That is how the program understands that a new link has been attached. The voltage drop for this circuit is also calculated to, determine the length of the added joint according to Ohm’s law (1) V˜R and R ˜L (2). Where R is resistance, ρ is resistivity, L is length and A is cross-sectional area.

$$V=I*R \tag{1}$$

$$R = \frac{\rho L}{A}$$

(2)

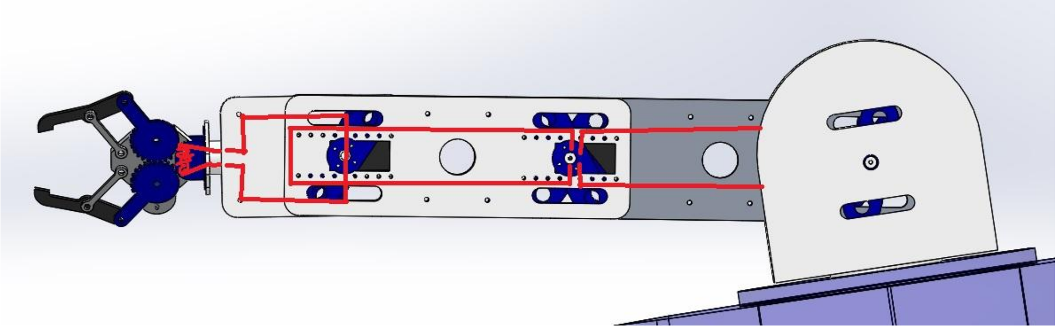
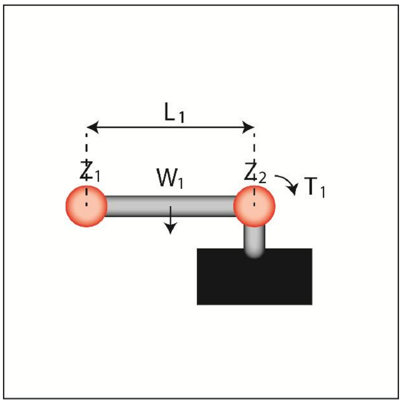
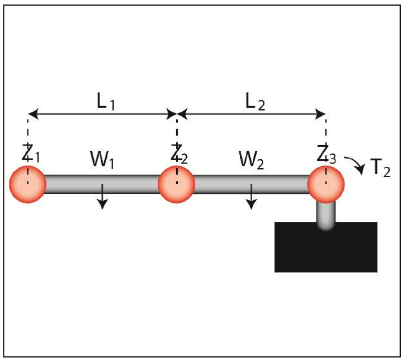


Fig. 2. The side view of the mechanical design. Wiring is sketched using the red lines

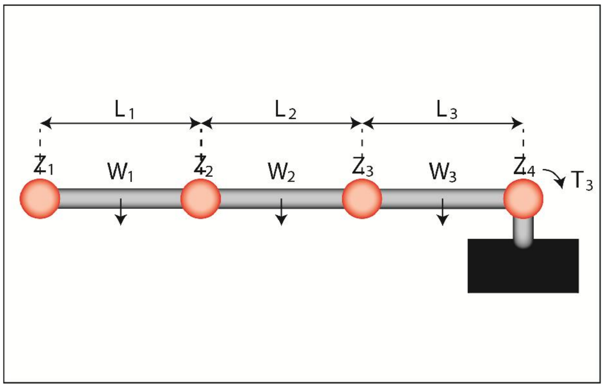
2.2 Torque Calculations



(a)



(b)



(c)

Fig. 3. Illustration of the position of the arm with different numbers of links for the torque calculations. L is the arm length, W is the arm weight, Z is the weight of the actuator.

Torque is calculated on the worst case scenario that the L1 is highest (where the arm is parallel to the Force = m*g (W1).

$$T_1 = L_1 Z_1 + \frac{1}{2} L_1 W_1 \tag{2}$$

As another link is added and the cables connected the open ended circuit is closed for the second link, and therefore the system understands that a link has been added. Therefore, it calculates the added links torque by the formula derived below.

$$T_2 = (L_1 + L_2) Z_1 + \left(\frac{1}{2} L_1 + L_2\right) W_1 + L_2 Z_2 + \frac{1}{2} L_2 W_2$$

$$T_2 = T_1 + L_2 Z_1 + L_2 W_1 + L_2 Z_2 + \frac{1}{2} L_2 W_2$$

$$T_2 = T_1 + L_2(Z_1 + W_1) + L_2(Z_2 + \frac{1}{2}W_2)$$

(3)

Torque values for 3DOF and 4 DOF is as follows.

$$T_3 = Z_1(L_1 + L_2 + L_3) + W_1\left(\frac{1}{2}L_1 + L_2 + L_3\right) + Z_2(L_2 + L_3) + W_2\left(\frac{1}{2}L_2 + L_3\right)$$

$$+ Z_3L_3 + W_3\frac{L_3}{2}$$

$$T_3 = T_2 + L_3(Z_1 + W_1) + L_3(Z_3 + \frac{1}{2}W_3)$$

$$T_4 = T_3 + L_4(Z_1 + W_1) + L_4(Z_4 + \frac{1}{2}W_4)$$

(4)

These formulas can be generalized for the cases different from 1DOF.

$$for\ i \in N\ \&\ i > 1,$$

$$T_i = L_i(Z_1 + W_1) + T_{i-1} + L_i(Z_i + \frac{1}{2}W_i)$$

(5)

Moment of inertia varies tremendously based on link numbers and sizes. Therefore, angular acceleration is not taken into consideration. Instead, the result is multiplied with a safety factor of 2, to account non-ideal actuators and joints.

2.2 Kinematic Calculations

Here are the forward kinematics calculations for the two link assembly.

$$x = L_1\cos(\theta_1) + L_2\cos(\theta_1 + \theta_2)$$

$$y = L_1 \sin(\theta_1) + L_2 \sin(\theta_1 + \theta_2)$$

$$x^2 + y^2 = L_1^2 + L_2^2 + 2L_1L_2 \cos(\theta_2)$$

$$\cos(\theta_2) = \frac{x^2 + y^2 - L_1^2 - L_2^2}{2L_1L_2}$$

$$x = L_1 \cos(\theta_1) + L_2(\cos(\theta_1)\cos(\theta_2) - \sin(\theta_1)\sin(\theta_2))$$

$$x = \cos(\theta_1)\,(L_1 + L_2 \cos(\theta_2)) - \sin(\theta_1)\,(L_2 \sin(\theta_2))$$

$$y = \cos(\theta_1)\,(L_2 \sin(\theta_2)) + \sin(\theta_1)\,(L_1 + L_2 \cos(\theta_2))$$

$$\cos(\theta_1) = \frac{x + \sin(\theta_1)\, L_2 \sin(\theta_2)}{L_1 + L_2 \cos(\theta_2)}$$

$$\sin(\theta_1) = \frac{(L_1 + L_2 \cos(\theta_2))y - L_2 \sin(\theta_2)\, x}{L_1^2 + L_2^2 + 2L_1L_1 \cos(\theta_2)}$$

(6)

Inverse kinematics calculations are also presented to validate the right positioning of the robotic arm. Here is the equation carried out for 2 links, L1 and L2 as an example.

$$\theta_2 = 180^\circ - \cos^{-1}(\frac{L_1^2 + L_2^2 - x^2 - z^2}{2L_1L_2})$$

$$\theta_1 = \tan^{-1}\frac{z}{x} + \cos^{-1}(\frac{L_1^2 - L_2^2 + x^2 + z^2}{2L_1\sqrt{x^2 + z^2}})$$

$$\theta_0 = \tan^{-1}\frac{y}{x}$$

(7)

Control of the robotic arm is rather simple for the case of a 1-link (L1) manipulator - where the end effector is attached directly to the shoulder (base). Only the θ1 angle gets the value according the coordinates of the moved arm. This configuration can be preferred when the arm is attached to a light mobile base such as an RC (Radio Control) car.

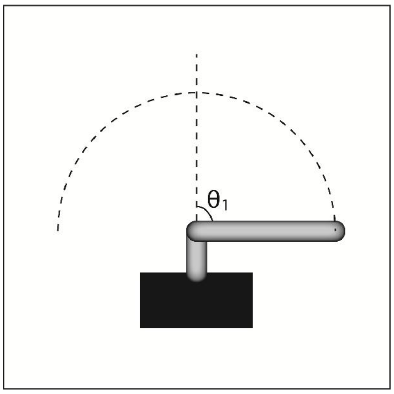


Fig. 4. Illustration of the end effector to the shoulder (*1 link*) assembly on the x-y plane.

When the second link is attached, creating a 2-link assembly, looking point of the end effector for arm to reach target first calculated. According to that measure, rest can be calculated.

When the end effector should be parallel to the floor the θ1 and θ2 angles should add up to 90 degrees at all time. First, the θ2 angle gets oriented by retrieving the θ1 angle. Then, increasing the θ2 angle, the arm reaches its destination.

When it needs to be perpendicular to the floor, the θ1 and θ2 angles should add up to 180 degrees at all time. Similarly, by increasing θ2, the arm reaches its destination

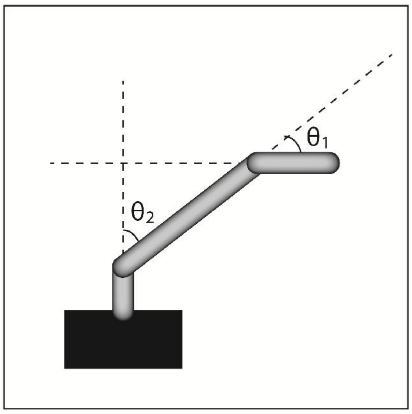


Fig. 5. Illustration of the 2-link (L2 and L2) assembly on the x-y plane.

Same procedure is applied for the 3-Link configuration (L1, L2 and L3). For the end effector to be parallel to the floor, the sum of θ1 + θ2 angles should be 90 degrees as well as the sum of θ1 + θ3 angles should be equal to θ2 + 90 degrees. First equation (θ1 and θ2 angles should add up to 180 degrees at all time) is taken account when increasing θ2 and second equation is taken account when increasing θ3.

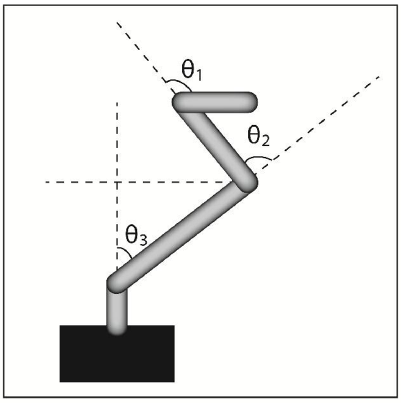


Fig. 6 Illustration of the L3-link assembly (L1, L2 and L3) on the x-y plane.

3 Conclusions and Further Work

As robotic applications have started to be used in daily life, the 20th Century science-fiction fantasy of the human-robot interaction may be in fact the common practice in near future. In this manner, the re-configurability and self-adaptability for a robotic arm has great potential in the future of the robotics. This paper illustrates a simple and low-cost solution to this kind of a robotic application.

Further work for this application consists of the production of the robotic manipulator using a 3D printer and its control using different motion control algorithms to test its performance and functionality. Afterwards, it will be implemented for a user-friendly mobile application as a personalized assistant robot.

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