Smart Actuators: A Review

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Abstract

Robotic systems are a combination of actuators and control systems for manipulating a tool or end effector along a specified path. Different types of actuators exist for different applications like bio mimicking, rehabilitation and prosthesis, and are classified based on their principle of actuation. These actuators include Serial Elastic Actuators, Shape Memory Alloys (SMA), Dielectric Elastomer Actuator (DEA), fluidic actuation etc. Various robotic systems have been developed with different actuators. SEA are conventional electric actuators are coupled with flexible elements. The main purpose is the introduction of compliance. Smart materials like SMA, Soft actuators like DEA and Flexible Elastomer Actuators using Fluidic actuation principles, pertaining to their actuation principles, can be used for biomimicking applications and their compliance nature due to their flexibility results in better shock absorbing and energy recovery capabilities. This paper presents a comprehensive literature survey relating to various actuators and their applications. A brief review of use of EMG and EEG as control systems is also presented in this article. Mathematical formulations have also been summarized in this article.

Keywords

Dielectric Elastomer Actuator, Shape Memory Alloy, Soft Actuators, Serial Elastic Actuators

Notations

J_m - Inertia of Motor
B_m - Motor Damping Coefficient
J_l - Inertia of Load
B_l - Load Damping Coefficient$_l$
K_s - Spring Constant
θ_m- Angular displacement variable for Motor
θ_l - Angular displacement variable for Load
θ_s- Angular displacement variable for Spring
τ_m - Force generated by motor from ground
τ_{out} - Force generated by deformed spring
τ_{ext} - Force applied externally by environment of load
F - Tension generated by actuator
θ_b - Braid angle
p - gauge pressure
$D_{\max}$ - Muscle Diameter at θ_b=60°
p_e - Electrostatic pressure in direction of current
ε_o - permitivity of free space
ε_r - reletive permitivity of material
ε_o - permitivity of free space
ε_r - reletive permitivity of material
t - Thickness of the elastomer
V - applied voltage
E - Young's Modulus
s_3 - strain in of applied current
δ_1 - deformation in directions perpendicular to applied current
δ_3 - deformation in of applied current

1. Introduction

Robotic systems are a combination of actuators and control systems for manipulating a tool or end effector along a specified path. Different types of actuators exist for different applications like biomimicking, rehabilitation and prosthesis. Rehabilitation is the area of prosthetics where technologies are used for amputees and people who suffered trauma due to accidents, to attain highest level of independence in doing their daily routine ("Prosthetic Rehabilitation," n.d.). Different rehabilitation techniques exist like use of splints, exoskeletons etc. All these involve use of various types of actuators which actuate various mechanisms that aid in movement of subject's limbs. Whatever be the situation, the more exact gait the exoskeleton can mimic, the better is the lifestyle of the subject using it (Berger et al., 2019). Different devices have been developed for this purpose. These involve rehabilitation devices supporting arms (Azeez et al., 2015; Parasa et al., 2016) to legs. For example Phoenix exoskeleton (Brewster, 2016) is a custom designed exoskeleton for rehabilitating a subject who got paralyzed below the waist in an accident. Yoshiyuki Sankai (Sankai, 2010, 2006) developed different types of Hybrid Assistive limbs using various actuators like ball screw drives, electric drives for both medical as well as warfare purposes. Ball screws are also used in other systems like HiBSO which is summarized by Baud, et al (Baud et al., 2018) while gait analysis of this actuator is presented by Oliver, et al (Olivier et al., 2014). Baud, et al (Baud et al., 2018) also compared HiBSO with other projects like Honda Stride Assist (Buesing et al., 2015; Jayaraman et al., 2019) and Cyber legs Hip Orthosis(Geeroms et al., 2013). The influence of HiBSO on gait is studied by Oliver, et al (Olivier et al., 2017).

The joints in human body are all compliant joints (Gálvez-Zúñiga and Aceves-López, 2016). Thus, compliance is another major factor influencing gait in lower exoskeletons. This controls the misalignment between instantaneous centers of prosthetic suits and human body during walking. To achieve compliance, prosthetic suits are developed as parallel mechanism (Hsieh et al., 2017; Niu et al., 2018). Thus, the actuators used in the exoskeletons along with mechanisms must be compliant. Two different electrically actuated actuators such as Series Elastic Actuators, Flexible actuators are used.

2. Serial Elastic Actuators

As specified in Arnaldo, et al (Junior et al., 2016), Series Elastic Actuators (SEA) are electric drives coupled with elastic elements. The main use of elastic elements is for providing compliance. Williamson (Pratt and Williamson, 1995; Williamson, 1995) discussed the design of SEA. SEA working principle has also been summarized in (Paluska and Herr, 2006). The schematic of serial actuator as presented in his work are shown in figure 1. The main difference between the SEA and regular actuators is the use of elastic component between the load and output shaft. This elastic component, which is generally a steel spring, brings about greater compliance and increased bandwidth or load range for the manipulator. This also helps in partial recovery of energy that is spent during actuation, provides impact load tolerance, higher mechanical peak power while the tradeoffs are power output, volumetric size, weight, efficiency, Back-drivability, impact resistance, passive energy storage, backlash, and torque ripple (Junior et al., 2016). Paine, et al (Paine et al., 2014; Paine and Sentis, 2012) discussed in detail regarding University of Texas Series Elastic Actuator (UT-SEA). They classified SEA into two types depending on the location of elastic element, namely FSEA (force sensing series elastic actuator) and RFSEA (Reaction force sensing series elastic actuator). The schematics of these are shown in figure 2. RFSEA, though compact in nature, have lesser force sensing and tracking when compared to that of FSEA. The cause is primarily attributed to location of the spring. The production design of UT-SEA is discussed in (Isik et al., 2017) where the actuator is re-engineered for reducing cost of the actuator without much trade-off in its specifications.

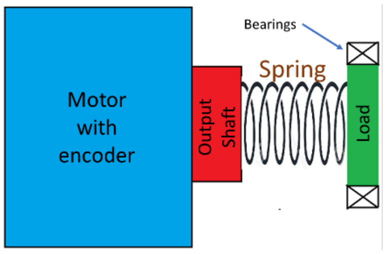

Figure 1: SEA schematic

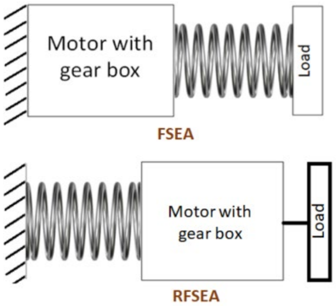

Figure 2: FSEA and RFSEA as described in

Lee, et al (Lee et al., 2017) listed various types of linear and rotary SEA that can be used for prosthetic suits. These include cRSEA, cPEA, SEA of MARIONET etc. A general formulation for different types of SEA (FSEA & RFSEA) has been presented. This formulation is given in equation (1). They also compared various parameters like force sensitivity, transmissibility and compliance for different SEA.

$$\left.\begin{aligned} J_m\ddot{\theta}_m + B_m\dot{\theta}_m &= \tau_m - N^{-1}\tau_{out} \\ K_s\theta_s &= \tau_{out} \\ J_l\ddot{\theta}_l + B_l\dot{\theta}_l &= \tau_{out} + \tau_{ext} \end{aligned}\right\} \qquad (1)$$

Veneman, et al (Veneman et al., 2006) discussed the design of a Bowden-Cable driven SEA and also with a schematic explained how these actuators can be used in lower exoskeleton for rehabilitation. A linear model was proposed for mathematically modelling the actuator. CSEA is a SEA with clutch (Rouse et al., 2014) and clutch is introduced to increase the compliance. These actuators are generally used for prosthesis and schematic of this actuator is explained in figure 3. The schematic of a CSEA as described in ("Clutch spring knee exoskeleton," n.d.; Elliott et al., 2014).

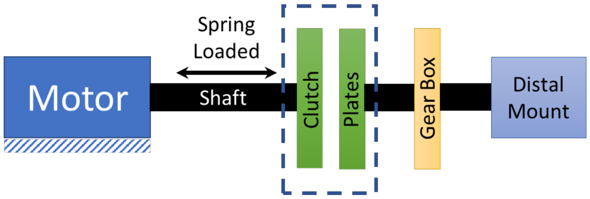

Figure 3: Schematic of CSEA

Though SEA have a huge range of speed and torque, efficiency is still low. To overcome this, Aló, et al (Veneman et al., 2006) designed F-IVT (Flywheel Infinitely Variable Transmission) actuator for use of knee actuation in exoskeleton. The schematic of this actuator is shown in figure 4. HD in the figure stands for Harmonic Drive. F-IVT allows the operation of electric motor at constant speed. A comparison of this actuator with SEA and C-SEA is presented in (Alò et al., 2016). For this comparison, various tests were executed with these actuators driving an artificial knee. The tests include walking on level ground at different speeds, step climbing etc. Two performance parameters, namely Energy Consumption and Peak Power are measured and compared. The studies showed that F-

IVT facilitated in reducing the peak power consumption drastically. Agarwal and Deshpande (Agarwal and Deshpande, 2017), Agarwal, et al (Lee and Oh, 2019) proposed two types of actuators, namely, Linear Compression SEA and Helical Torsion SEA. Both are Bowden-Cable driven SEA. The working principle of these actuators as indicated in the paper is shown in figure 5. They demonstrated the application of the mentioned SEA using finger exoskeleton.

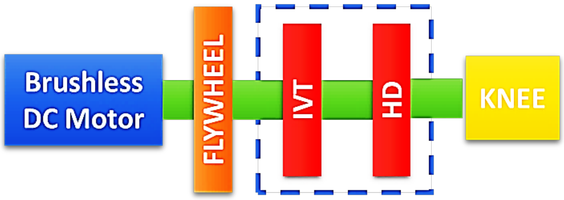

Figure 4: F-IVT for actuating Knee joint

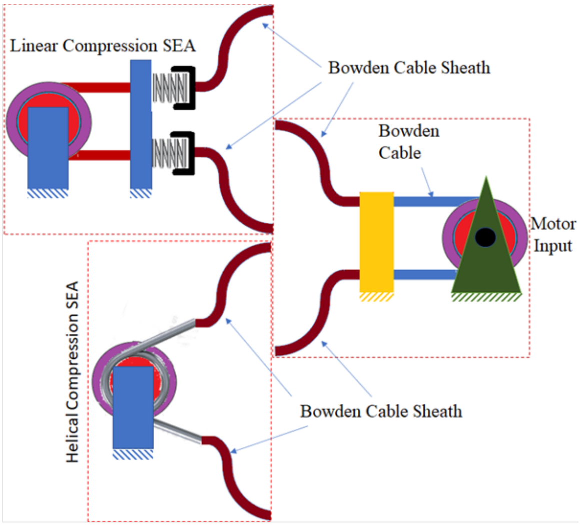

Figure 5: HT-SEA and LC-SEA

Sariyildiz, et al (Sariyildiz et al., 2015) proposed a linear SEA. For this actuator, they used a variable stiffness flexible element. Variable stiffness is achieved by a combination of soft and hard springs while linear and torsional springs are also employed in the design. Arnaldo Gomes, et al (Junior et al., 2015) proposed a new hydraulic linear SEA by combining hydraulics with flexible elements i.e. linear springs. Dynamic model is presented for the same.

One of the very ideas of development of SEA and F-IVT is to bring compliance into robotic actuator. Despite of being compliant, still an approximation in gait shall be required. An alternative to this situation is the actuators developed using soft polymers and smart materials. These actuators are fabricated using Electroactive Polymers (EAP), Shape Memory Alloys (SMA). The next section details these actuators.

3. Soft-Actuators

Soft-Actuators are those actuators which are deformable but can provide actuation force. Best example are the muscles of living organisms which are soft and deformable, yet can provide actuation force. These actuators are highly compliant. Development of soft-actuators dates back to 1950 when Shadow Robotics company used Flexible Pneumatic Actuator or Pneumatic Artificial Muscles (PAM) for development of dexterous hand (“Pneumatic artificial muscles - Wikipedia,” n.d.). Fluidic actuation, electroactive polymers (EAP), Shape Memory Alloy (SMA) and Shape Memory Polymers (SMP) etc. are being used for development of soft-actuators.

3.1 Fluidic Actuation

As mentioned earlier, fluid actuated soft-actuators have long been investigated. One of the first of these are McKibben actuators (Daerden, 1999; Daerden and Lefeber, 2002; Klute et al., 1999; “Pneumatic artificial muscles - Wikipedia,” n.d.). These contain an flexible tube with a braided sleeving (Daerden and Lefeber, 2002) as shown in figure 6 and use pneumatic power for actuation. Liu and Rahn (Liu and Rahn, 2003) numerically modeled this as fiber reinforced cylindrical shell using large membrane theory. This idealization is demonstrated in figure 7. As per (Daerden, 1999), tension is related to the pitch angle of the braid with the expression (2). Application of these actuators for wearable technology is reviewed in (Wehner et al., 2014).

$$F = \frac{\pi D_{\max}^2 p}{4}\left(3\cos^2\theta_b - 1\right) \qquad (2)$$

Another class of pneumatic actuators are the Pleated Pneumatic Actuators. Frank Daerden in his works (Daerden, 1999; Daerden et al., 2001) gave a detailed discussion regarding these actuators and also employed them. These actuators are designed in such a way that parallel stress is made zero in the actuator membrane. This is achieved by introducing folds or pleats in the muscle membrane parallel to the axis of the actuator. Figure 8 demonstrates the working principle of Pleated Pneumatic Actuator. Various other types of pneumatic actuators like Netted Muscles and Embedded Muscles have been detailed in (Daerden, 1999).

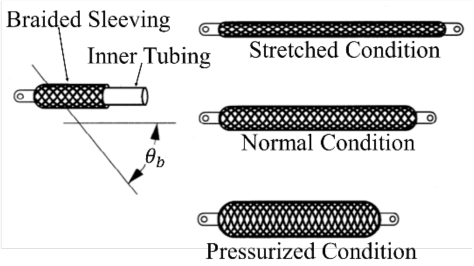

Figure 6: McKibben Actuator

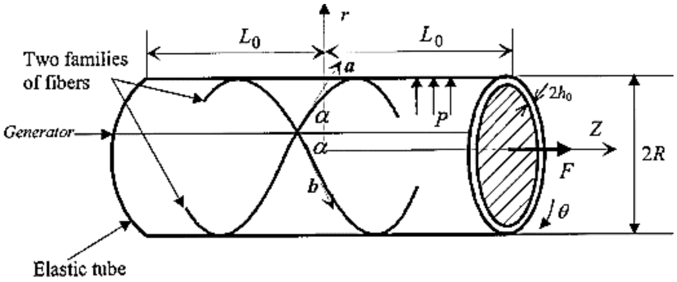

Figure 7: Idealization of McKibben actuator

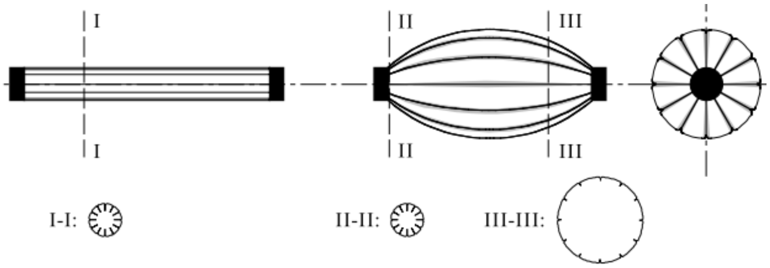

Figure 8: Pleated Pneumatic Actuator working principle

Another way of implementing Pneumatic Flexible Actuators is the use of vacuum and interconnected chambers (Boyraz et al., 2018). When pressurized flexible chambers are depressurized, there will be change in shape or deformation of total body in which the chambers are present. This deformation is used for actuation purpose. Different challenges with various soft actuators are also reviewed in this article.

Biomimicking is a hot research area for its varied application area which are from medical to defense sector. Fluidic actuation proves to be a viable solution in this case. Marchese, et al (Marchese et al., 2015) explained how soft actuators can be used for biomimicking. Fluidic Elastomer Actuators (FEA) are explained in detail in this article. Fabrication processes are also discussed. Hydraulic fish is a good example of FEA implementation. Figure 9 shows the implementation of hydraulic force as described in (Katzschmann et al., 2018, 2016b, 2016a; Marchese et al., 2015) for actuation. The same type of actuator is implemented with air as working fluid (Marchese et al., 2014). Use of gallium-based liquid metals (LMs) in place of hydraulics has also been reviewed by Wang, et al (Wang et al., 2019). Niiyama, et al (Niiyama et al., 2015) explained the procedure for fabricating a printable pouch actuator.

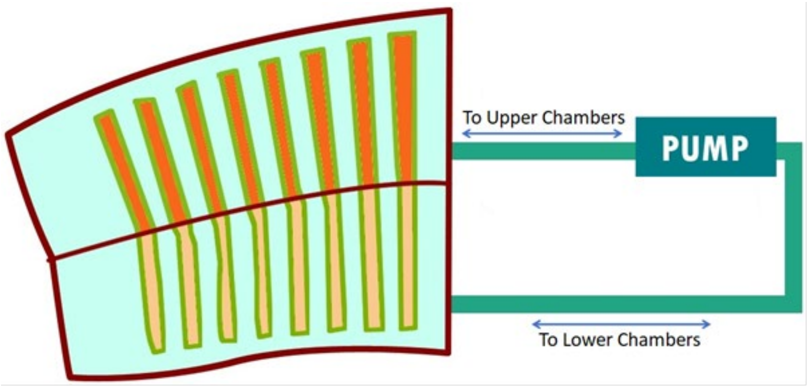

Figure 9: Flexible Elastomer Actuator

3.2 Electro Active Polymer (EAP)

As mentioned by Wang, et al (Wang et al., 2018), investigations on the concept of Electro Active Polymers dates back to 1880. These are the polymeric materials that deform on the application of electric field. The strain produced in these polymers will be perpendicular to the direction of current. This principle is explained in detail by Hodgins, et al (Hodgins et al., 2014) and is shown in figure 9. This strain is due to the fact that the polymer is subjected to an electrostatic force and the stress generated is called as Maxwell stress (Kim et al., 2019).

Cao, et al (Cao et al., 2019) reviewed works of various researchers relating to soft actuators and indicated that Dielectric Elastomers (DE) or EAPs have greater strain compared to their counterparts. This is also indicated in (Kim et al., 2019), and is also mentioned that strain as high as 215% with an efficiency of 60 – 80% can be achieved. Also, some of the applications of Dielectric Elastomer Actuators (DEA) have been reviewed in (Cao et al., 2019) of which one of the applications is the biomimicking of flapping wings presented in (Lau et al., 2014). The assembly consisted of a CFRP shell held under compression by rolled DEA under tension. This construction as well as working principle are explained in figure 10. When an electric signal is applied to DEA, DEA expands and thus there will be relaxation in CFRP shell. When the signal is removed, DEA contracts and thus CFRP again goes into compressed state. This *to and fro* movement is used to actuate wings. Ram, et al (Ram et al., 2018) experimentally evaluated the feasibility of the use of VHB4910 (an EAP) as DEA for flapping wings mechanism. Prahlad, et al (Prahlad et al., 2005) explained citing examples as to how DEA can be used for both actuation and power generation.

Linear and Non-Linear modeling of EAP has been discussed in (Wang et al., 2018). Most generally, EAP is considered incompressible and has a poison ratio around 0.5. For any such material, the volume of the material is always constant, in other words, if L_1, L_2 and L_3 are the dimensions of the polymer, then the volume $L_1.L_2.L_3$ is always constant. If liner model is used for calculating the strain in DEA when voltage is applied, then equations (3) & (4) can be employed.

$$p_e = -\varepsilon_o \varepsilon_r \frac{V^2}{t^2} \qquad (3)$$

$$s_3 = -\frac{p_e}{E} \qquad (4)$$

If L_3 is the direction along which the voltage is applied, L_1=L_2=L, and being elongation along L_3 as in figure 11, while being deformations in other two directions, since volume is always constant, the deformation in other two directions can be calculated using equation (5)

$$\left(L-\delta_1\right)^2 (L_3-\delta_3) = L^2 L_3 \qquad (5)$$

When linear model is valid, then deformation per unit voltage in direction perpendicular to applied voltage Various materials like Rosin, Rubber, Beewax, Carnauba Wax (Gunter et al., n.d.) strain on application of DC electric field. Linear model discussed above is not valid when modeling large deformations in DEA. Hyper-elastic material models such as Arruda-Boyce model for materials like silicone (Wang et al., 2018) or viscoelastic model for materials exhibiting viscous properties like VHB4910, VHB4905 (Zhang, 2007) are being employed for computing of deformation. Experimental results presented in (Zhang, 2007) indicate that there shall always be a discrepancy in the calculated and experimental results for the actuator response largely relies on the way it is fabricated. Guggi Kofod (Kofod, 2008) pre-streach EAP largely attenuates the response of DEA. This can be attributed to the incompressibility of material. Mukherjee and Ganguli (Mukherjee and Ganguli, 2010) idealized the flapping wing of a dragon fly as cantilever and mathematically modeled the wing dynamic characteristics. Parametric studies are then executed on the wing model using the formulation. Hsien Low, et al (Hsien Low et al., 2012) showed that Electroless deposition can help in making extendable and self-healing electrodes for DEA. EAP is also being used for energy harvesting purposes also. Singh and Patra (Singh and Patra, 2015) discussed how Dielectric Elastomers can be used for generating current.

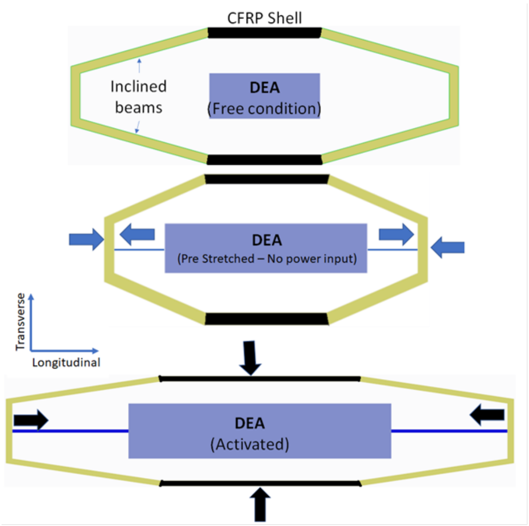

Figure 10: DEA powered flapping mechanism

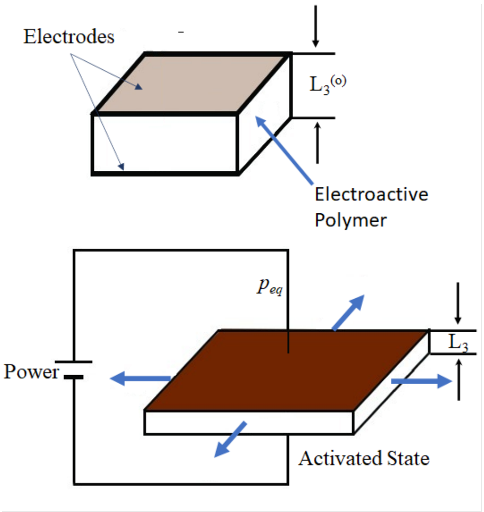

Figure 11: Working principle of EAP

4. Shape Memory Alloy (SMA) Actuators

Shape Memory Alloys (SMA) is a material that can return to its undeformed state when heated after being deformed in cold state. In other words, it can be programmed to remember the shape. This Shape memory property of the material can be used for actuation (Borboni and Faglia, 2014; Miková et al., 2015). SMA has been classified as solid state actuator (Kim et al., 2019). SMAs are now widely used as soft actuators like in the case of Under Water Vehicles like robotic jelly fish (Frame et al., 2018; "IIT Indore Invents Robotic Jellyfish To Keep A Check On The Marine Ecosystem. Know How!," 2019), crawlers, walkers and biomedical applications (Kheirikhah et al., 2011) and even for guiding Radomes (Sankar, 1994). Hambling (Hambling, 2018) demonstrated the use of SMA for designing Robot Stingray. Tao, et al (Tao et al., 2006) detailed the fabrication and working of SMA actuated fish tail fin.

Min-Saeng Kim, et al (Kim et al., 2011) demonstrated the use of SMA wire for Inch-Worm Technology. William Coral, et al (Coral et al., 2012) gave a detailed review of use of SMA in achieving muscle like actuation in bio-mimetic robots like ray robot fish, Lamprey Robot, Robojelly, beetle-mimicking flapping-wing system etc. Other applications include the use of SMA in spherical robots (Pan et al., 2019), bio-mimicking swimming system (Chu et al., 2012; Tao et al., 2006; Yu et al., 2017), three finger flexible gripper (Yang and Wang, 2008), Legged Robot (Shaikh et al., 2018), even for morphing wings for airplanes (Borboni and Faglia, 2014) etc. Naresh, et al (Naresh et al., 2016) and Rao (Rao, 2016) also reviewed the applications of SMA actuators. Polyphase actuator employing SMA as shown in figure 12 was developed by Sharma, et al (Sharma et al., 2008). Keerthi Sagar and Sreekumar (Sagar and Sreekumar, 2013) used a SMA wire wound round a silicone pipe to regulate the flow. Sreekumar, in his works, presented the kinematics of a 3DOF spherical manipulator (Sreekumar et al., 2006) actuated using SMA drawings of which are given in figure 13, as well as a spatial mechanism which is compliant (Sreekumar et al., 2009).

Work is in progress to develop a robotic exoskeleton for hand that employs SMA (Hope and McDaid, 2017). Major issue identified during this is the cooling of the actuator for which a series of fans have been used. Another disadvantage is that the response is non-Linear (Kluszczynski and Kciuk, 2013) and thus when developing control system for these actuators, care needs to be taken to account for non-linearity. The advantages of using SMA actuators are, these are rigid and hard as well as they can get great strain rates and quick response times without any prestressing.

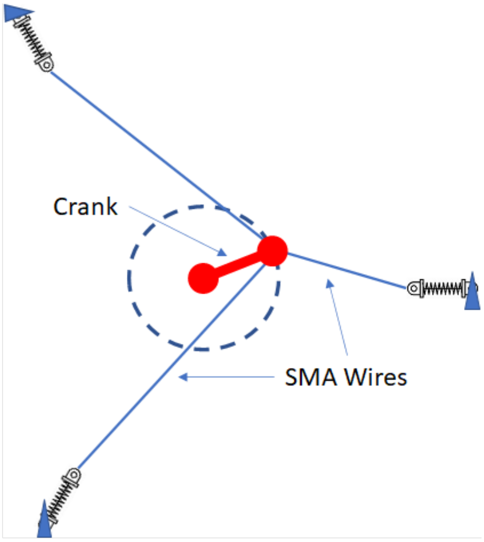

Figure 12: Polyphase SMA Motor described

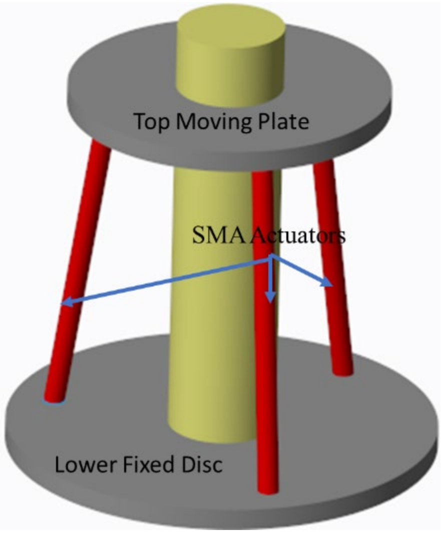

Figure 13: spherical Manipulator as described

5. Control Systems for Exoskeletons

Lee and Oh (Lee and Oh, 2019) employed serial elastic actuators for actuation of robotic leg. A mathematical model using Jacobian analysis for modeling the dynamic performance of the leg has been proposed in their work. Not just in robotics, SEA are also used for achieving better control and stability in mobility devices like Segway in high speed (Yun et al., 2019). But when employing highly non-linear actuators like SMA and DEA, choice of controller is important. As per Sreekumar, et al (Sreekumar et al., 2007), SMA is a highly non-linear actuator with large hysteresis and slow response. They also classified the control techniques for these types of actuators into four categories, namely, Sensorless Control, PMW Techniques, Linear Non-Linear Control techniques. Figure 14 gives a detailed classification of these techniques.

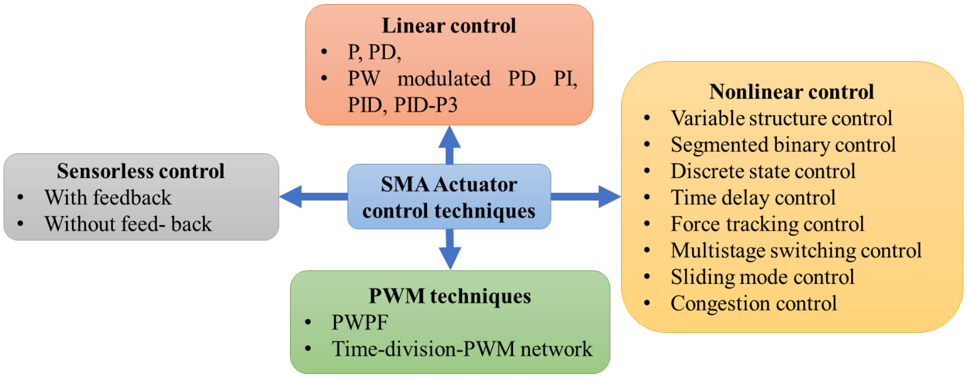

Figure 14: SMA Actuator Control techniques

Many exoskeletons that are currently in market which help in assisting lower body movement. These include Ekso bionics (“Ekso Bionics,” n.d.), Indego (“Indego,” n.d.), rewalk (“ReWalk - more than walking,” n.d.) etc. All these systems are using electric drives controlled by EMG. EMG control helps in achieving better gait (Wall et al., 2015).

6. Conclusions

Various types of actuators are used in robotic systems. These include SEA, DEA, SMA, and Fluidic systems. Different actuators suit different applications. Whatever be the application, compliance of the robotic actuator is of importance. Actuator with greater compliance will result in better shock resistance. In this work, a survey of literature pertaining to compliant actuators has been presented. Ninety references, with the list containing various articles and websites, were reviewed as a part of this work.

General electric actuators are not compliant and thus have little shock resistance and energy recovery capabilities. Serial Elastic Actuators are designed to counter this disadvantage. These are made by introduction of a flexible element between the drive shaft and the load thus making general electric actuators compliant. But still, when using these actuators in fabrication of robots, a little approximation in gait is required.

Soft-actuators, on the other hand, due to their flexible nature, help in achieving biomimicking to the greatest level, for they can be arrange in the way actual muscles are present. DEA are soft-actuators which are polymeric actuators. Literature suggests that these can be treated as incompressible polymeric actuators and when simulating these materials for stress analysis using FEA, various models for defining the behavior of material, like viscoelastic and hyperelastic models can be used depending on the material. Considering the advantages, DEA have faster response time. Pre-stretching gives greater strain response for given input electric signal.

SMA on the other had are metallic actuators which regain their shape from the deformed shape when heated. Heating can be achieved by passage of electricity. The major disadvantage is cooling of SMA actuator. It has been indicated in the reviewed literature that the response characteristics of DEA are highly non-linear and depend on the manufacturing process as well as pre-stretching. Another major disadvantage highlighted is the life expectancy of the same. Fluidic actuation can also be used along with soft materials. Different applications of these actuators are summarized in the article.

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