Design and Analysis of a Passively Compliant, Biologically Inspired Robot Arm

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Abstract: *This paper is on the design and analysis of a robot arm that is passively compliant so as to safely interact with humans. The robot arm is actuated by Mckibben Artificial muscles which operate in an agonistic-antagonistic manner, and is an inspiration from the human biceps and triceps. The robot arm is a pick and place manipulator and the pick and place positions are derived using forward kinematics. MATLAB is used for calculating link positions, velocities and accelerations. Joint torques, joint angles and forces acting on the robot arm are also calculatedusing MATLAB. Solidworks is used in the design and analysis of the robot arm. The robot arm links are designed using Aluminum 6061 alloy and the joints are designed using acrylic (medium-hard) material to achieve the compliance that is required with the help of Pneumatic artificial Muscles(PAMs).*

Keywords: Passively compliant, Mckibben Artificial Muscles, Forward Kinematics, Revolute joints, pick and place positions, Von Mises stress

1. Introduction

When a robot is designed to operate in the same environment with humans, such as in domestic use or cooperative material handling tasks, its compliance is different from a robot designed for industrial purposes [1]. Compliance is one of the most fascinating characteristics of human joints. It gives the possibility to crash an aluminum can and also makes possible the grabbing of human internal organs gently.

Methods of achieving compliance in robots have been studied for a long time in robotic literature. In industrial robotics, accurate positioning of a manipulator or end effector is by far the most common application [2]. To achieve accuracy is very difficult for robots operating in the vicinity of human if there is to exist a danger free interaction. For this reason, compliant actuators and compliant joints have to be used so as to achieve passive compliance. In this paper, Pneumatic Artificial Muscles are used for actuating the robot arm. Pneumatic artificial muscles operate in the same manner as human biceps and triceps. Link positions and angles are calculated using MATLAB. The robot arm is then analyzed using solid works SimulationXpress software.

2. Biological Inspiration

The bio-robotic approach to solving problems is used to emulate the very properties that allow humans to be very successful [1]. Due to complexity of animals, both structurally and functionally, it is obvious that a complete reproduction of any animal in hardware or software is impossible [2]. The human muscles work by contracting. When a muscle contracts, it pulls the bone and the bone can move if it is part of the joint as shown in fig 1. Muscles can only pull and not push, this means they have to exist in pairs so that movement of the bone back to original position is achieved [3]. Owing to the biceps and triceps, Pneumatic Artificial Muscles are used and pneumatic energy is used for pulling the robot links. The PAMs that are used for actuation in this paper are Mckibben Artificial muscles.
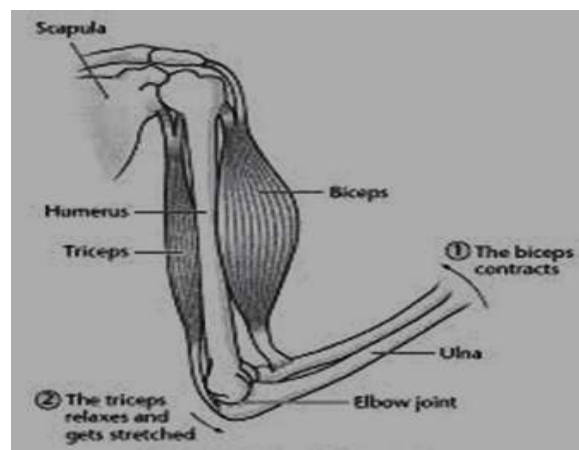

Figure1: Muscle interaction. Extract from Pam Walker and Elaine Wood, Muscle Interaction: Pairing of Biceps and Triceps. John Weiley and Sons, Inc, 2010 [3]

3. Achieving Compliance in the Robot Arm

Compliance cannot be fully defined by initial material properties or geometric configuration; other factors have to be taken into consideration. These factors include, but are not limited to, geometric boundary condition (location type), the loading situation (location, type, magnitude, direction and loading history) and the environmental conditions (thermal and chemical) [4]. In PAMs, compliance is due to the compressibility of air and as such can be influenced by controlling the operating pressures [5]. PAMs are extremely light weight and behave like nonlinear springs in their operation. Their stiffness is not constant throughout the operating period but changes with applied force [6]. The pneumatically actuated muscle consist of an inner bladder tube and an outer cord netting, both of which affect the compliance of the arm depending on the material used in their construction.[7]

On their own, PAMs cannot achieve passive compliance, as such, joints are designed using acrylic (medium-high) material which has a displacement that is greater than that of Aluminum 6061 used in link design. This material will allow the robot arm not to offer resistance to an external force of more than 441N so as to ensure safety if collision with humans occur. The properties of acrylic (medium-high) are listed in table 1.

Table 1: Properties of Acrylic (medium-high impact) material

Property	Value	Units
Elastic modulus	3000000000	N/m^2
Poisson's Ratio	0.35	N/A
Shear Modulus	890000000	N/m^2
Density	1200	Kg/m^3
Tensile strength	73000000	N/m^2
Yield strength	45000000	N/m^2
Thermal expansion coefficient	5.2e-005	/K
Thermal conductivity	0.21	W/(m-K)
Specific heat	1500	J/(Kg-K)

4. Robot Kinematics

For a robot to perform a specific task, the position and orientation of the end effector relative to the base should be established first [8].

4.1. Forward kinematics

In this design, forward kinematics was used to establish the coordinates at point P1 and P2 which are pick and place positions respectively.

Figure 2: Kinematic relations of a 2DOF manipulator

In forward kinematics, the position and orientation of the end effector of the manipulator are calculated when joint angles and link lengths are given [9]. Since the robot arm is a pick and place manipulator, two positions are critical in its motion, and these are the pick position and the place position.

For this robot arm all links have the same mass of 2.61kg and are of same length of 500mm. Angleθ_1=a=-60 degrees measured in anticlockwise direction since link L_1rotates about the y-axis. Angle θ_2=b=120 degrees but rotating in a clockwise direction about y-axis. LinkL_1 andL_2 give the first position P1. Angles for position P_2 areθ_1=c=-35^0 (anticlockwise) and θ_2=d=70^0 (clockwise). Forward kinematics is used to get point P1 and P2 and matrices to get the positions were calculated with help of MATLAB. DenavitHatenberg (DH) parameters shown in table 2helps in determining the variables for the matrices used to calculate the points P1 and P2.

Table 2: DenavitHartenberg (DH) parameters for RR manipulator

Link	d_i	θ_i	a_i	α_i
1	0	θ_1(JV)	L_1	0
2	0	θ_2(JV)	L_2	0

Table 2 shows that only θ_i is a variable since both joints are revolute and all the other parameters are constant. Using information from link length and link angles, 4x4 matrices are constructed which are used to determine the positions P1 and P2. The link motion is described by two matrices, a rotation matrix about y-axis and a translation matrix along x-axis, which are multiplied together. The link direction is along the x-axis because with a rotation of zero degrees the link will lie along the x-axis. The rotation about y-axis is given by the matrix:

$$Rot(z, \theta) = \begin{bmatrix} \cos\theta_i & 0 & \sin\theta_i & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta_i & 0 & \cos\theta_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Where for point P1θ_1=-60^0 and θ_2=120^0 and for P2 θ_1=-35^0 and θ_2=70^0.

The translation along x-axis is given by the matrix:

$$Trans(x, L_i) = \begin{bmatrix} 1 & 0 & 0 & Li \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Where Li=500mm for all links.

Since the robot arm shown in figure 1 has two links and two revolute joints, two sets of rotation and translation matrices are used to get the points P1 and P2. The rotation of both links is about the y-axis with link L_1 rotating in the anticlockwise direction i.e. negative direction and Link L_2 in the positive clockwise direction. The position of the end-effector is found by multiplying the matrices.

Table 3: Pick and place positions calculated using MATLAB

Point	X (mm)	Y(mm)	Z(mm)
1	499.9780	0	0
2	819.3290	0	0.2240

4.2. Link velocities

The relationship between the joint velocities and angular velocities is described by a matrix termed the Jacobian, which depends on the manipulator configuration. Since the two joints in the robot arm are revolute, it means the links will have angular motion and the angle $\theta_i$is the variable. Thus the Jacobian matrix of the two-link manipulator is expressed as:

$$J = [e_1 \times a_{1e} \quad e_2 \times a_{2e}] \quad (3)$$

Using MATLAB, the Jacobian for point P1 is:

$$J = \begin{bmatrix} 0 & -433.012 \\ 500 & 250 \end{bmatrix} \quad (4)$$

and The Jacobian for point P2 is:

$$J = \begin{bmatrix} 0 & -286.788 \\ 819.152 & 409.576 \end{bmatrix} \quad (5)$$

4.3. Link Accelerations

Acceleration expressions are obtained by differentiating the velocity expressions. This gives equation (6).

$$J = \begin{bmatrix} -a_1 c_1 s\dot{\theta}_1 - a_2 c_{12}(\dot{\theta}_1 + \dot{\theta}_2) & -a_2 c_{12}(\dot{\theta}_1 + \dot{\theta}_2) \\ -a_1 s_1 \dot{\theta}_1 - a_2 s_{12}(\dot{\theta}_1 + \dot{\theta}_2) & -a_2 s_{12}(\dot{\theta}_1 + \dot{\theta}_2) \end{bmatrix} \quad (6)$$

The accelerations were calculated using MATLAB program and the solutions are shown in table 4.

Table 4: Link accelerations to get to pick and place positions

P	Acc in mm/s^2 of link 1 in x direction	Acc in mm/s^2 of link 1 in y direction	Acc in mm/s^2 of link 2 in x direction	Acc in mm/s^2 of link 2 in y direction
P1	-500.000	-250.00	-433.01	-433.01
P2	-819. 152	-409.57	-286.78	-286.78

5. Forces and Moment Balance

Assuming a force **f** is acting on the end effector frame, that is frame 3 in figure3,the required joint torques are found as a function of the arm configurations and applied force components as shown in equation (7)

$$[f_{23}] \equiv [f_x \quad f_y \quad 0]^T \quad (7)$$

Note that gravity does not play any role when the manipulator is lying on the horizontal plane.

Figure3: 2 DOF RR robot arm applying a force

Referring to figure3:

$$[\mathbf{f}_{23}]_3 \equiv \begin{bmatrix} f_x \\ f_y \\ 0 \end{bmatrix} \quad (8)$$

and $[\mathbf{f}_{12}]_3 = [\mathbf{f}_{23}]_3$ for i = 2. Hence

$$[\mathbf{f}_{12}]_2 = \mathbf{Q}_2[\mathbf{f}_{12}]_3 = \begin{bmatrix} f_x c\theta_{2} - f_y \theta_2 \\ f_x s\theta_2 + f_y c\theta_2 \\ 0 \end{bmatrix} \quad (9)$$

Where the orientation matrix $\mathbf{Q}_2$ is given by:

$$\mathbf{Q}_2 \equiv \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 \\ s\theta_2 & c\theta_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (10)$$

Since no external moment, i.e. $\mathbf{n}_{23} = \mathbf{0}$ is exerted by the end effector, the moment $[\mathbf{n}_{12}]_2$ is obtained as:

$$[\mathbf{n}_{12}]_2 \equiv \mathbf{Q}_2[a_2 \times \mathbf{f}_{23}]_3 = [\mathbf{a}_2]_2 \times [\mathbf{f}_{23}]_2$$

$$= [a_2 \times f_{12}]_2 = \begin{bmatrix} 0 \\ 0 \\ a_2 f_y \end{bmatrix} \quad (11)$$

Where $[\mathbf{a}_2]_2 \equiv \begin{bmatrix} a_2 c\theta_2 \\ a_2 s\theta_2 \\ 0 \end{bmatrix} \quad (12)$

The force $[\mathbf{f}_{01}]_1$ and moment $[\mathbf{n}_{01}]_1$, are then evaluated as:

$$[\mathbf{f}_{01}]_1 = \mathbf{Q}_1[\mathbf{f}_{01}]_2 = \begin{bmatrix} f_x c\theta_{12} - f_y s\theta_{12} \\ f_x s\theta_{12} + f_y c\theta_{12} \\ 0 \end{bmatrix} \quad (13)$$

$$[\mathbf{n}_{01}]_1 \equiv \mathbf{Q}_1[\mathbf{n}_{12} + a_1 \times \mathbf{f}_{12}]_2 = \mathbf{Q}_1[\mathbf{n}_{12}]_2 + [a_1 \times \mathbf{f}_{01}]_1$$

$$= \begin{bmatrix} 0 \\ 0 \\ a_2 f_y + a_1 f_x s\theta_2 + a_1 f_y c\theta_2 \end{bmatrix} \quad (14)$$

and:

$$[\mathbf{a}_1]_1 \equiv \begin{bmatrix} a_1 c\theta_1 \\ a_1 s\theta_1 \\ 0 \end{bmatrix} \quad (15)$$

Where $\mathbf{Q}_1[\mathbf{n}_{12}]_2$ will have the same expression as $[\mathbf{n}_{12}]_2$ of equation (14).

Forces acting in link 1 with mass of the link, m=2.61kg:

$$fx_1 = m_1 g\cos\theta_1 = 2.61 \times 9.8\cos - 60 = 12.789N \quad (16)$$
$$f_{y_1} = m_1 g\sin\theta_1 = 2.61 \times 9.8\sin - 60 = -22.15N \quad (17)$$

Forces acting on link 2

$$fx_2 = m_2 g\cos\theta_2 = 2.61 \times 9.8\cos120 = -12.789N \quad (18)$$
$$f_{y_2} = m_{12} g\sin\theta_2 = 2.61 \times 9.8\sin120 = 22.15N \quad (19)$$

Finally the joint torques to generate the force f at the end effector are given by:

$$\tau_1 = a_1 f_x s\theta_2 + (a_2 + a_1 c\theta_2)f_y$$
$$= 500 \times 12.789\sin120 + [(500 + 500\cos120) \times 22.15]$$
$$= 11075.299Nmm \quad (20)$$
and
$$\tau_2 = a_2 f_y = 500 \times 22.15 = 11075Nmm \quad (21)$$

For the two link robot arm shown in figure3,Inverse dynamics for two link robot arm was used to calculate and plot the joint angle and torque graphs shown in figure4 and figure5 respectively.

The graphs were plotted using link lengths 1 and 2 equal to 500mm and the end points of joint angles for joints, θ_1 and θ_2 taken at end point with values $\theta_1(T) = \pi$ and $\theta_{2=} \pi/2$. The use of inverse dynamics is important for calculating actuator torques and forces particularly those based on robot dynamics. MATLAB was used to plot the graphs.
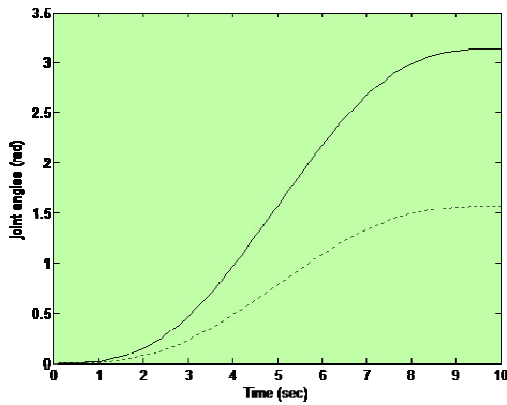
Figure4: Joint Angles of the Two Link Robot Arm generated by MATLAB with the vertical axis showing joint angles (rad) and horizontal axis showing Time (sec).
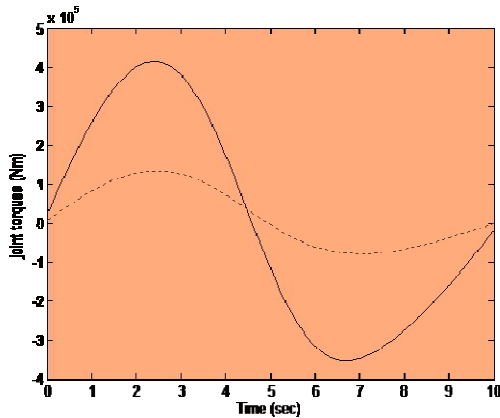

Figure 5: Joint Torques for the Two Link Robot Arm generated by MATLAB with the vertical axis showing joint torques (Nm) and horizontal axis showing Time (sec).

6. Analysis

Analysis of the design was done using Solid works SimulationXpress software. Both links of the robot arm have a length of 500mm and a diameter of 50mm and are designed using aluminum 6061. The standard mass of a 500mmx50mm aluminum 6061 alloy is 2.61kg. This means that its weight is:

$$w = mg = 2.61 \times 9.81 = 25.604N \qquad (22)$$

The calculated value of the weight of the link is 25.604N and the one from solid works SimulationXpress software is 21.8677N. The difference is because the link has a hole of diameter 16mm and depth 40mm that is to use to attach joint coupling. The link was analyzed using a force of 441N. This value was taken considering the fact that the robot arm is to be used in the same environment with people and a person with a mass of 45kg was assumed to be the lightest person who can come into contact with the robot arm. SimulationXpress uses Von Mises stress to determine whether the part will fail at a given load or not. Von Misses stress values are stress values that can simply compare with yield strength of the material. If the Von Mises stress is greater than yield strength, the part will fail (according to Von Mises criteria) and if less than yield

strength the part is said to be within yield criteria and will not fail.
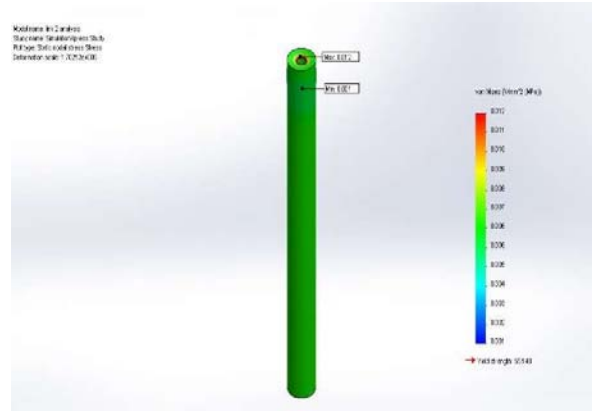

Figure 6: Analysis for static nodal stresses using SimulationXpress to get Von Mises stress.

The equation forgetting the VonMises stress is:

$$\sigma = \sqrt{0.5 \left[(\sigma_x - \sigma_y)^2 + \left(\sigma_y - \sigma_x \right)^2 + (\sigma_z - \sigma_y)^2 \right] + }$$
$$\sqrt{3 \left(\tau_{xy}^2 + \tau_{yx}^2 + \tau_{xz}^2 \right)} \qquad (23)$$

Where σ corresponds to normal stress values and τ corresponds to the shear values.

By using Von Mises stress criteria, the link will not fail since the yield strength of the material is $55.148N/mm^2$ which is greater than the maximum Von Mises stress of the link which is $0.0115711N/mm^2$.

Figure7 and figure 8 show the analysis done on joint coupling using SimulationXpress. The joints were designed using acrylic (medium-hard material). A comparison of Aluminum 6061 and acrylic (medium-high)was done and results are shown in Table 5.

7. Discussion

The results in table 5 shows that under the applied load of 441N, maximum Von Mises stress of Acrylic is lower than that of Al 6061 even though both are lower than their respective yield strength. This implies that both materials will not fail under the given load. The minimum displacement of both materials is 0Thisshows that the part will not break away from its fixed position under the given load. Acrylic (medium-high) has more displacement on the free end than Al 6061. These displacement values show that the flexibility of Acrylic is more than that of Aluminum which makes Acrylic a more suitable material for the joint design to achieve passive compliance.
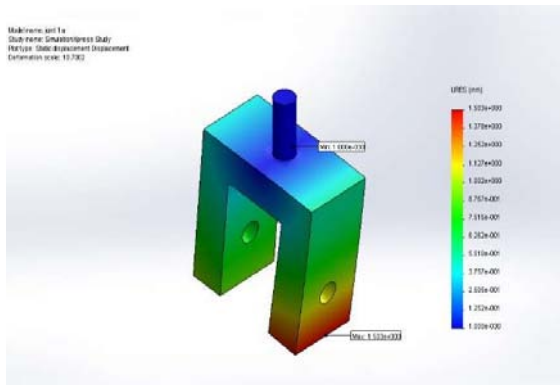
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Figure 7: SimulationXpress showing displacement of Acrylic (medium-high) under a load of 441N on robot joint 1a coupling
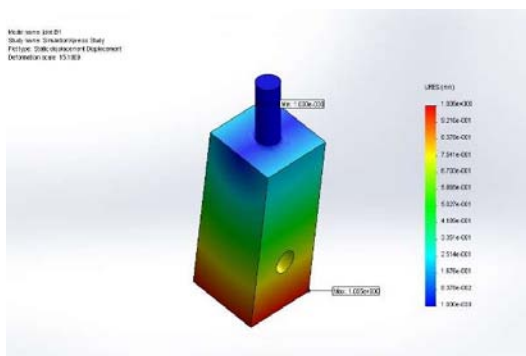

Figure 8 SimulationXpress showing displacement of Acrylic (medium-high) under a load of 441N on robot joint 1b coupling

If the load applied to the joint is increased to 1500N, Acrylic will fail but Aluminum will hold up since the Von Mises stress for Acrylic will be 67.690N/mm^2 which is more than its yield strength of 45N/mm$^{2.}$

Table 5: Comparison of Al 6061 and Acrylic (medium-high) material under a load of 441N

Yield strength	55.14N/mm^2	45N/mm^2
Tensile strength	124.08N/mm^2	73N/mm^2
weight	8.9092N/mm^2	3.95967N
Min Von Mises stress	8.9096e-006N/mm^2	4.27589e-006 N/mm^2
Max Von Mises Stress	40.35N/mm^2	19.9008 N/mm^2
Minimum Displacement	0	0
Maximum displacement	0.131762mm	1.5029mm

For this design though, the applied force will be below 900N since the robot arm is designed for a payload of 1kg. This therefore means that the robot joint is safe and suitable for the intended use.

8. Conclusion

The use of acrylic (medium-high) material for revolute joints ensures that passive compliance is achieved. Acrylic (medium-high) is not too flexible to fail while lifting the intended robot arm payload of 1kg. Increasing the force to a value greater than 441N makes acrylic (medium-high) less rigid and more compliant. This makes the robot arm

safe to be used in the same environment with humans. By using PAMs, who have a high power to weight ratio of 400:1, heavy gearing of joints is avoided which means no unnecessary weight is added to the joints.

9. Future Scope

In this era of technological advancement, more robots will be designed which will interact more with humans. Those being the case, new materials have to be developed to suit specific environments and tasks. The use of composite materials, which are materials whose properties are designed to be superior to those of the constituent materials, in compliant mechanisms will help in achieving passive compliance easily.

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