Soft Robot with New Pneumatic Rubber Actuators for Medical Assisting Device

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Abstract

Soft robots came into focus after for a long time the coexistence between human and conventional robot has never been an achievement. Unlike hard robot, soft robot has the potential to be more adaptable, capable, and safer devices especially in conditions where the robot has a close contact with human in unstructured environment such as in homes, offices, and public places. However, actuating soft robot is a challenging task as any rigid mechanism and electrical motor will impair the soft and safe characteristics of the robot. Therefore, pneumatic and/or fluidic type of actuation became common for robot operation.

Basically, the motion generated from soft material such as rubber and silicone, is by the deformation of the soft structure when pneumatic pressure is applied. Only 1 and/or 2 degree of freedom (DOF) can be achieved through this soft actuator mechanism. Nevertheless, to produce a significant motion of actuation, large deformation is necessary resulting a slow and rough movement if such actuators are to be employed in soft robot as a means of locomotion. In this research, a novel mechanism of fast response and an omnidirectional soft actuator is proposed. The actuators serve as soft robot legs with 6 DOFs for omnidirectional, smooth and precise locomotion ability.

One interesting application of such soft robot; and taking the advantage of transparence characteristic of silicone material, is in fluoroscopy examination. In this examination, an X-ray is used to scan a small lesion and polyps inside stomach as an early detection of stomach cancer. Due to shrinking nature of stomach, it has to be compressed from an external force in order to expose any concealed lesion. Normally, radiologist used a commercialized compression paddle and folded towel as an assisting medical device, positioned manually under the patient stomach to give a pressure to the stomach. The adjustment of the device is bothersome to the patient and here the soft robot has the opportunity to be employed and operated remotely without being detected by the X-ray image.

The development of soft actuator as pneumatic rubber leg for our robot begins with the idea, operating principle and the design of the leg. The design parameters were identified and simulation was conducted to achieve the optimum design from the construction of the leg. For elastomeric material simulation, Finite Element Analysis (FEA) was employed with several prototype designs were simulated until the optimum results is achieved for the specific design
parameters. In addition, simulation works provides better understanding of the leg motion and any modification can possibly be made before fabrication of the prototype.

Then, the fabrication of the prototype took place based on the optimum results obtained in the simulation works. Computer Aided Design (CAD) was used to design the leg and silicone molds of the leg. The information in CAD was then used in Computer Aided Manufacturing (CAM) for rapid prototyping and the silicone mold was produced using polyester resin plate. Two-component Room Temperature Vulcanizing (RTV) silicone rubber were used to produce the rubber leg where the process involves mixing of the silicone material, bubble elimination, and heating. Since the fabrication of the leg was layer by layer, the assembly of the layer was done before tubes were connected to the chambers inside the leg.

The leg prototype was then tested in experimental works in order to achieve the characteristics of the leg prototype. Leg displacement and deflection in vertical, sideway and diagonal direction were measured with different pressure ranging from 0 to 150 kPa. The results were compared with simulation works and show an agreement between the experiment and simulation data thus validating the static analysis characteristics of the leg. In addition, force generated from the deflection in sideway and diagonal direction was also measured using force gauge to identify leg ability in climbing a slope, a condition that may require the robot to perform during the fluoroscopy examination.

An achievement in establishing the leg prototype and its characteristic led to the design of soft robot. Eight legs were arranged in square to form a square-shaped walking soft robot without a leg at the center as the center leg will provide unnecessary analysis during locomotion. The locomotion gait was identified to generate a thrusting force for robot movement. Four stages of locomotion gait was achieved and corresponding pressurized chambers were identified in order to control the pneumatic valve for locomotion direction. The information is crucial in developing the programming of valve activation that dictates the direction of robot locomotion. Furthermore, locomotion pattern were decided where the legs were categorized into two groups in order to achieve static stability locomotion.

Afterwards, the development of soft robot that involve fabrication and control system setup were accomplished. The fabrication process was principally the same as in the fabrication of leg prototype. However, the new molds were produced as the soft robot was fabricated in one complete unit instead of combining each single leg together as it was time consuming and energy wasting. Forty pneumatic valves were used to control the pressure to the chambers
where Digital Input Output (DIO) card was connected to the valve via Darlington’s circuit as electronics interface between a PC and the valves. The human interface was developed in Microsoft Visual Studio (MVS) 2005 environment using C programming where the user able to control the robot via command prompt window. The characteristics of robot locomotion was investigated through experiment and omnidirectional locomotion ability, locomotion speed, traction force and maximum payload were able to establish.

Finally, the adaptation of soft robot and pneumatic pillow was confirmed with several experiments. The pillow was implanted on top of the robot and robot movement was observed. The ability of the robot to carry the pillow and remain stable after the inflation of the pneumatic pillow 7 times higher than the height of the robot without fall aside confirm a successful coordination between the soft robot and pneumatic pillow to serve as medical assisting device in fluoroscopy examination.

As a conclusion, we managed to produce a new pneumatic rubber leg able to perform omnidirectional motion from a unique mechanism. The characteristics of the leg was validated through experiment and simulation results. The combination of eight legs were used to form a soft robot square in shape to carry a pneumatic pillow as the transparence property of the robot and pneumatic pillow is an advantage of not being detected under X-ray examination. With the omnidirectional locomotion ability, adequate locomotion speed, smooth and precise locomotion ability; the soft robot has the potential to replace the commercialized compression paddle and folded towel as medical assisting device in fluoroscopy examination as an early detection of stomach cancer.
Dedication

To my dear parents, and my loving family;

Zanariyah binti Ab Karim
Muhammad Afiz Hakimi, 11
Nuralisya Hani, 9
Muhammad Affan Haikal, 5
Muhammad Afdhal Hafiz, 3
Nuramira Hafsa, 4 month
Acknowledgement

I would like to take this opportunity to commemorate my dearest former supervisor, Professor Koichi Suzumori for his guidance and assistant during my early year of study. His idea and suggestion really open my eyes and broaden my knowledge to cultivate research culture as common practise inside myself. Thank you very much for those enjoying days yet in a short period of time.

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Chapter 1

Introduction

1.1 Introduction

This chapter gives a brief idea of soft actuator, soft robot and fluoroscopy medical examination. It begins with the introductory of actuator, its type and the advent of soft actuator. Then, the arrival of soft robot is briefly explained as a results of to spur the coexistence between human and robot in social life. Next part introduces the fluoroscopy medical examination, where the soft robot has a potential application as medical assisting device. Finally, the purpose and contribution of the thesis is presented.

1.2 Soft Actuator

Basically, actuator converts an energy into a motion. The source of energy comes from many forms including electrical current, hydraulic fluid pressure, pneumatic pressure, thermal and magnetic field. Meanwhile, the motion generated from these energies are fundamentally the same. Motion such as linear, rotation, and oscillatory motion are the examples of type of motion produced by the actuator in order to generate a movement for a mechanical system that provide solution to any specific mechanical problem.

However, the selection of actuator depends on the type of actuator used. Four main types of actuators are electrical, mechanical, hydraulic, and pneumatic actuator. Electrical actuator such as motor and valve are widely used due to their cleanliness and readily available for any application. Mechanical actuator that involves gears, rails, pulley, chain, etc. converts a rotary motion into linear motion and normally this actuator is combined with the rest of type of actuator. Hydraulic actuator, consisting of cylinder or fluid motor utilizes liquid such as an oil to generate linear, rotary and oscillatory motion. Similarly, pneumatic actuator applied the same concept as in hydraulic actuator except the compressed gas is used instead of an oil.

Among these type of actuators, the advantages of cleanliness, quick response, easily constructed, high power to weight ratio, lightweight and economical set up is provided by pneumatic actuator. More importantly, these attributions made pneumatic actuator more adaptable to soft structure. For example, soft materials that can be easily deformed such as
polymers, foams, granular materials, rubber, etc. can only be actuated using a compress air or vacuum; the domain solely under pneumatic system operationalization. The utilization of soft materials in pneumatic actuator, or referred as soft actuator offers a good human interaction as it can be safe by its compliance property and its ability to absorb the force if collision accidentally happen during the close interaction between human and robot.

Nevertheless, the combination of rigid structure implanted within the soft material is also possible to produce the soft actuator. For example, Shaped Memory Alloy (SMA), Ionic polymer metal composite (IPMC), Ionic Conducting Polymer Film (ICPF), Electroactive Polymer Actuator (EPA), Dielectric Elastomer Actuator (DEA), Ferro fluid, cable, wire and composite granular embedded inside soft material structure can generate motions from input such as electrical and mechanical energy.

1.3 Soft Robot

Ever since the discovery of the word ‘robot’ used by Czech writer, Karel Capek in 1921, the world has been seen a tremendous explosion of robot technology in every aspect of human life. Although the word was referred to ‘automata’, originated from a great history and evidences - dated back as far as circa 270 BC, until today the progressive of invention of robot has never been at its peak. The pace of innovation continues in tandem with technological advancement in several areas particularly in design, construction, operation, application of robot, computer system, control system, sensory feedback and information processing, where these areas are referred as ‘robotics’.

Although the two fathers of robotics, Isaac Asimov and Joseph Engelberger have made a significant contribution in the robotics field, perhaps the effort itself confines the robot into limited human interaction. Isaac Asimov, science fiction writer, introduced Three Laws of Robotics in 1942 as follow,

1. A robot may not injure a human, or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given it by human beings excepts where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.
Meanwhile, Engelberger started the first robotics company, Unimation in 1961 for the famous industrial robot, Unimate that widely used in automotive industry. Yet the dispersion of robots are only common in industrial and research area where human population could not taste the direct impact and benefits from its existence.

Due to this limitation of safety requirement and possible human error, soft robots were introduced quite recently and still in infancy stage [1] with substantial progress are now happening in all over the world. Although some researchers tend to mix up the bio-inspired and/or biomimetic as ‘soft’ robot [2-11] where a solid-structure was embedded under soft material as a means of actuation, we agree on the definition where soft robot is composed exclusively from soft material with stiffness in the range of soft biological materials [12]. This is because of our interest to maintain the compliance property of the robot for human interaction and with the existence of solid structure in the system will jeopardize the safety and reliability of the robot. Figure 1.1 shows the tensile modulus (Young’s modulus) for certain material including biological materials.

![Figure 1.1: Tensile modulus for selected materials [12].](image)

1.4 Fluoroscopy Medical Examination

1.4.1 Procedure

Fluoroscopy is a kind of medical imaging intended to examine specific area in the body such as bones, muscles, joints; and an internal organs such as heart, lung, kidney and stomach. In the case of patient whom undergoing stomach fluoroscopy test, he/she will be asked to drink a contrast media or “dye” such as barium prior to the examination. During the test, a continuous wide beam of X-ray is exposed to the patient’s stomach. Exam table where patient is located in prone or supine position will be tilted at several angles to allow the barium coating the stomach wall. This will results in an excellent video image throughput. However, along the
process to discover any abnormality during the examination, patient is required to hold his/her breath and some intervention from radiologist is necessary to compress the abdomen. As stomach just like a balloon which is shrinking in nature, the compression of the stomach will expose and spread the barium hence revealing the small ulcer and polyps which identified as the root cause of stomach cancer. This procedure took about 15 to 30 minutes to complete with different position of patient as well as tilting angle of the exam table.

Figure 1.2 shows the condition of patient during fluoroscopy examination. The patient is in the exam room while the radiologist whose operate the machine is in separate room, namely control room. The exam table is controlled by the radiologist in order to incline the patient at specific angle to thorough investigation of any abnormality inside the stomach based on the output image from the display.

![Figure 1.2: Environment of fluoroscopy examination where patient is slanted for clear output image.](image)

1.4.2 Medical assisting device

A commercialized compression paddle and folded towel has been widely used as a compressing device, which is placed between the exam table and patient’s stomach to push the stomach at specific area. They work to prevent superimpose of the image since both the compression paddle and bath towel are X-ray transparent. Figure 1.3 shows the usage of compression paddle and Figure 1.3 (a) shows the pressurized compression paddle while Figure 1.3 (b) shows compression paddle under normal condition.
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http://www.auntminnie.com/index.aspx?sec=ser&sub=def&pag=dis&ItemID=53089 (a) Compression paddle is pressurized, and (b) compression paddle in normal condition. https://o.quizlet.com/Ng-DGkzRQAz-U0b09STlS5g_m.jpg

Meanwhile, the employment of folded towel has been practised by some radiologist and can be seen as in Figure 1.4 (a). Figure 1.4 (b) shows the way how the towel is folded and placed between the patient stomach and the exam table. From the improvisation, Figure 1.4 (c) and Figure 1.4 (d) show the comparison between an X-ray images of stomach without compress and stomach being compressed respectively using the folded towel. The orange box highlight the area of the compressed stomach with clear image at the specific area.
Figure 1.4: (a) Folded towel located under patient’s stomach, (b) way of folding the towel, (c) uncompressed stomach, and (d) compressed stomach with clear image. [http://www.syoukaki-kensinseido.jp/index.html](http://www.syoukaki-kensinseido.jp/index.html)

Nevertheless, frequent intervention by radiologist during the adjustment of the assisting device to the specific location around the stomach can be bothersome for the patient. This includes the radiologist having to enter the examination room, asking the patient to lift his/her body, adjusting the assisting device manually, exiting the examination room and continuing to operate the fluoroscopy machine. This process will repeat several times for different stomach areas and besides uncomfortable to the patient, the level of radiation exposure also increases both to the patient and the radiologist.
1.5 Research Purpose

The purpose of this study is to establish a soft actuator with X-ray transparent property able to perform higher DOF of actuation that includes linear extension and oscillatory motion in different direction. This gives the actuator an omnidirectional ability which is useful for locomotion if the actuator serves as the legs for a soft robot. The design property of the actuator which dictates the output performance need to be identified in order to obtain the characteristics of the actuator.

Once the soft actuator is established, the investigation continues to develop the soft robot in term of realizing the omnidirectional locomotion. Components such as locomotion stability, traveling speed, distance and ability to carry a load need to be identified in order to evaluate the soft robot performance. Furthermore, the potential ability of replacing the existing medical assisting device need to be confirmed as well as its workability to ensure the safety and reliability of the soft robot during its operation.

1.5.1 Aim and objectives

Based on the requirement of X-ray transparency and distraction experienced by the patient, this study aims to produce a soft robot able to transfer a pneumatic pillow as an assisting medical device. This device will be serve as stomach compression during stomach fluoroscopy examination as a means to eradicate human intervention and radiation risks. The soft robot is constructed from soft actuator made from silicone rubber to form a horizontal platform for pneumatic pillow transportation to the specific location with omnidirectional locomotion ability. The soft robot operates pneumatically and remotely controlled thus eliminating radiologist intervention during the medical examination.

Following are the objectives of the study to ensure the aim is achievable,

1. To establish an actuator with omnidirectional mechanism from soft materials exhibits properties such as translucent, safe and human compliance.
2. To produce a prototype of soft robot, based on the established actuator to perform omnidirectional locomotion and operate in clean and quiet environment, e.g. Healthcare centre and hospital.
3. To develop the control system of soft robot in order to govern the locomotion direction.
4. To evaluate the characteristics and parameters associated with the performance of the soft robot.
5. To incorporate pushing mechanism on the soft robot for stomach fluoroscopy examination and confirm its workability as medical assisting device.

1.5.2 Thesis contribution

The principal contribution of this thesis are as follow,

1. The establishment of new soft actuator with linear and oscillatory motion in different direction for higher degree-of-freedom (DOF).
2. Based on the soft actuator, an omnidirectional locomotion soft robot is realized eliminating a complex mechanism for turning and changing direction.
3. The property of stiffness and thickness of soft material, specifically a silicone rubber towards the detection of an X-ray is established.

1.6 Thesis Outline

The thesis is divided into five chapters. In Chapter 1, which is the Introduction, the background of the study is discussed. It covers the explanation of soft actuator, soft robot and fluoroscopy medical examination, where the problem statement is identified and how the soft robot can be potentially employed to facilitate the medical procedure. In addition, the introduction of soft actuator and soft robot are also delivered to give a general idea about the branch of actuator and robot. Besides explanation of research purpose, this chapter also highlight the aim and contribution of this research to be acknowledged and appreciated.

In the second chapter of the thesis, represented by Chapter 2, a review on the development of soft actuator, soft robot and issue regarding stomach fluoroscopy examination are presented. The soft actuator, which hold the basic mechanism for the soft robot movement is the main subject of this study and required a complete review. From the review, any gap and disadvantage of existing actuator is identified and stem the idea to create a new mechanism for the new soft actuator. Then, the literature on soft robot is explained to provide the current progress in soft robotics field. The final part of Chapter 2 discusses the impact of stomach fluoroscopy examination towards life threatening cancer with case study conducted in Japan.
Chapter 3 discussed the development of soft actuator. It covers the design of the soft actuator, its operating principle and parameters associated with the design. The simulation works are described in order to achieve the optimum design of the actuator which assists the fabrication process. Afterwards, the description of fabrication process is presented including Computer Aided Design (CAD), mould design, Computer Aided Machining (CAM), etc. until the prototype of the actuator is obtained. Then, the validation of all the theory and hypotheses from the previous works is demonstrated through series of experimental works.

In Chapter 4, the development of soft robot is discussed. The discussion focused on the design and operation of the soft robot. This includes the theory of locomotion gait and locomotion pattern in order to identify the thrusting force and robot ability to perform the omnidirectional locomotion. Then, fabrication process is explained until the prototype of the soft robot is achieved. In order to control the soft robot, the development of both software and hardware are presented. From the configuration, a series of experiments managed to be performed and explained in this chapter. The results from the experiments contribute to the characteristics and behaviour of the robot based on input parameters applied to the control system.

Chapter 5 reports on the works of combining the soft robot with pneumatic pillow as medical assisting device in stomach fluoroscopy examination. The pneumatic pillow which has been tested under X-ray examination and confirmed its workability, is implanted on the top of the robot. The compatibility between the two subjects is investigated through a series of experiments. Results from the experiments provide the evidence for potential ability of the combination of soft robot and pneumatic pillow, to be used as medical assisting device in fluoroscopy examination.

The final Chapter 6 summarizes the works and outcome of the investigation. The accomplishment of the research is compared to the previous aim and objectives in order to reflect the achievement of the works. In addition, any drawback in every aspect during the study is addressed and possible improvement is suggested. This benefits the future works of the study and to ensure a continuous and active research progress in the area of soft robotics.
Chapter 2

Review on Soft Actuator, Soft Robot and Stomach Fluoroscopy

2.1 Introduction

This chapter begins with a review on soft actuators and their corresponding mechanism that generates several motions. Then, the application of the actuators is briefly explained. Afterwards, a review on soft robot is presented to update the current progress in the field of soft robot. These information provide the niche area where the soft robot has never yet been explored. The final part discusses the relation between stomach cancer and fluoroscopy examination based on case study in Japan.

2.2 Soft Actuator and Its Application

The classification of Elastic Fluidic Microactuators can be seen as in Figure 2.1 based on Volder [13]. However, with the intensive research and fast progress in soft actuators, the categorization of soft actuator can be expanded.

![Figure 2.1: Classification of elastic actuator according to Volder, 2010 [13].](image)

In general, pneumatic soft actuator can be divided into five categories: Pneumatic Artificial Muscles (PAMs), Flexible Micro Actuators (FMAs), Pneumatic Balloon Actuators (PBAs), bellows, and composite granular jamming. Figure 2.2 shows the division of soft actuator and the categorization method as guidance for the classification.
Figure 2.2: Pneumatic soft actuator classification and method of classification.

In principle, McKibben or PAMs or Pneumatic Muscle Actuators (PMAs) is constructed from a rubber and covered by sheath or nylon sleeves with specific braid angle to allow an extension and contraction when pressurized. This mechanism allows one Degree-Of-Freedom (1-DOF) linear motion as well as bending, and rotation, depending on the arrangement of the actuators. For linear motion, the actuator is arranged with both ends are located in straight position as in Figure 2.3 (a). The bending motion is realized when several actuators are arranged in parallel as in Figure 2.3 (b). These configuration was established by Fukuda for his in-pipe inspection robot [14]. In rotational motion, two actuators are arranged and connected to roller as in Figure 2.4 where the actuator works antagonistically.

Figure 2.3: PAM and its application in in-pipe inspection mobile robot by Fukuda, 1989 [14].
Several researchers have demonstrated variation of arrangements to achieve similar motion of linear, bending and rotational based on their application. In power assist and exoskeleton system, PAMs are used as demonstrated in [16 – 22] as can be seen in Figure 2.5.

Another application which close to power assist is rehabilitation where PAMs are widely used as reported in [23 – 27]. Among favourite body parts for rehabilitation are hand finger, ankle and knee as in Figure 2.6.
Nevertheless, invention of device based on PAMs showed intensive progress as described in [28 – 40]. Device such as endoscope, minimal invasive surgery tool and robot actuator were among the device produced as in Figure 2.7.

Another application which PAMs are used is in producing continuum limb. Although several continuum limbs has been demonstrated, the pneumatically operated continuum limb has been established in [41 – 42] as in Figure 2.8.
An FMA consists of several chambers arranged in parallel within one elastic structure with or without sleeve and the sleeve do not determine the contraction and extension of the actuator as in PAM. It was first developed by Suzumori where the structure and application can be seen in Figure 2.9 [43 – 47]. For linear motion, all the chambers are pressurized whilst bending motion can be achieved by pressurizing one of the chamber. Nevertheless, rotational motion is difficult for this kind of actuator.

Figure 2.9: Structure of FMA and its application produced by Suzumori, 1991[44].

Most of the application of FMA are as manipulator and device for medical purpose [48 – 52]. Interestingly, besides as manipulator as demonstrated by Suzumori previously, it also be used as conveyor as in Figure 2.10.

Figure 2.10: FMAs as conveyor carrying glass plate by Suzumori, 1994 [46]

Figure 2.11 shows the application of FMAs as mechanism to be used with forceps during medical surgery as well as endoscope.
Figure 2.11: FMAs as medical device by Chishiro, 2013 [49].

By using simple mechanism of balloon deformation, PBA is constructed from elastic material with chamber independently operated whilst the arrangement is not parallel as in FMA. The simple linear motion was described in [53 – 55] by pressurizing the chamber as in Figure 2.12. In fact, most of the employment of PBAs are taking the advantage of the linear motion as demonstrated in [56 – 66].

Figure 2.12: Linear motion from PBA by Hayakawa, 2003 [53].

Bending motion can be obtained by using different thickness of material or different elasticity of material as in Figure 2.13. For rotational motion, the arrangement of PBAs are in series as in Figure 2.14.

Figure 2.13: Bending motion using PBA presented by Konishi, 2001 [67].
Due to its versatility, PBAs are widely used to produce devices for wide range of applications. For example, by sequencing the pressurized chambers PBAs can be used as micro pump as demonstrated in [69 – 70] as well as sorting table as in [71 – 73] and mimicry of esophageal [74]. However, rehabilitation device remains the preference of application of PBAs among researchers and Figure 2.15 shows an example of rehabilitation device [75 – 78].

Another category of pneumatic soft actuator, bellow type actuator is constructed from elastic materials with chambers arranged in series within one structure and pressurized only from one input. A large displacement and bending angle can be obtained from bellows mechanism with single input hence linear motion seldom be applied in application except in [79 – 82] as in Figure 2.16.
Figure 2.16: Linear motion from employment of bellow by Sasaki, 2012 [79] and Chang, 2015 [82].

Many researches have been conducted by taking the advantage of bending motion ability from bellow-type of actuator [83 – 89] as in Figure 2.17.

Figure 2.17: Bellow-type actuator for bending motion by Konishi, 2002 [83], Choi, 2009 [84] and Meng, 2015 [84].

Interestingly, rotational motion and a few difficult motion can be produced using bellow-type actuator [90 – 92]. Figure 2.18 (a), (b) and (c) show the twisting, rotational and helical motion respectively generated from bellow-type of actuator.
Bellow-type actuators are mostly used for medical device purposes as mentioned in previous reviews and in [93–97]. Nevertheless, it also been used for producing manipulator in [98–102] and Figure 2.19 shows the example of medical assisting device and miniature manipulator.

![Figure 2.19](image.png)

**Figure 2.18:** (a) Twisting motion by Gorissen, 2014 [90], (b) rotational motion by Niinyama, 2014 [91], and (c) helical motion by Amase, 2015 [92].

Although the previous discussed pneumatic soft actuators are based on each category, there are investigations that combined two categories of the actuator to produce a motion such as peristaltic. This will be discussed in soft robot development in the next chapter. The final type of pneumatic soft actuator which is granular jamming is constructed from elastic materials with granular are filled inside the chamber. The generated motion depends on the unjamming skin.
and membrane as in Figure 2.20. In addition, construction shape of the actuator also determine the type of motion that include rolling, linear and bending motion. [103 – 105].

![Diagram of Rolling Motion](image)

**Figure 2.20:** Rolling motion from jamming type actuator by Steltz, 2009 [103].

Due to its high ability to change stiffness, granular jamming is used in exoskeleton and manipulator for invasive surgery [106 – 108]. Figure 2.21 shows an example of granular jamming used robotic exoskeleton.

![Granular Jamming Example](image)

**Figure 2.21:** Granular jamming used as robotic exoskeleton by Bean, 2015 [107].

Nevertheless, the review of pneumatic soft actuator potentially used in medical application has been studied by Greef [109]. The term pneumatic soft actuator was referred as flexible fluidic actuator in the study and in the report, he summarized the mechanism for achieving bending and rotation motion as both are crucial to produce higher degree of freedom (DOF) medical instrument.

In order to generate a locomotion ability, the actuator need to have the ability to create linear and oscillatory motion. These motions will provide a gait or step-like motion that pushes the soft robot to one direction. In addition, how the robot changes its direction or makes a turn to
arrive to its destination is also an important point of consideration. An omnidirectional ability will provide simple and fast motion for the robot to change its direction. Although previous literatures have shown some example of locomotion from FMA, PBA and PAM type of actuator, we can anticipate that the locomotion is sluggish due to the time taken for the soft material to deform and make a step. Furthermore, buckling is experienced for a long leg if a load is applied to the robot.

Therefore, a new mechanism of soft actuator with fast response and efficient leg length is required. In order to achieve fast response, parameters such as type of soft material, stiffness and thickness play an important role to the actuator performance. Similarly, to avoid buckling effect the determination of the leg length with correct stiffness and thickness is crucial hence both smooth and fast locomotion can be achieved successfully.

### 2.3 Development in Soft Robot

Based on several type of pneumatic soft actuators, soft robot was introduced as an approach to promote the coexistence between human and robot. The research area has become intensify these several years with intriguing product and uniqueness. PAM type of actuator was exploited in early work by Fukuda [14] with inchworm locomotion technique by stretching and shrinking of twelve rubber actuators in two inches inner diameter pipeline inspection. The employment of PAM underwater was presented with swimming ability [110] by robotic fish. An interesting application of PAM was demonstrated in [111] with rolling tensegrity robot while locomotion robot using PAMs was described in [112 – 113]. Figure 2.22 shows some examples of soft robot using PAMs as a means of movement.

![Figure 2.22: Soft robots using PAMs by Cai, 2009 [110], Koizumi, 2012 [111], and Godage, 2012 [113].](image-url)
The implementation of FMA in soft robot was kind of similar to PAM where the applications include locomotion and swimming of soft robot [114 – 115]. However, one of unique and brilliant approach of utilizing FMAs for soft robot was presented in [116] where six FMAs were braided to produce in-pipe locomotion robot. By sequentially pressurized the FMAs, forward locomotion is achieved and able to turn in elbow shape pipe. Figure 2.23 shows the examples of the soft robots.

![Figure 2.23: Soft robot from FMAs by Suzumori, 1996 [114], 2007 [115] and Takeshima, 2015 [116].](image)

The PBA type of pneumatic soft actuator receives diverse kind of application. Suzumori introduced Bubbler by sequentially pressurized twelve chambers that created linear motion, and by pairing them, steering motion was achieved as mobile robot base [117]. Based on the principle, Suzumori applied the concept to colonoscopy assisting device with multi-room rubber tube and Bubbler tape that was twisted around colonoscope [118]. The improvement of such mechanism in colonoscopy assisting device were continued until number of chambers were reduced to three whilst traveling speed was increased [119 – 122]. Underwater application was demonstrated in [123] where the deflation of balloon from its elasticity releasing the fluid inside hence thrusting the robot forward. The fast inflation of balloon with high pressure was used as jumping robot as described in [124] and complete humanoid soft robot was presented in [125]. Figure 2.24 shows an examples of these robot based on PBAs.
Meanwhile, the research on soft robot using bellow type of pneumatic soft actuator mostly focused on gripper and locomotion type of robot. Considering the merit of large bending angle [126 – 127], the gripper demonstrates ability to hold soft and delicate object such as elastic ball and an egg as in Figure 2.25.

**Figure 2.25:** Gripper using bellow type actuator by Noritsugu, 2000 [126] and Ilievski, 2011 [127].

For locomotion type of soft robot [128 – 134], various configurations of bellow were exploited to produce different type of locomotion. Walking soft robot with bellows served as the legs of the robot was achieved to slip under short gap and for search and rescue robot as in Figure 2.26.
Jumping robot was also demonstrated using bellow type actuator as well as rolling and snake-like locomotion as depicted in the figure.

Figure 2.26: Variation of locomotion ability from soft robot by Shepherd, 2011 [128], Florez, 2014 [129], Tolley, 2014 [131], and Onal, 2011 [132] and 2012 [133]. Although each type of soft actuator can be employed individually to produce soft robot, some researchers have demonstrated a combination of type of pneumatic soft actuator to generate a soft robot. However, the innovation confined to one locomotion pattern and application [135 – 141]. The combination of PBA and bellow type of actuator for realizing peristaltic locomotion for endoscopic application has long been investigated and the example of such soft robot can be seen as in Figure 2.27.

Figure 2.27: Peristaltic locomotion soft robot from combination of PBA and bellow type of actuator by Dario, 2004 [139] and Yanagida, 2013 [141].
Nevertheless, these locomotion of soft robots restricted to linear motion with 1 and/or 2 degree-of-freedom (DOF) while some required steering capability that made it impossible to achieve an omnidirectional locomotion. The only omnidirectional locomotion from soft actuator were discussed by few researchers including Suzumori whose demonstrated omnidirectional walking and turning robot from FMA [114], while Shepherd established locomotion with combination of crawling and undulations motion based on pneu-net (PN) architecture [128], and Godage with quadruped robot using continuum limbs [113]. Steering type of turning mechanism can be achieved by reducing operating pressure of one of the front leg of six legged soft robot [129].

One interesting application that took an advantage of silicone rubber transparent was demonstrated by colour changing and camouflage ability with soft diffraction grating and injecting colour fluid in microfluidic network [142–143] as in Figure 2.28

![Figure 2.28: Colour changing and camouflage ability from soft robot by Suzumori, 2011 [142] and Morin, 2012 [143].](image)

Although an omnidirectional locomotion from soft robot has been presented, the traveling speed was sluggish in PN whilst using FMA, the long size of actuator affects the stability of the platform or robot base. Meanwhile, if any rigid structure is to be employed for accurate and fast response of locomotion, it will impair the compliance of the soft actuator. Therefore, an exclusively soft robot with fast, smooth and omnidirectional locomotion ability have yet to be established.

The previous paragraphs have demonstrated some efforts to promote the symbiosis between human and robot through soft robot in various kind of applications. Although the nearest example of close interaction between human and soft device was possibly presented by colonoscopy and endoscopy assisting device, the favourite equipment for the procedure still dominated by solid structure device as reviewed by Beasley [144]. While soft materials are
References


delicate objects inspired by caterpillar locomotion


jamming,” in *IEEE Int. Conf. on Advanced Intelligent Mechatronics (AIM)*, pp. 165-170, 2015.


