Chapter 7
Conclusions and Future Work

The following conclusions can be made based on the investigations carried out in this research work:

(a) Mathematical Modelling

- A mathematical model for the bending angle of the pressurized AFPA is obtained by treating the actuator as a cantilever beam using Euler-Bernoulli's non-linear bending equation.
- A second model is arrived at by treating the AFPA as a parallel combination of springs of different stiffnesses to account for the different thicknesses at the top and bottom.
- Two FEM models are obtained by treating the AFPA as a 10 DoF and 18 DoF bending element respectively and solved for the deflection by using one dimensional bending elements.
- The statics and dynamics characteristics of the actuators are obtained. The dynamic modelling will offer an insight into the dynamic system, as it constitutes a fundamental step to understand how to design a soft robot.

(b) Three fingered Miniature gripper

- A single chamber asymmetric flexible pneumatic bellow actuator based on silicone rubber is developed that can generate bending motion better than the symmetric actuators of two or more chambers. It could lift up to 30 grams mass of objects, of various geometries, at 3 bar pressure.

- Simulations in ABAQUS software resulted in optimized design of the actuator. Using three such actuators a miniature soft gripper is also fabricated. The assembled actuator in the form of gripper has shown good results in pick and place of small parts such as integrated circuits (IC).

(c) Four fingered gripper

- The four-fingered gripper made with medical grade Poly Vinyl Chloride (PVC) AFPA can lift objects up to about 50 grams at 5 bar pressure.

- A nitrile rubber AFPA driven by pneumatic system has been developed and applied to four fingered robotic soft gripper that can lift objects weighing up to 100 grams at 5 bar pressure.
- The gripper can lift various soft and hard objects like fruits, container, water bottles, etc.

(d) Design and Manufacturing of Actuators for Multi-Fingered Soft Robotic Hand

- Asymmetric actuators give bending performance better than symmetric actuators.
- The fingers of the multi-fingered hand are made with 2 DoF whereas the general soft hand has 1DoF in one finger.
- Smooth exterior asymmetric flexible pneumatic actuator (AFPA), Square 6-corrugated and 12-corrugated ABFPAs, Semi-circular 3-corrugated ABFPAs and Triangular tapered ABFPAs have been designed, analyzed, optimized, manufactured and experimented to get maximum deflection for the stated application.
- The square corrugated ABFPA, semi-circular corrugated ABFPA and triangular corrugated taper ABFPA have been combined to obtain two dof finger actuators.
  The finger actuators have been combined to fabricate a 10 dof hand that have successfully been tested for various grasps for pick-and-place operation.
- The hand is powered using 5 bar BTC-IIS diaphragm air compressor and the air flow is controlled using miniature solenoid values that are in turn controlled by an Arduino Nano PCB.
- A hydraulic pump with about 8 bar output pressure and 555 ml/min discharge has been designed and manufactured and can be used for the 3D printed PLA multi-fingered hand.

(e) Five Fingered Soft Robotic hand for prosthetic application

- A single chamber asymmetric rubber and metallic bellow flexible pneumatic actuator (ABFPA) has been designed and manufactured for the construction of a novel underactuated multi-fingered hand for prosthetic application.
- The basic characteristics of the ABFPAs have been analysed theoretically and experimentally. The statics and dynamics can be predicted easily and the ABFPAs are

designed efficiently. The step response characteristics of the nickel ABFPA is better compared to rubber ABFPA.

- Due to limitations in the availability of suitable material and also the difficulty in making the bellow wall thickness less than 0.1 mm by additive manufacturing technique, nickel bellow of wall thickness of 40 µm manufactured by electro-deposition method is chosen.

- The nickel bellow actuator is found to be more effective and the behavior observed was consistent and reliable.

- It is found that the effect of shape and eccentricity of the ABFPA plays an important role in the bending of the actuator and the deflection of ABFPA is influenced by the eccentricity up to a certain extent.

- Also the effect of instability while gripping when the pressure of the working fluid reaches a critical limit as in the case of symmetric FPAs or FMAs is avoided.

- A tapered triangular ABFPA is designed and fabricated by a single mould to prevent leakage of air due to joining of the bellow parts as in the case of square bellow actuators.

- The tapered triangular rubber ABFPA and the nickel ABFPA gives a bending angle of about 80° and 65° respectively subjected to an internal pressure of 5 bar which is close to the results obtained by FEM analysis.

- The fabricated nickel ABFPAs hand can carry weight twice (~450 gms at 5 bar pressure) than that of the hand made of rubber ABFPAs (~220 gms at 5 bar pressure).

- The bursting pressure of the nickel bellow actuator used in the prototype hand is about four times than that of rubber bellow actuator of approximately same average size.

- The rubber ABFPA hand can carry a payload more than its own weight provided the battery and the mini compressor are mounted separately on the human body. This will reduce the weight of the hand drastically.

- The multi-fingered hand is able to grasp various types of objects of different shapes and sizes and the bending of fingers is close to the human hand.

- The total mass of the full prosthetic arm is just about half the mass of the conventional motorized prosthetic arm.
- It is possible to open and close the hand with a speed of 5 to 8 times faster than conventional prostheses.
- The hand made of nickel ABFPAs can lift light to heavyweight objects which can be extended to industrial applications based on pneumatic or hydraulic systems.
- The hand constructed with this kind of bellow joint will have advantages of low price, simple structure and good flexibility.
- The entire hand including the arm can be built within few days using materials worth less than US$ 800.

(f) Application of Principle to Novel Anti-Bourdon tube pressure gauge (Appendix A)

- An Innovative Pressure Gauge which can measure pneumatic and hydraulic pressure has been fabricated and tested.
- The principle of measurement of the novel device is opposite to that of the Bourdon tube.
- The deflection of anti-Bourdon tube is due to dual effect of differential expansion and the end moment induced.
- Relatively easier to manufacture asymmetric circular tube than C-shaped elliptical Bourdon tube.
- Locating the gear mechanism at the center of the C-shaped tube is not necessary in case of anti-Bourdon tube.
- Very high pressures can be measured which is not possible using Bourdon tube.
- Comparative results with the existing Bourdon pressure gauge show that the innovative pressure gauge is a reliable and promising pressure gauge in future.

Future work

- Theory will be extended to non-linear bending characteristics.
- More robust model to describe various geometries, holding or grasp types, loads and pressures may be studied.
- The manufacturing of circular metallic ABFPA by electro-deposition technique to the required wall thickness can be made to avoid wire soldering to the symmetric metallic bellow actuator.
- With the advancement in Additive Manufacturing technology in future, suitable asymmetric metal bellow actuators can be manufactured at less cost for the required thickness and flexibility.
- A tactile sensor can be incorporated at the tip of the fingers to measure a contact force and a suitable feedback control system can be developed to make the hand very stable for grasping and handling various objects.
- Also a miniaturized hydraulic pump can be used to reduce the hand weight and to avoid vibration generated by the miniaturized compressor.