Investigating the Possible Actuation Mechanisms for the Dynamic Hand-like Structure

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Chapter 1

Actuator Selection

1.1 Introduction

In the research area of emotionally expressive movements, studies such as [1] suggest that hand-like structures are capable of expressing emotion through movement. So far, these works have used ~~structure made in computer~~ animation to carry out their research. In order to ~~further confirm the results of this research in the physical world~~, a physical and dynamic hand-like structure ~~that is~~ capable of performing ~~the~~ emotionally expressive motions has to be implemented. One ~~very~~ important design question ~~on~~ these dynamic structures is how the~~ir~~ motion ~~will~~ be actuated. In this work, the possible actuation solutions ~~that can provide the capability~~ of performing emotionally expressive motions on a hand-like structure~~,~~ are investigated. In order to ~~organize~~ the decision making process between the different possible actuation methods, a set of criteria and constraints were defined. These criteria and constraints were based on the ~~applications intended~~ for the dynamic hand-like structure ~~which is mainly~~ emotional conveyance through motion. Since a hand-like structure is ~~intended for~~ this research, the actuation methods ~~on the~~ current robotic hand designs in the literature were investigated in order to determine what actuation methods are possible candidates that can meet the defined criteria and constraints. The investigation revealed that, DC (Direct Current) motor actuators and pneumatic artificial muscle (PAM) actuators are both capable of meeting the criteria and constraints. ~~How well these actuation methods meet the criteria and constraints was relied upon in order to make the final conclusion on which actuation method is most suitable for providing the dynamic movement of this structure.~~ The actuation method ~~that was concluded~~ to be the most suitable candidate was a type of PAM design called curved PAMs. This actuation method met the criteria and constraints better than the other candidates and also ~~it~~ provided ~~some other~~ advantages that were no part of the initial ~~analysis of the research~~.

1.2 Mechanism Structure

~~In order to be able to determine an optimal actuation method for the dynamic structure of this research, more information is required on the mechanical specifications of this structure. It is important to note the emphasis on the fact that the structure intended for is only similar to human hand and the~~ ~~purpose here~~ is not to copy the structure of the human hand and mimic its motions. ~~This is why the term dynamic hand-like structure is used to refer to the structure instead of just using robotic hand.~~ Looking at the motions performed by the hand structure in [1], it is observed the movements in the study ~~are all mostly made up~~ of closing and opening the fist ~~at different dynamics with different patterns~~. This observation~~,~~ lead to the assumption that a hand-like structure capable of imitating opening and closing ~~of the fist~~ at different ~~dynamics~~ will be capable of conveying the same emotions ~~through the similar movements~~. ~~In order to perform the actuation method analysis, this assumption was used as guide to purpose a possible mechanical design for the hand-like structure.~~ A mechanical structure illustrated in figure 1.1 is an example of a hand-like mechanical structure that will be used for the actuation method analysis of this ~~research.~~

~~Essentially,~~ the structure consists of the three middle fingers of the hand that are placed on top of a static palm. The kinematic models of the fingers are the same.

Figure 1.2 ~~is~~ the kinematic structure of the fingers ~~in this hand~~. ~~The~~ finger has 4 DOFs consisting of 4 revolute joints (J1-J4) and 3 links. J1 and J2 represent the MP (metacarpophalangeal) joint in the finger with 2 DOF. J3 represents the PIP (proximal interphalangeal) joint and J4 represents the DIP (distal interphalangeal) joint. MP, PIP, and DIP joints of the human finger are illustrated in figure 1.3

The link between the MP and the PIP joint is ~~considered~~ to be $6cm \times 2cm \times 2cm$. The link between the PIP joint and the DIP joint is ~~considered~~ to be $5cm \times 2cm \times 2cm$. The link after the DIP joint is ~~considered~~ to be $4cm \times 2cm \times 2cm$. These result in the dimension of the finger when the joints are at 0^o to be $15cm \times 2cm \times 2cm$ which is almost twice the size of an average human middle finger.

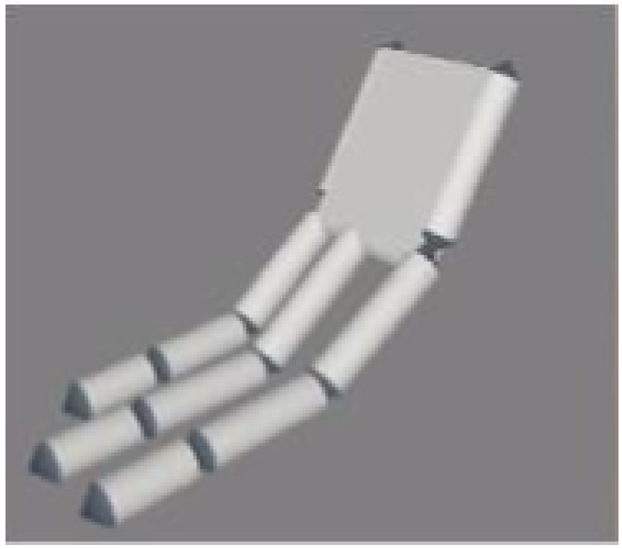


Figure 1.1: Example of a hand-like mechanical structure

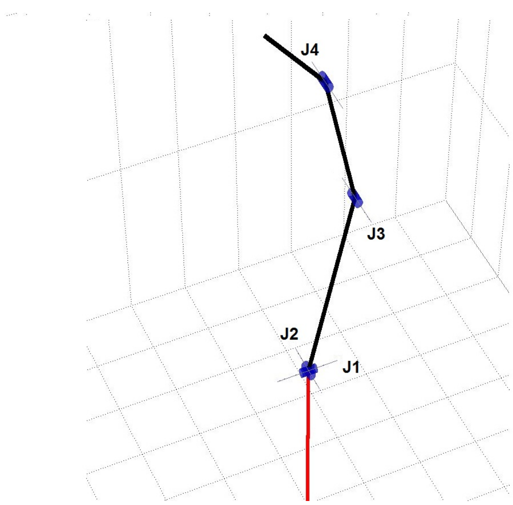


Figure 1.2: Finger Kinematic structure created using the robotics toolbox by [2]

1.3 Comparison Analysis on the Actuation Methods

~~As discussed,~~ the dynamic mechanism intended ~~for this research will~~ be similar to the structure of the human hand in terms of shape and kinematic structure. Due to this similarity, the actuation methods for robotic hands are chosen to be the strongest candidates

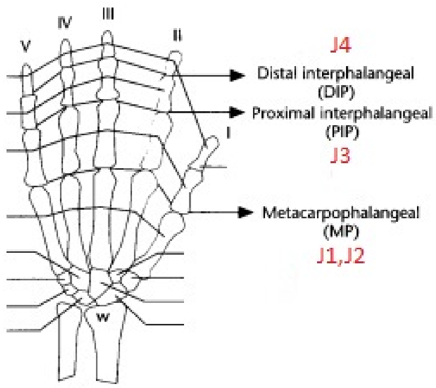


Figure 1.3: Human finger joint names [3]

for the actuation of this structure. In current literature, there is a variety of actuation methods used for robotic hands. This variety is mainly due to the applications that are desired from these robotic hands. For example, some robotic hands are intended for grasping objects. For these robotic hands, force control is essential and compliance is very desirable [4]. However, there are other robotic hands that are intended for dexterous movements and fast responses. For these applications, compliance is undesirable and usually position control is used to achieve fast and precise movements [5]. For each of these examples, the intended application dictates the criteria to be used for choosing the suitable actuation method.

1.3.1 Actuator Criteria

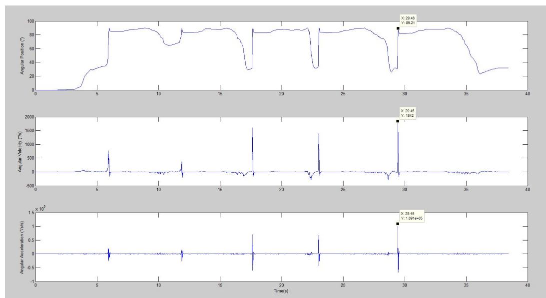
For the hand-looking dynamic structure envisioned for this research, the ultimate application is t~~hat the structure is emotionally expressive~~ through ~~its~~ movements. [1] suggests that in order for the structure to convey different emotions, the range of motion, the maximum velocity and the maximum acceleration achievable by the structure are particularly important and highly impact the expressiveness of the structure. Therefore, the actuation method for the structure has to be capable of providing movements ~~on the structure~~ that ~~meet the criteria on th~~e range of angular motion, angular velocity and angular acceleration. In order to determine the required level for each criterion, the motion data used for the animations in [1] are analyzed. Three emotions of sadness, joy and anger were studied in this paper. The motion data for each emotion was captured using data gloves. The time series motion data from the glove consisted of the angular data of all of the revolute

Criterion	Required Value		Unit of Measurement	
Range of Motion	π/2	90	rad	°
Max Angular Velocity	35	1.96×10^3	rad/s	°/s
Max Angular Acceleration	1.9×10^3	1.09×10^5	rad/s^2	$°/s^2$

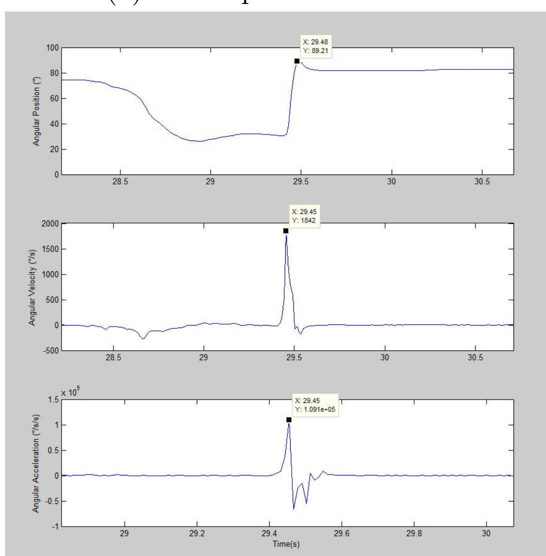
Table 1.1: Criteria on the motion of the MP joint

joints in the hand. These motion data sets were used to determine the maximum range of angular motion, angular velocity and angular acceleration. First the maximum range of angular motion for each joint was calculated. ~~Essentially,~~ the maximum and minimum angular position of each joint in the time series was determined and their difference was considered to be the range of motion on that joint. The maximum range of motion within all of the joints was chosen as the required range of angular motion. Second, the time series data was differentiated using discrete time differentiation. ~~The resulting time series was considered to be the time series data for the angular velocities of the joints.~~ The maximum magnitude of angular velocity was then calculated for each joint. The highest maximum angular velocity was chosen as the required angular velocity. Third, ~~similar to how the angular velocities were calculated,~~ the angular accelerations were calculated by differentiating the angular velocities of the joints. The maximum angular acceleration within all of the joints was chosen as the required angular acceleration. Figure 1.4 illustrates the time series data of the angular position, angular velocity and the angular acceleration. As the visual inspection of the animations suggested, the motion of the MP joint of the middle finger in angry motion possesses the highest range of angular motion, angular velocity and angular acceleration. ~~As mentioned, the same motion data used for the animation in[1] will be used to reproduce the emotional movements on the physical hand-like structure. Therefore, the selected actuation method has to enable the revolute joints on the structure to achieve the same range of motion, angular velocity and angular acceleration.~~ The required values for the three criteria are given in Table 1.1.

In order to compare the actuator designs using these criteria, the worst possible situation that the actuator can face is examined. Figure 1.5 illustrates the worst case scenario, when trying to produce dynamic motions that meet the criteria. In this scenario, the MP joint is at $-\pi/2 rads$ from the origin. The intended dynamic motion at the MP joint is for the finger to move back to its resting position at $0°$ with an acceleration of $1900 rad/s^2$ and a max velocity of $35 rad/s$. This motion is similar to the joy motion where a closed fist opens up to a full open hand with high accelerations. However, since the worst case scenario has to be considered, the maximum possible inertia has to be considered for the finger. Thus,



(a) Entire periodic data set



(b) Maximum acceleration iteration

Figure 1.4: Anger motion dynamics

the finger's PIP and DIP joints are fixed at $0°$ keeping the finger fully extended and the inertia at maximum during the entire period of the motion. The force of gravity is also working against the intended motion for the finger. Therefore maximum torque is required on the MP joint in this configuration. ~~The size of the finger was considered to be twice the size of an average human finger, $16cm \times 2cm \times 2cm$.~~ Because the finger is fully extended, it is assumed to be a rigid rod of length r_F with the center of gravity at its halfway point. The maximum radius of the the MP joint can be $r_P = 1cm = 0.01m$ any radius ~~higher~~ will cause the joint to be larger than the fingers. The maximum actuator force is defined as F_m. The maximum acceleration for the motion is defined as $\alpha_m = 1900rad/s^2$. The mass of the finger is m and lastly the gravitational acceleration is $g = 9.8m/s^2$.

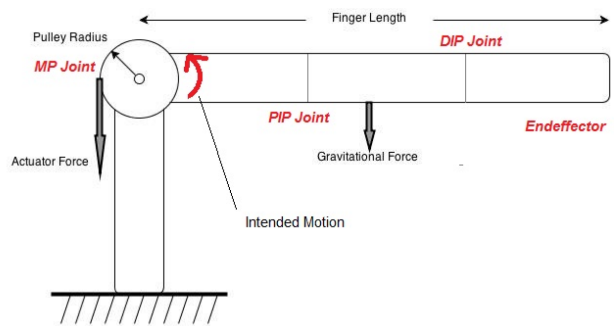


Figure 1.5: Worst case faced by the actuator

$$\tau_j = \tau_m - mgr_F/2 \tag{1.1}$$

Equation 1.1 defines the torque τ_j at the MP joint in terms of the torque by the actuator τ_m and the torque applied to the joint by the gravitational force $mgr_F/2$. Note that in case of linear actuation, equation 1.3 relates the force by the actuator to the torque applied to the joint.

$$\tau_j = \alpha_m I \tag{1.2}$$

$$\tau_m = F_m r_P \tag{1.3}$$

where

$$I = mr_F^2/3 \tag{1.4}$$

From equations 1.1-1.4, equations 1.5-1.6 are obtained which provide the relationship between the maximum required torque or force form the actuators and the mass of the finger.

$$\tau_m = m(\frac{\alpha_m r_F^2}{3} + \frac{g r_F}{2}) \tag{1.5}$$

$$F_m = \frac{m}{r_P}(\frac{\alpha_m r_F^2}{3} + \frac{g r_F}{2}) \tag{1.6}$$

1.3.2 Actuator Constraints

In addition to the criteria which have to be met by the candidate actuation mechanisms, there are also constraints that ~~unlike the criteria do not have to be met but it will be very advantageous if they are met~~. The first constraint ~~is regarding~~ the quality of the movement of the structure which has to be natural looking and not machine like. This constraint is highly qualitative, making it difficult to measure and scale. However, to achieve a basic decision making scale, a smooth motion with no sudden jerks or accelerations can be correlated with a natural looking movement. Therefore, mechanical side effects such as motion stutters and jitters which are mainly caused by stiction between the moving parts are highly undesirable. This means that actuation mechanisms less prone to these mechanical side effects are desired. The second constraint is ~~on~~ the amount of audible noise produced by the actuation mechanism. Audible noise~~s are~~ undesirable during the motion of the structure as ~~they~~ can interfere with the ~~conveyance~~ of the intended emotion performed by the structure. The third constraint is on the size of the actuation mechanism. ~~As mentioned, the envisioned structure for this research consist of three finger-like structures each twice the size of an average human finger.~~ It is highly desirable that the actuation method does not restrict the shape and size of the hand. The forth constraint ~~is regarding~~ the compliance capabilities of the actuation mechanism. While the dynamic structures intended for this research are mainly for ~~display~~, the possibility of the structure physically interacting with the human environment around it exists. In that case, the compliance of the structure becomes ~~really~~ important both in terms of safety and also in terms of feeling natural and not machine like. The last constraint ~~on the actuator mechanism~~ is ~~the~~ cost ~~of the mechanism.~~ ~~While the most suitable actuation mechanism is desired to be used for this research, the cost of the selected actuation mechanism should be feasible for the research group. Especially considering that eventually multiple of these structures will be needed later on,~~ cost of one prototype should be no more than \$500 CDN. Table 1.4 lists the ~~discussed~~ constraints and their desired values.

Constraint	Desired Value or State
Natural Motion	Yes
Audible noise	Low
Size	15cmx2cmx2cm
Compliance	Yes
Cost	<500$

Table 1.2: ~~Criteria on the motion of the MP joint~~

1.3.3 Actuator Placement

~~Actuators are the source of kinetic energy for the joints of the robot. The question of where to place these sources of energy on the structure is a very important design question.~~ Springer robotics handbook [6] provides an intuitive categorization of actuator placement in robotic hand designs. The handbook suggests two placement methods ~~for actuators.~~ ~~The first method is in-site actuator placement.~~ In ~~this method,~~ the actuator is either placed on the axis joint without any transmission mechanism or it is placed on the two links that constitute the joint. ~~The second placement method for actuators in robotics hand is remote actuator placement.~~ ~~In this method~~ the actuator of a joint is placed away from the joint and its constituting link. The kinetic energy of the actuator is transferred to the joint using ~~different~~ transmission mechanism. ~~Using flexible elements or tendons is the most common transmission mechanism to transfer the energy of the actuator to the joint.~~ Since in this placement method the actuators are not placed on the movable parts of the structure, there are much looser constraints on the size and the mass of the actuator. Therefore, better actuation performance~~s~~ such as higher torques and higher operational velocities can be achieved at lower cost~~s~~. N~~ote that~~ in comparison to the other constituting parts of a robotic structure, actuators have high masses. Therefore when they are not placed on the moving parts of the robotic structure the required ~~amounts of energy and~~ torque to move the structure at the desired velocities and accelerations ~~are~~ reduced. ~~As mentioned,~~ flexible tendons are mainly used as the transmission mechanism for remote actuators. These cables are guided through the structure of the robot using pulleys and sheaths. These guiding mechanisms are sources of static and kinetic friction~~s~~. The static friction makes the control of the joint more difficult. More importantly static friction results in an unnatural, jerky and machine looking movement of the structure. The kinetic friction results in loss of energy and brings down the efficiency of the system. ~~Also, the assumption of the tendons being entirely non-elastic is not a correct assumption either. In reality the tendons do stretch when tension is applied. The~~ stretching of the tendons reduces the transmission efficiency and ~~it~~ produces lag in the movement response of the joints, making their control more difficult. Because of the reduced number of moving and guiding elements in in-site actuation designs, there is less friction in the transmission of ~~the~~ energy. Therefore, the movement of the joints is smoother or more natural looking and the transmission of energy is more efficient. Another less important benefit of in-site actuation is that there is a possibility of designing a modular structure with each module being operable individually. Modular designs provide the ~~ability of rearranging~~ the parts of the structure and design~~ing~~ new configurations easier and quicker. This advantage is not very important at this stage of the research but can be more beneficial at the later stages ~~of the research~~. The clear disadvantage of in-site actuation is that it ~~puts a high constraint on~~ the size and the mass of the actuators. This makes the design of these systems more difficult as the weight of the movable parts of the structure becomes more important. Also more efficient actuation designs with higher power to weight ratios need to be used, most likely increasing the cost.

1.4 Actuator Selection

In the field of robotics, a variety of actuation mechanisms and solutions exist for different type of applications and structures. ~~In the case of this research, the selected actuation method has to satisfy all of the criteria on the dynamic movement of the structure. It also should satisfy as many of the constraints as possible.~~ [7, 6] analyze the different types of actuation mechanisms available for robotic applications. Five main ~~type of~~ actuation methods are ~~suggested by these references~~. Electric energy based ~~actuators are,~~ electro-magnetic direct current motors and Electroactive Polymers (EAPs)~~ actuators.~~ Pressurized fluid based~~ actuators are,~~ pneumatic and hydraulic actuators~~. Lastly~~ heat energy based ~~actuators are~~ Shape Memory Alloys (SMAs)~~ actuators~~. These actuation methods have to first be examined against the three criteria of range of motion angular speed and angular acceleration. In the ~~primitive~~ stages of the analysis, it was clear that SMAs cannot provide the required speeds and acceleration. [8, 9] The motion of SMA actuators is heat dependent and their stretch or expansion rate is directly dependent on the cooling rate of the actuator [10]. These rates are usually slow except for some rare cases such under water applications [11]. Therefore SMAs are not ~~a~~ suitable ~~candidate~~ for the actuation method of the dynamic structure of this research. ~~In addition to SMAs, while~~ hydraulic actuators and EAP actuators ~~can theoretically achieve the actuation criteria, they are still not suitable candidates for the actuation of the dynamic structure in this research,~~ EAPs are ~~relatively~~ a new concept for actuation and are still in the research and experimental stages [12]. Therefore due to availability issues, EAPs cannot be considered as candidates for the actuation ~~of this research structure~~. As for Hydraulic actuators, they have two main issues. ~~Their first issue is liquid fluid leaks [6].~~ Liquid leaks have a high possibility of interfering with the emotion conveyance of the structure if they become visible during the movements of the structure. The second issue with hydraulic actuators is that for full range control, they require very expensive high speed and high pressure valves [6]. In general hydraulic actuators are only superior to pneumatic actuators in terms of ~~amount of~~ force ~~that they can~~ output [7, 6]. The cost of control valves for pneumatic actuators is more reasonable. ~~Also if they have leaking issues, due to the invisibility of air they will not interfere with the emotion conveyance of the structure during movement.~~ Therefore unless pneumatic actuators are incapable of producing the required amount of force for the dynamic motion of the structure, pneumatic actuators are the better candidate for this application between the two pressurized fluid based actuators. ~~This means that~~ pneumatic actuators and electromagnetic DC motors ~~are~~ the main candidates ~~for the actuation of the hand-like dynamic structure in this research~~.

1.4.1 Electromagnetic Direct Current (DC) Motors

Electromagnetic DC motors are ~~very well known actuators~~ available in variety of designs. ~~Brushed and brushless dc motors are the two main designs for this actuator.~~ Brushed DC motors ~~are mainly known for their~~ simpler design~~s which intern brings down their~~ cost. In robotics, however brushless dc (BLDC) motors are ~~more~~ preferred~~. BLDC motors are more suitable for robotics applications~~ because they provide better efficiency, operate at higher speeds, have smoother torque outputs, and have longer lifetimes. DC motors in general operate at high angular velocities and low output torques. ~~This makes direct drive DC motor actuation unsuitable for most applications in robotics.~~ A variety of torque increase mechanisms are available~~ for DC motors.~~ Harmonic drives are ~~one these mechanisms that are very popular~~ for robotic applications~~. Harmonic drives have~~ high torque increase ratios, negligible backlash, and are very light weight [6]. Gearboxes ~~are also~~ used for increasing the torque output of DC motors ~~because of their simpler designs and lower costs. In recent years, the popularity of using gearboxes~~ in robotics ~~is lowering~~ ~~most importantly~~ because of ~~their~~ backlash. Generally backlash is undesirable ~~in robotics~~ because it creates difficulty in controlling the exact position of a joint. In other words, backlash makes it more difficult to achieve zero steady state error. For the applications of this research however steady state error of the joints and in turn the steady state error on the posture and position of the structure does not ~~require~~ to be zero. In fact a small and reasonable amount is desired. The desired amount of steady state error will be discussed further in the thesis. Small steady state errors are desired because the movements of biological mechanisms such as human hand fingers do possess steady state errors to some degree. Gear backlash is still undesirable in this research because the free play that is created at the end of the links of the finger due to backlash can create very unnatural and machine looking movements.

Among the numerous robotic hand designs ~~that were studied in this research,~~ DC motor was the most type of actuation method used ~~in these designs~~. All of these design ~~as expected~~ used BLDC motors. All ~~of~~ motor drives also had torque increase mechanisms applied to their output before their power was transferred to the joint. Harmonic drives were the most common torque increase mechanism used in these designs. In term of actuator placement, both in-site and remote actuator placements were used. ~~A primitive analysis was done on the DC motor actuation designs that were observed in the literature for robotic hands.~~ Within all of the observed designs, four main groups of DC motor designs were found which could theoretically meet the criteria and the constraints of this research~~.~~ Remote DC motor actuation using flexible elements, in-site actuation using bevel gears, in-site actuation using screw and, in-site actuation using rigid tendon ~~are the four main groups of DC motor actuation methods that were observed in academic and industrial literature on robotic hands~~. In the following sections a brief explanation of these DC motor designs and ~~the possibility of them meeting the~~ criteria are given. ~~At last,~~ a conclusion with respect to the criteria and the constraints is provided.

In-site Actuation Using Bevel Gears

Bevel gears in general have the purpose of tilting the axis of rotation of gearing mechanisms. In robotics, they are usually used to rotate the axis of rotation of the actuator by 90°.The rotation of the axis allows for the DC motor to ~~be place~~ in the link before or after the joint. Similar to normal gears, bevel gears provide bidirectional actuation and they can be used to increase the torque. Also similar to normal gears they have backlash. [5] is a good example of bevel gears being used in robotic hands. Similar to the hand-like structure intended for this research, the hand in [5] consist of three fingers. BLDC motors coupled with harmonic drives ~~for torque increase~~ are the actuators ~~used for this hand~~. The DIP and the PIP joints on the finger are actively actuated and their actuators are placed in-site. The actuators for the DIP and the PIP joint are placed in the previous link of the joint and 1:1 bevel gears are used to rotate the axis of rotation of the motors to the axis of the joints. In [5] the mechanical specifications of the structure and the actuators are provided. The maximum torque that the MP and PIP joint can provide is $1.71Nm$ and the maximum angular speed that the actuators can reach is $300rpm = 1800°/s$. The actuators on these joints weigh $60g$. The actuator~~s~~ on the DIP joint is $25g$. The entire structure is claimed to be $< 800g$ ~~this mean~~ that each finger weigh $\frac{800g}{3} - 60g \approx 200g$. Note that since the actuator of the MP joint is not placed in the movable finger its mass is ~~subtracted~~. $1800°/s$ angular velocity is within 8% range of the criterion on this category which is $1960°/s$. The maximum allowable mass of the finger can be obtained by substituting the maximum output torque of the actuator as $\tau_m = 1.71Nm$ in to equation 1.5 with the rest of the variables in the equation kept the same as defined before. The maximum allowable mass turns out to be $m = 114g$. Considering that the two actuators for the DIP and PIP joints weigh $25g + 60g = 85g$, that leaves $114g - 85g = 29g$ for the rest of the structure of the finger ~~which are basically~~ the bevel gears, ball bearings on the joint axis and the cover on the fingers. Keeping in mind that in [5] the mass of the bevel gears, the bearings and the cover of the finger was is around $200g - 85g = 115g$, while it is not impossible to achieve the $29g$ mass for these parts, it is ~~unnecessarily~~ difficult and most likely costly. The better solution would be to increase the torque output of the actuators. The reduction ration of the harmonic drive cannot be increased since that will reduce the maximum angular velocity ~~even more~~. In [5], most likely to keep the entire hand small in size the MP joints use the same actuators as the PIP joints ~~actuators~~. However since the actuators for the MP joints are not on the movable fingers and are located on the stationary base, their size and mass can be increased. This in turn means more motor winding, allowing more current which will increase the output torque and the maximum angular velocity. Assuming that the fingers of the dynamic structure ~~in this research~~ are designed to have a mass of around $200g$ similar to [5], the maximum torque required for the MP joint actuator using equation 1.5 is $\tau_m = 2.997Nm$. The range of motion of the MP and PIP joints in [5] are also provided to be $-\pi/2 to \pi/2$. This is well ~~beyond the criterion on the~~ range of motion required from the actuators.

In-site Actuation Using Rigid Links

Rigid tendons transfer the energy of the actuator to the joint using a rigid link that lets the actuator ~~to~~ rotate the joint in both directions. [13] and [14] are two examples of rigid tendons being used in robotic hands. Both of these examples are commercial robots and unfortunately their mechanical and actuator designs and specifications are not ~~as~~ available ~~as academic examples~~. Figure 1.6 illustrates a simple rigid tendon design. The actuation is still in-site as the actuator cannot be placed on any link further than the link previous or next to the joint. However, rigid tendons provide the ability to place the actuator of a joint all the way at the other end of one of the links leading to the joint. This brings the benefit of lowering the inertia of the structure as the high weight actuators can be placed closer or even on the rotation axis of the previous joint. Rigid tendons do not have backlash. They also provide bidirectional actuation and they can be used can be used at torque ratios other than 1:1 to increase or decrease torque output. Since rigid tendon designs can provide 1:1 torque ratios, same BLDC motors and harmonic drives used for bevel gear designs can be used to drive the system at the dynamic performances required by the criteria. In fact in rigid tendon designs the constraint on the output torque of the actuator could be weaker. This is because ~~as explained earlier,~~ rigid tendon designs usually have lower inertias than other in-site designs ~~such as bevel gear designs~~ due to the more efficient placement of the actuators. One issue with rigid tendon designs is that they require the axis of the actuation and the joint to be parallel. In the case of the PIP joint in the finger structure~~s~~ this is not a concern~~ing issue~~ because the actuator can be placed in the stationary base of the finger. However, for the DIP joint, this is an issue because the actuator can at most be placed at the PIP joint which is still on the movable part of the structure. Since the motor and drive system has to be placed horizontally to be parallel with the DIP joint, the actuation system will not meet the size constraint of the hand. Rigid tendons do complicate the mechanical design of the structure as well because the entire traveling space of the tendon has to be considered and no mechanical interference should exist in that travelling space. Rigid tendons can also reduce efficiency due to friction.

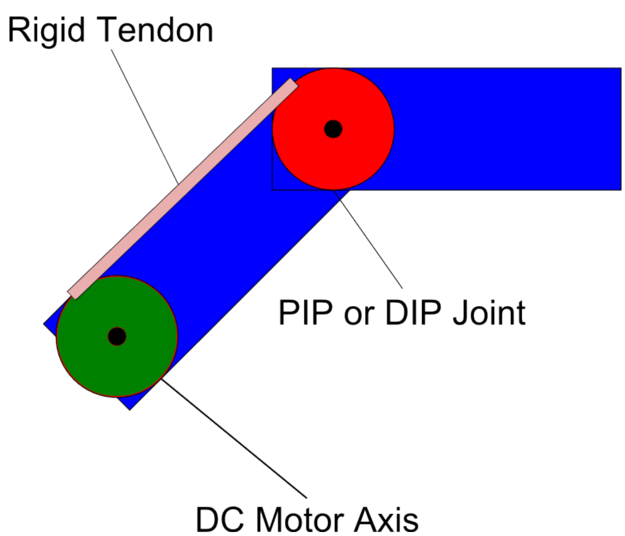


Figure 1.6: Simplified Rigid Tendon Design

In-site Actuation Using Ball Screw

In worm screw transmission design, the rotational movement of the dc motors is converted to linear movement using a screw mechanism. Figure 1.7 provides an example of ball screw gearing in a finger like structure. As illustrated, the linear bidirectional force provided by the ball screw actuation mechanism is used to pull and push against the next link in the structure. Ball screw designs have a relatively high range of torque ratios and therefore BLDC motors in these designs are usually not coupled with harmonic drives and their output torque is applied directly to the screw gear. The omission of harmonic drives brings the relative cost of this design down considerably. Ball screw designs also have backlash. Efficiencies are lower due to the friction between the ball and the screw teeth.

[15] is an example of ball screw gearing used in robotic hands. In this example, BLDC motors coupled with ball screw gearing produced by Faulhaber are used. The specification manual by Faulhaber [16] suggests that the maximum possible linear velocity achievable by these actuators is $150mm/min = 2.5 \times 10^{-}3m/s$. This maximum linear velocity translates to maximum angular velocity when the actuator is pulling on the link perpendicularly. Looking at the mechanical design of the finger, it is observed that perpendicular force cannot be applied to the link. However, for the purpose of analysis assume that actuator is pulling perpendicularly. Assuming that the actuator is applying force to the link is 1cm away from the joint, the resultant angular velocity at the joint would be, $\omega = 2.5 \times 10^{-}3/0.01 = 0.25rad/s$ this ~~is~~ angular velocity is lower than the required angular velocity of $35rad/s$ by an order of more than 100. Since this actuation design for DC motors clearly cannot meet one of the criteria, it is not ~~suitable for the applications intended for the dynamic structure of~~ this research.

Remote Actuation with Flexible Elements

In this actuation method, the power of the DC motor is transmitted to the joint using flexible elements or tendons. [17] , [18], ,[4],[19] are all different examples for tendon actuation designs for a hand like structure. In comparison to in-site actuation designs such as the bevel gear design, the tendon driven designs have a lower constraint on the size and the mass of the DC motors and drives. This means that ~~in actuation with tendons,~~ the same or ~~even~~ better dynamic performance~~s~~ can be achieved with larger and heavier DC motors and drives ~~that are more~~ likely lower ~~in~~ cost~~s too~~. ~~While this can be very appealing, as discussed earlier,~~ remote actuation result in a very unnatural and machine looking movements due to friction. The unnatural and jerky movement of the fingers can be observed in the videos provided publically for the DLR hand [4] and the Shadow

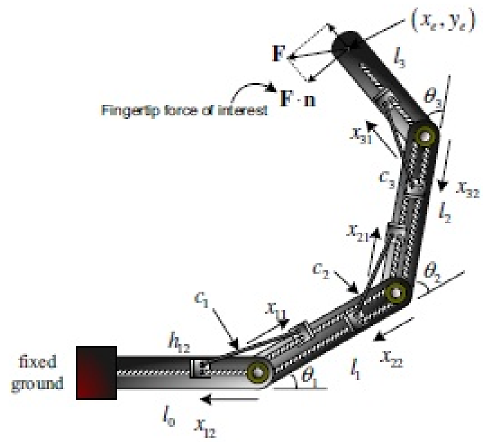


Figure 1.7: in-site ball screw design [15]

robotics hand [19] who are two very well-known teams in both industry and academia working on robotic hands. This unnatural movement can have a substantial effect on the emotional conveyance of the structure. Therefore, actuation with flexible elements designs are disregarded as an option for the actuation of the dynamic structure in this research.

1.4.2 Criteria and Constraint Analysis of DC Motors

Within the four DC motor actuation candidates, bevel gears and rigid tendon DC designs seemed to be most suitable DC motor candidates for meeting the actuation criteria of this research. To further analyze these candidates, they are also tested against the constraints ~~that were~~ defined ~~for this research~~. ~~The five constraints of this research were, natural motion, audible noise, size, compliance and, cost.~~ Natural-looking motion is a qualitative measure and it is very difficult to assess a design around this constraint without observing the final implemented design. Videos from [5] and [13] can be used to predict to some degree how natural-looking the motion of these DC motor designs ~~are~~. These videos suggest that while the motion is not absolutely natural-looking, it is possible to reproduce ~~motions~~ naturallooking ~~enough~~ so that emotional conveyance of the structure is not interfered with. The audible noise~~s~~ of DC motor~~s~~ designs ~~will~~ most likely ~~be sourced~~ from the DC motor and the drive. Similar dc motor and harmonic drives will be used in both designs and therefore both designs will result in ~~a~~ same level audible noise. In general, ~~it was experienced that~~ the audible noise of the drives and the dc motors can be reduced using sound insulators to a level where it is not noticeable much by human. In terms of size, [5] demonstrates that it is possible to implement a bevel gear DC motor design for a finger like structure ~~within the size constraints of the finger-like structure of this research~~. In rigid tendon designs, considerable space is required for the rigid tendon to travel in freely~~. Essentially~~ half of the volume inside each link of the finger should be dedicated to the rigid tendon. This fact can ~~bring a lot of difficulties to~~ the mechanical design of the structure. In terms of cost ~~of the designs, again~~ the DC motor and the harmonic drive will be the factors that determine the cost for implementing either of the DC motor designs. For example a DC motor and harmonic drive combination that fits the size constraints ~~of this research~~ by Maxon motor /citemaxon2013BLDCHarmDr will cost somewhere from 300$ to 500$ CDN. Considering each active DOF of the structure will cost around this amount means that the sum cost of one prototype will be around 1000$ CDN or more. This is above the budget~~ed~~ ~~that was planned for the cost of one~~ prototype. Lastly, neither of the DC motor designs can provide compliance unless a compliance component is introduced in their design.

In conclusion, DC motors do not meet the constraints of this research on an acceptable level. Compliance and cost constraints are simply not met by these designs. Natural-looking motion can be achieved to some extent but it is not inherently achieved by DC motor designs. By a precise and fixed mechanical design they can meet the size constraint of the structure however flexibility both in the size of the actuators and the overall mechanical design of the structure will be minimal. The level audible noise constraint was experimented and it was achieved by sound insulations.

1.4.3 Pneumatic Actuators

Pneumatic actuators are ~~mechanical~~ mechanisms that transform the potential energy stored in pressurized gas to kinetic energy. Pneumatic actuators are certainly not as popular in robotics as DC motors; ~~however there are applications that pneumatic actuators are suitable for. These actuators are also~~ gaining more popularity in recent years because of the advancements in pneumatic valve designs, feedback sensor designs and ~~in~~ nonlinear control strategies. In general, pneumatic actuators have relatively higher power to weight ratios and output higher forces and torques. However, they have highly non-linear characteristics and are hard to control~~. T~~he compressibility of air ~~specifically adds more difficulty to the control of these actuators~~. ~~But, it also~~ brings inherent compliance to these actuators. The output characteristics of these actuators are pressure dependent. Thus, in order to control their output, the pressure has to be controlled. Mechanisms that provide the ability ~~of~~ controll~~ing~~ the pressure of pneumatic actuators are relatively expensive. More importantly, the relationship between their control signal and the pressure is nonlinear, adding more non linearity to the system. Pneumatic actuators can be categorized into three main groups~~.~~ Pneumatic cylinders, pneumatic artificial muscles (PAMs), and pneumatic motors ~~are the main three categories of pneumatic structures~~. Pneumatic motors provide rotary motion and pneumatic cylinders and PAMs provide linear motions. ~~In fact,~~ the equation of motion of PAMs and pneumatic cylinders are very similar and therefore ~~they~~ result in similar ranges of motion and output forces. In general, the main advantage of pneumatic cylinders over PAMs is that they have the ability to provide bidirectional actuation [6]. For the applications ~~of this research~~, bidirectional movement can be beneficial. However ~~as it will be discussed later~~, antagonist pairing of PAMs with another PAM or a passive actuator allows for a bidirectional movement with PAMs. Therefore, pneumatic cylinders are discarded as an option for the actuation design ~~of the structure of this research~~ and PAMs and pneumatic motors are the only pneumatic actuators ~~that are going to be~~ analyzed. In the following sections a brief explanation of these actuators and ~~the possibility of them~~ meeting the criteria are given. ~~At last~~, a conclusion with respect to the criteria and the constraints is provided.

1.4.4 Pneumatic Motors

Pneumatic motors ~~are pneumatic mechanisms that~~ transform the energy stored in pressurized gas to rotational kinetic energy~~. There are various designs for mechanism that can achieve such goal.~~ [20], [21] ~~are examples of pneumatic motors. In~~ [20] provides the torque and RPM characteristics of ~~the~~ air motors. Their mechanical specifications such as their size and mass are also included. The smallest actuator discussed in this paper has a diameter of $70mm$, ~~this is~~ well above the size limits of ~~the~~ finger structures ~~intended for this research~~ and therefore if these actuators are to be ~~implemented~~ they can only be implemented using remote actuation. ~~Looking at~~ the torques that these actuators can output, it is observed that torques well above the required torque of around $3Nm$ are achieved ~~with these motors~~ at pressures around $200kPa - 300kPa$. Another example of air motors is [21]. ~~These motors are commercially built.~~ The sizes listed ~~for these actuators~~ are slightly below the size constraints for the finger structure ~~of this research~~. At $1.9cm \times 5cm$ in diameter and length, these actuators can be placed in-site. They ~~do~~ provide torques above $3Nm$ with angular velocities at, $200RPM = 21rad/s$. Since the $3Nm$ required torque was calculated for DC motors which are considerably heavier than air motors, torques smaller than $3Nm$ are required if air motors are to be used. While these actuators certainly meet the criteria ~~of this research~~, they are still not considered as a suitable actuation mechanism for the finger mechanism intended for this research. Availability of these actuators is an issue. While it is possible to build these actuators ~~from scratch~~ particularly with a help of a 3D printer [20] it is outside the scope of this research to pursuit the design of these relatively complex mechanical structures. Air motors only provide a slight advantage in output torque and angular velocities over DC motors. However, the analysis on DC motors already shows that there are solutions with DC motors that can meet the criteria of this research. Controlling air motors is also more difficult due to their nonlinear equation of motion. The nonlinearity is ~~because of~~ the pneumatic nature of air motors and their dependence on air pressure. Therefore, mainly due to problem with the availability of air motors and the difficulty of controlling them all while they provide a very similar actuation to DC motors; these actuators are discarded as an option for the actuation of this research.

1.4.5 Pneumatic Artificial Muscle (PAM)

PAM actuators convert the potential energy stored in pressurized gas to kinetic energy. Due to the simple mechanical concept of PAM actuators and the fact that they do not require ~~very~~ special tools or skills to build; a variety of PAM actuators have been designed ~~over the years~~. [22]~~looks at~~ some the most common designs for PAMs. All of the~~se~~ designs are comprised of two main components~~. The first component is~~ the elastic tube or bladder that stretches and expands when pressurized~~. The second element is~~ a guiding mechanism that transfers and directs the force of the pressurized elastic ~~into a desired direction~~ resulting in force and displacements in a desired direction. In addition to the PAM designs suggested by [22], in recent years, new designs for PAM actuators have been developed and implemented that possess features that were not present in older designs of PAMs [23] [24],[25]. ~~These new designs are still comprised of the two main components of PAMs.~~ The ~~way the~~ older designs ~~of PAMs~~ differ from these newer designs ~~is~~ in the ~~different~~ type of guiding components ~~that they have~~. In older designs ~~of PAMs~~, the guiding mechanisms are designed so that they result in a straight motion. In the new PAM designs, the guiding mechanisms ~~cause the PAM actuator to~~ result in movements that follow curves. The new curved motions ~~of new PAM actuators~~ allow for ~~some~~ unconventional approaches in robotic mechanism~~s~~ designs. Most notably, these PAMs can be designed in such way that need for a separate mechanical skeleton is eliminated. In a sense, the actuator becomes the structure of the mechanism as well. Therefore due to the difference in the characteristics of the new and old designs ~~of PAMs~~, analysis is done on each type separately. First, the older design ~~of PAMs~~ which is labeled as straight PAMs is tested against the criteria ~~of the research~~. Second, the newer design ~~of PAMs which is~~ labeled ~~as~~ curved PAMs is tested against the criteria. Lastly, a final conclusion based on how well these actuators meet the criteria and constraints ~~of this research~~ is presented.

Straight PAMs

~~As discussed earlier,~~ straight PAM actuators are designed ~~in such a way that causes them~~ to provide straight movement. McKibben PAMs are the most common type of straight PAM design~~s~~. An elastic tube usually made out of silicone is placed inside a braided sleeve ~~similar to what is demonstrated~~ in figure 1.8. When the tube is over pressurized it starts to expand ~~in the three dimensional space~~ and increases in volume. The braided sleeve can only expand in volume either by expanding in the x and y directions while shortening in the z direction or by shrinking in the x and y direction while stretching in the z direction. Stretching or shortening of the sleeve ~~on~~ the z axis provides a pushing or a pulling linear force respectively. When designing these PAMs, choosing between stretching or shortening ~~of the sleeve on~~ the z axis is ~~decided~~ by ~~choosing~~ the weaving angle of the sleeve when at rest to be above or below a certain angle [26]. The weaving angle of the sleeve θ is demonstrated in figure 1.8. Therefore, these actuators are only capable of providing force in one direction. For bidirectional movement, they require an antagonist pair either with another PAM or a passive actuator such as a spring or an elastic band.

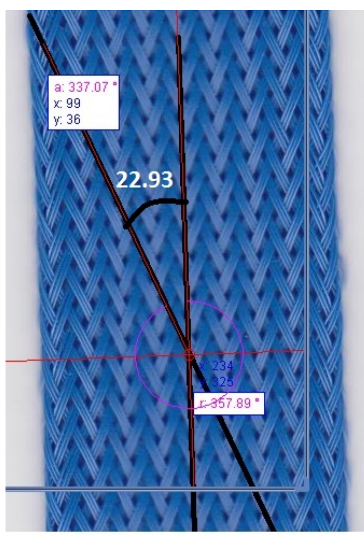


Figure 1.8: Braided sleeve θ value

Both in-site and remote actuation placement are possible for ~~the placement of~~ straight PAM actuators. In in-site designs, the actuators are placed on the link before the intended joint. The power is transferred to the joint by a short flexible tendon. Since no guiding mechanisms such as sheaths or pulleys are used no energy is lost to friction. Also, because the cable is relatively ~~very~~ short, it is safe to assume that the cable is not stretching. An in-site antagonistic pair using two straight PAMs is considered for the analysis ~~of these pneumatic actuators~~. Remote placement will only be considered if meeting the criteria proves to be very difficult because of the size limitation that in-site placement causes. This in-site antagonist actuation setup of a single DOF joint is presented in figure 1.9. Similar designs are used in [27] and [28].

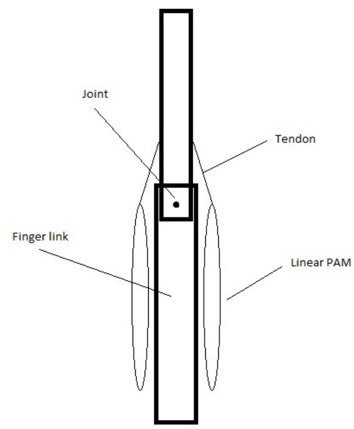


Figure 1.9: Antagonist pair of PAMs installed on the structure skeleton

In order to determine the peak force that has to be produced by the straight PAMs, the worst possible situation that the actuator can face is considered. The worse possible case is illustrated in figure 1.5. In order to get and estimate on the mass of the finger, it is assumed that the finger is a rigid piece of wood with the size of $15cm \times 2cm \times 2cm$ The density of wood is around $\rho = 500kg/m^3$, therefore with the given dimensions of the finger, the mass of the finger will be around $m = 30g$.Using equation 1.6, with the rest of the parameters in the equation kept the same; the maximum required force will be $F_m = 45N$.

By modeling the output force of the PAM in terms of its pressure, the required pressure for achieving the output force of $F_m = 45N$ can be determined. Starting with the energy equation of PAMs, equation 1.7 describes the input potential energy of the pressure gas coming into the PAM and the output work of the PAM[29].

$$(P - P_{atm})dV = -F_m dL F_m = (P - P_{atm})\frac{dV}{dL} \tag{1.7}$$

P is the pressure inside the actuator, P_{atm} is the pressure of the surrounding atmosphere, V is the change in the volume of the PAM due to the change in length and diameter. F_m is the linear force the PAM is outputting and dL is the change in the length of the PAM.

Assuming that the threads of the braided sleeve are not extensible, the length of the PAM L can be expressed in terms of the length of the threads b and the weaving angle of the threads θ. L, b and θ are illustrated in figure 1.10

$$L = bcos\theta \tag{1.8}$$

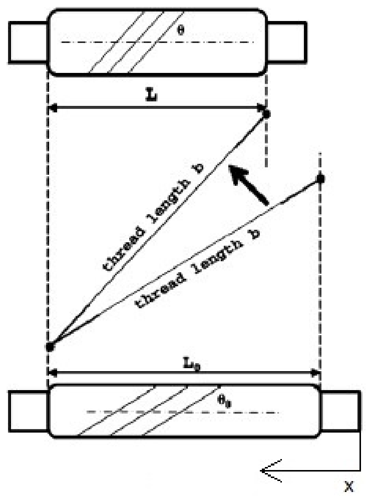


Figure 1.10: Braided strands of the sleeve of the PAM [29]

Assuming that the shape of the PAM is a cylinder, the diameter of the PAM D can be expressed in terms of b, θ and the n, the number of times a strand encircles the PAM's circular circumference.

$$D = \frac{bsin\theta}{n\pi} \tag{1.9}$$

Using the equation for D and L, the volume of the PAM V can be defined as

$$V = \frac{1}{4}\pi D^2 L = \frac{b^3}{4\pi n^2} sin^2\theta cos\theta \tag{1.10}$$

Using equations 1.10 and 1.8, $\frac{dV}{dL}$ can be defined as,

$$\frac{dV}{dL} = \frac{dV/d\theta}{dL/d\theta} = \frac{-b^2(3cos^2\theta - 1)}{4\pi n^2} \tag{1.11}$$

Substituting 1.8 into 1.11 gives:

$$\frac{dV}{dL} = -\frac{L^2(3 - \frac{1}{cos^2\theta})}{4\pi n^2} \tag{1.12}$$

Substituting 1.12 into 1.7 gives:

$$F_m = \frac{L^2(3 - \frac{1}{cos^2\theta})}{4\pi n^2}(P - P_{atm}) \tag{1.13}$$

Equation 1.13 shows that the output force of the PAM F_m is dependent on the variables L, the length of the PAM, P the inside pressure of the PAM and, θ, the weaving angle of the braided sleeve of the PAM. F_m is also dependent on the constants n, which is the number of times a strand encircles the PAM's circular circumference, and P_{atm}, which is the atmospheric pressure and is normally at $P_{atm} = 101KPa$ ~~is constant~~.

In order to confirm the accuracy of the obtained force model equation, the model is tested against experimental results from [30]. The PAM used in this experiment is shown

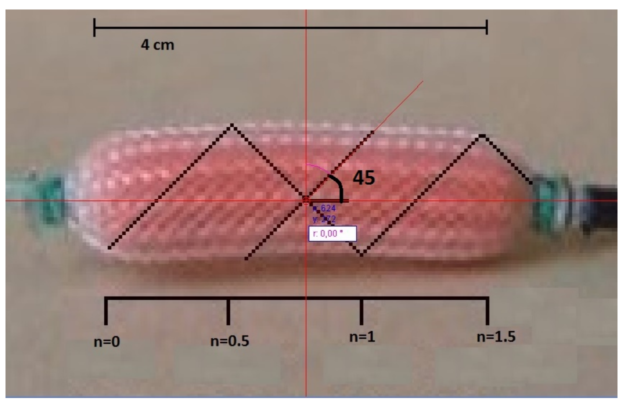


Figure 1.11: PAM geometric characteristics [23]

in figure 1.11.This figure shows the PAM actuator at ~~the~~ rest, meaning that its contraction ratio is 0. [30] provides the length of the PAM as $L = 4cm$ when at rest. As illustrated in the figure, the angle of the braid θ is measured on the figure to be around 45^o, and the number of encirclements n is measured to be near 1.5. Inserting these values into equation 1.13 will result in equation 1.14:

$$F_m = 5.66 \times 10^{-5} P_a - 5.71 \tag{1.14}$$

Pressure (kPa)	Measured Force(N)	Modeled Force(N)	Error (%)
121	1.1	1.2	9
201	7	5.7	19
281	12	10.2	15

Table 1.3: Modeled forces vs Measured forces

Equation 1.14 defines the output force of the PAM used in [30] when with respect to the internal pressure of the PAM when the contraction ratio is at zero or in other words, the length of the PAM is at $L = 0.4cm$

[30] also provides the amount of exerted force by the PAM when the pressure of $281kPa$, $201kPa$, and $121kPa$ are applied to the PAM when it is at rest. These measured forces along with the forces calculated using equation 1.14 are presented in table 1.3.

Comparison of the measured and the calculated force values of the PAM in [30] suggests that this model can have an error as high as 20%. The inaccuracy of this model ~~can be~~ mainly due to the assumption that the PAM is cylindrical in shape and its volume can be obtained using the equation of volume for a cylinder. The high error rate of the model means that the results obtained by this model cannot be used to make conclusions about the ~~possibility~~ of straight PAMs ~~meeting~~ the criteria ~~of this research~~. In order to make the final ~~conclusion on~~ if straight PAMS are capable of meeting the required forces ~~to meet the criteria of this research~~, physical experiments are designed to test these actuators.

In addition to the force characteristics of their PAM designs, [30] provided information on the frequency response of their designed PAM. This information can be used to investigate the velocities that these PAMs can reach.

Figure 1.12 shows the Bode plot of the open loop response of the PAM actuator. The gain of the response is $0dB$ up to $6Hz$. ~~This means that at a frequency up to $6Hz$ the actuator fully expands and contracts at the frequency of $6Hz$ or theoretically can perform only contractions at $12Hz$ because each contraction takes half the period.~~ Note that since the intended motion for the actuator is not periodic the phase log is not analytically significant. Assume that a full contraction on the joint translates to a $90°$ rotation on the MP joint illustrated in figure 1.5. This means, the actuator is capable of performing a $90°$ $\pi/2$ rotation at $12Hz$, therefore it can achieve angular velocities of $12Hz \times \pi/2rads = 18.8rad/s$. This velocity value is below the required $37rad/s$. However, this value is just a lower bound on the possible angular velocity of the implementation. Another important

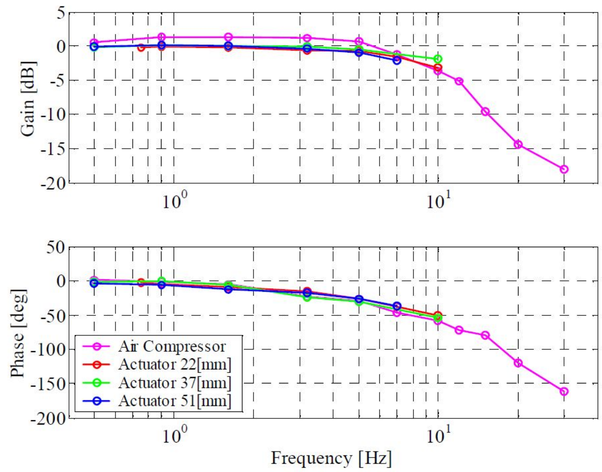


Figure 1.12: PAM open loop frequency response [31]

point to consider is the validity of the gain graph in figure 1.12 after $6Hz$. The purple curve in the graph represents the frequency response of the air compressor used for pressurizing the PAMs. It is clearly observed that at $6Hz$ the compressor starts decaying in gain which results in the gain reduction of the actuators. To achieve better bandwidth, a pneumatic system capable of changing pressure ~~more~~ than $6Hz$ should be used. In conclusion, while the frequency response of the PAMs in [30] do not guarantee that straight PAMs are capable of meeting the required velocities ~~to meet the criteria of this research~~, they do not rule out the possibility reaching the required peak velocities.

~~As for the~~ range of motion on the joints, the length of the PAM actuators can be selected so that enough contraction is provided ~~that results in the proper range of motion~~. For example in the case illustrated in figure 1.5 the amount of contraction x is calculated using:

$$x = \theta r_P \tag{1.15}$$

In equation 1.15, θ is the range of angular motion required on the joint and r_p is the radius of the pulley. Therefore for a range of motion of $\pi/2$ a contraction range of $x = 1cm \times \pi/2 = 1.6cm$ is required. The maximum contraction ratio for PAMs is $\epsilon = 0.3$ therefore the length of the PAM has to at least be $1.6cm/0.3 = 5.2cm$ for a range of motion of $\pi/2$. In conclusion, for PAM actuators experimental results and simulations show that the required maximum force can be achieved and as a result ~~of that~~ the required acceleration is achievable. In terms of maximum velocity more experiments and research is required. A lower bound is put on the maximum velocity of the actuator however the bound is not close enough to the required value of around $37rad/s$. Lastly, the range of motion of the actuator also meets the requirement as the initial length of the PAM can be set so that the required range of motion is covered.

Due to the ~~inability of the theoretical analysis on PAMs to suggest any conclusions on the possibility of meeting the criteria of this research,~~ the McKibben ~~design of straight~~ PAMs were designed and implemented to perform physical experiments ~~on these actuators~~. The ~~comprising~~ components of the McKibben PAMs can be bought off the shelf separately and ~~they can be~~ assembled ~~together~~ by hand. The main components of the McKibben actuators are~~,~~ braided sleeve as the guiding mechanism, silicone tube for the core, pneumatic fitting for the intake of air, another pneumatic fitting for closing off the ~~other end of the muscle~~ and lastly tightening clamps for tightening the fittings to the ends of the braided sleeve and the end of the silicone tube. In order to operate these hand-built PAMs a pneumatic circuit comprising of an air compressor, tubing, and an electronic or mechanical on/off valve is required. On the left side of figure1.13 the pneumatic circuit is illustrated. Two experiments are designed for the developed PAM to investigate how well these actuators perform under the ~~criteria of this research~~.

In order to ~~make the final conclusion on~~ the force capabilities of PAMs, the following experiment is designed to test straight PAMs ~~capabilities in providing~~ the required amount of force in order to meet the criterion on the angular acceleration. In the theoretical analysis ~~of straight PAMs~~ it was calculated that with a pulley of radius $1cm$ on the MP joint, a linear force of $45N$ is required for the described wooden finger to reach an angular acceleration of $1900rad/s^2$. In order to investigate if the is capable of producing this required force, a mass with a gravitational force of $> 45N$ is hanged from the straight PAM. When the PAM is pressurized, if the mass is lifted even by a small amount, it means that the PAM is capable of producing the required force for this experiment. Figure 1.13 illustrates the setup used in this experiment.

$150kPa$ which is the middle point of the pressures used in [30] was taken as the initial pressure value for this experiment. After turning the valve on at $150kPa$ and letting the air flow into the PAM, slight upward and side movements were visible from the weight. The pressure of the source was then increased by $20kPa$ at each step. After a pressure of around $240kPa$, a very clear upward motion was visible on the weight. Therefore, this test suggests that with a source pressure of more than $240kPa$, the required force of $45N$ can be achieved by the straight PAM meaning that the required angular acceleration of $1900rad/s^2$ is achievable ~~with these actuators~~.

The second experiment ~~that was performed on the straight PAMs~~ was designed to test the feasibility of achieving the required angular velocity of $35rad/s$ on the MP joint of the finger structure ~~describe earlier~~. While the analysis ~~on~~ the data provided by [30] on

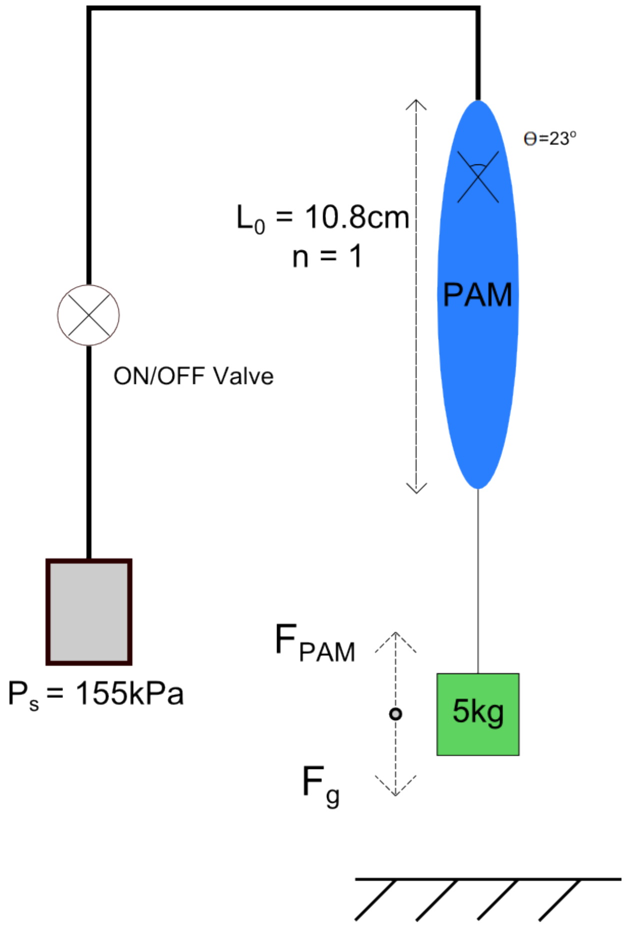


Figure 1.13: PAM output Force Experiment

the bandwidth of PAMs suggested a lower bound on the achievable constant velocities of straight PAMs, it did not provide any information ~~on~~ the possible peak velocity of PAMs which can be considerably higher than their constant velocity. Thus it was decided to use the same PAM from the previous test and investigate if it has the capability of achieving required peak velocities when facing the worst possible case.

More info and Numerical results to be added

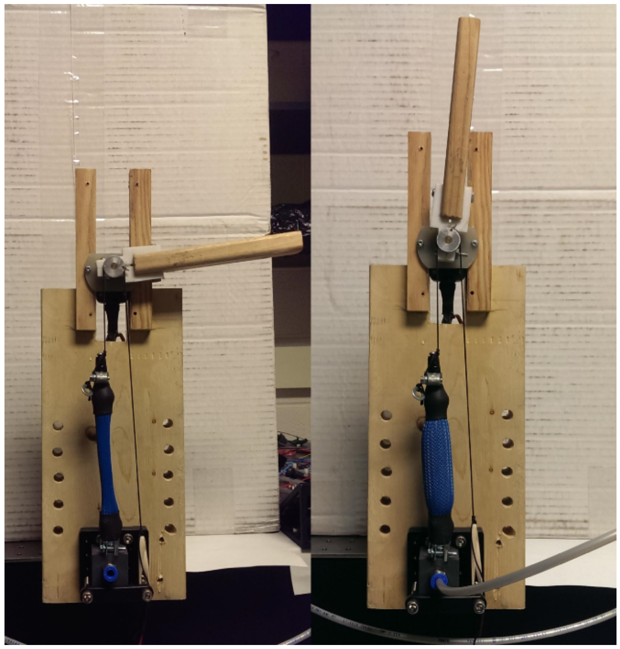


Figure 1.14: PAM Output Dynamic Experiment

Curved PAMs

Curved PAMs are an innovative ~~way of~~ designing and implementing pneumatic artificial muscles which ~~results in some unique characteristic from the actuator. Going back to the main elastic and guiding components of PAMs, it was mentioned that different curved PAM designs are achieve by designing different types of guiding components for the actuator.~~ Figure 1.14 illustrates two examples of curved PAMs that can resemble a finger like structure. The actuator on the left has a silicone structure with custom weaved braids~~.~~ [24]. The elastic component and the guiding component ~~on~~ this example ~~of Curved PAMs~~ are intertwined together in~~-~~to one structure. ~~The actuator on the right is slightly different.~~ In ~~this design of curved PAMs~~ the guiding component and the elastic component are separate ~~very~~ similar to McKibben Air Muscle ~~in this sense~~. The elastic core ~~of this PAM~~ is Latex based and the guiding component is a modified braided sleeve with a curved figure when in rest. It can be observed that both of these curved PAM designs resemble a finger like structure with the ability to be both fully closed, fully open or somewhere in between. Of course, these curved PAMs are just two of the many possible designs and there could very well be other ~~Curve PAM~~ designs such as the one presented by [25] that resemble finger like motions and structures.

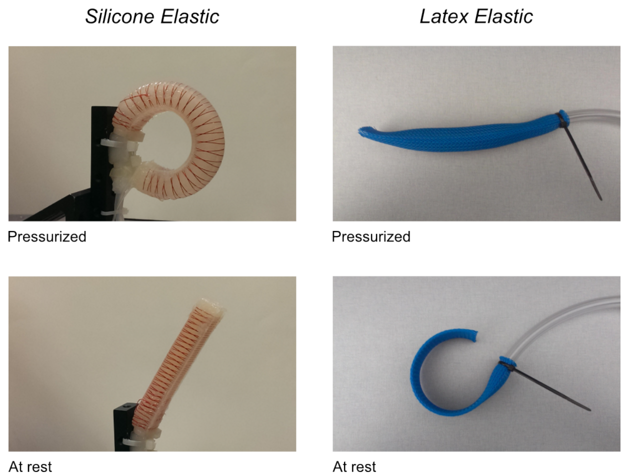


Figure 1.15: Example Curved PAMs

The main advantage that these curved PAM designs provide is that they do not require a separate design and implementation of a mechanical skeleton structure. ~~Because of their bidirectional actuation, the way the structure of the actuator looks like a finger and follows a curve very similar to the curve that human finger follows, no additional skeleton is required for these actuators. All of the other actuation designs that have been discussed so far need a mechanical skeleton. This is a very important advantage since it significantly advances the progress of the research by eliminating probably one of the most time and budget consuming parts of a robotic research project which is building the mechanical skeleton. This advantage comes at a cost.~~ As it can be observed from 1.14 the entire curved PAM has one DOF. The three ~~number~~ MP, PIP, and DIP joints of the structure ~~explained in the previous sections is~~ replaced with one unconventional joint. Clearly this reduces the ~~amount~~ of freedom on the motion of the structure. But, it has to also be noted that in human finger PIP and DIP joints are coupled meaning that DIP joint follows the joint trajectory of the PIP joint. ~~Also, as mentioned, all of the emotionally expressive motions that the dynamic mechanism is going to perform are essentially closing and opening of the fist at different dynamics and patterns. In terms of the fingers of the hand, this means that the MP joints and the PIP joints act as if they are coupled as well. In other words, the PIP joint follows the movement of the MP joint in each finger. Because of all of these couplings between the joints, it is safe to assume that the three DOF structure initially intended for this project also acts as a one DOF structure.~~ The ~~circular shape~~ that these curved PAMs follow can ~~also be problematic and can interfere with the emotional conveyance capabilities of the dynamic structure. Modifications in the design of the~~ guiding component ~~of these~~

~~curved PAMs can help with the problem. If a more a shape more similar to human finger is designed for when these actuators are fully closed, then the structure will follow more natural looking paths and will have poses more similar to poses by the human finger.~~ The response of these actuators is highly non-linear ~~as well; however this is an issue that straight PAMs possess to a very similar extent~~. Lastly, since there are no conventional revolute joint on these PAMs, it is difficult to get position feedback on these structures because ~~the more~~ conventional sensors cannot be used.

The main question that remains is to investigate if these actuators are capable of meeting the criteria ~~of this research~~. ~~As discussed, no~~ conventional revolute joint can be associated to the structure of these PAMs~~. This means that~~ the ~~conventional way that was sued~~ for testing the other actuation options against the criteria cannot be used.

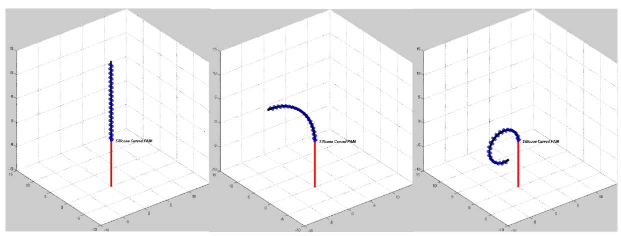


Figure 1.16: Curved PAM represented as a high DOF serial link structure

The procedure explained in the previous paragraph was implemented on the silicone PAM illustrated in figure 1.14. Gyroscope sensor L3G4200D was used to measure the local angular velocity of the tip of the PAM. To create the step response of the actuator, it was pressurized from $101kPa$ atmospheric pressure to $200kPa$ using an ON OFF valve. The angular velocity readings of the gyroscope during the step response ~~was~~ read and fed to MATLAB. In MATLAB, the angular velocity was ~~both~~ integrated and differentiated to obtain ~~both~~ the angular displacement and the angular acceleration of the structure. The resulting angular displacement, velocity and accelerations are illustrated in figure 1.16 Note that the length of the movable part of these PAMs was around $12cm$, which is shorter than $15cm$, the intended length for the structure of the fingers in this document. The effect of ~~the~~ increasing the length of the PAM on its dynamic motion has to be investigated through modeling ~~these PAMs. Modeling silicone PAMs is out of the scope of this stage of the research.~~ However, if increasing the length of the actuators to $15cm$ slows the dynamic of the structure down, increasing the operating pressure of the PAM can very likely compensate for the slowdown of the dynamics of the PAM.

Numerical results to be added

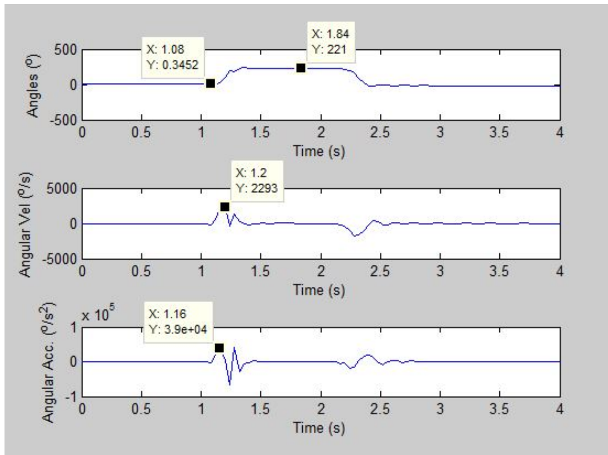


Figure 1.17: Curved silicone PAM step response angular displacement, velocity and accelearation

AS illustrated by 1.16 silicone PAMs are capable of meeting the criteria ~~of this research~~ and are a strong candidate for the actuation method of the dynamic structure ~~of this research~~.

1.4.6 Constraint Analysis ~~and the conclusion on~~ Pneumatic Actuators

~~Pneumatic artificial muscles or~~ PAMs were considered the most suitable pneumatic actuation mechanism ~~for the dynamic structure of this research~~. Both curved and straight PAMs were capable of meeting the criteria ~~of this research~~. In order to further examine these two PAM designs, they are tested against the constraints ~~of this research~~. In terms of natural-looking motion, since extra mechanisms have to be used to transfer the motion of the straight PAMs to the DOFs of the structure, friction in those mechanisms will cause unnatural behaviors in the motion. Curved PAMs have much more natural-looking motion. Due to the mechanical nature of these actuators, many of the high frequency movements are filtered out. Also, since in a way the force of the actuator is directly transferred to the structure and there is no transfer mechanism, unnatural behaviors due to stiction and friction are not observed. In term of size, both designs ~~of the actuators~~ provide a lot of flexibility on their size. Understandably, the size of these actuators affects their output dynamic performance. However since these actuators can operate at a variety of pressures, their operating pressure can be modified so that the required output dynamics are met ~~with that size of the~~

~~actuator~~. The ~~main~~ costly components of these actuator designs are the compressor that is needed to produce the required pressure and the control valve that is used on each DOF for its control. While compressors are relatively expensive their price should not be associated with the cost of one of these structures as one compressor can be used to operate multiple ~~of these~~ structures. As for the cost of the control valve ~~which is required by each one of the active DOFs in the structure~~, for example, a suitable valve by FESTO [32] is quoted around 100$CDN.Thereforethetotalcostofathreefingeredhandlikestructurewillbearound$300 with the curved PAM and for the straight PAMs, it will be a similar price unless more than one active DOF is ~~decided to be~~ present on each finger. In terms of audible noise, because full range position control is envisioned with these actuators, the valves need to be pulse width modulated in order to achieve a range of pressures and consequently a range of displacements. The pulse width modulation of the PAMs will create considerable noise. However, ~~in the experience with these valves,~~ the source of the noise ~~was~~ mainly ~~from~~ the valves especially with the curved PAM designs. Because the valves are not required to be close to the structure, they can be placed in an insulated environment. This will significantly reduce the audible noise~~s~~ of these actuation mechanisms. Lastly, due to the compressibility of the air and the elastic core material of these actuators, both of these PAM designs provide inherent compliance which is an important advantage if physical human interactions are desired later on.

In conclusion, curved PAM designs are capable of meeting ~~more~~ of the constraints ~~of this research~~. Both designs meet the cost and compliance constraints. In terms of audible noise, while both are not quiet, the insulation of the control valve almost eliminates the noise~~s~~ in a curved PAM system however in straight PAMs, ~~a hearable~~ ~~amount~~ of noise is still emitted from the actuator itself. Therefore, curved perform much better against this constraint. ~~AS for the size constraints, it~~ while both ~~deigns~~ are capable of meeting the constraint, it will be ~~a~~ simpler ~~process of finding~~ the right combination of size and operable pressure that meet the output dynamic criteria with the curved PAMs tha~~t~~ with the straight PAMs. Lastly, curved PAMs provide the most natural looking motion within all of the discussed actuation methods ~~in this research definite~~ meet this criteria better than straight PAMs.

1.4.7 Final Conclusion

~~Looking at~~ how well the actuation mechanisms ~~discussed in this research~~ meet the criteria and constraints ~~defined for this research~~; curved PAMs ~~meet these criteria and constraints the best and thus are~~ the most suitable actuation method ~~for the dynamic structure intended for this research~~. Straight PAMs, Curved PAMs, bevel gear DC motors, and rigid

~~motor~~ DC motors designs were all capable of meeting the criteria ~~of this research~~ defined by the required angular motion range, angular velocity and angular accelerations ~~of the dynamic structure~~. However in terms of meeting the constraints ~~of this research~~, curved PAMs meet almost all of the constraints except for the constraint on audible noise. ~~This is while~~ DC motor designs ~~barely~~ meet one ~~or two~~ constraints and straight PAMs have difficulty meeting at least three of the constraints. It has to be noted that in addition to how well curved PAMs meet the constraints and the criteria of this research, they also eliminate the need for the design of a separate skeleton structure. This is a very important advantage as designing and implementing the skeleton structure of the robot consume a considerable amount of the time and budget ~~that is planned for building the dynamic structure of this research~~.

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