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A Review on Dynamics and Control of Soft Grippers

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Abstract : This paper thoroughly examines the dynamics and control of manipulators emphasizing their importance, in the field of robotics. It explores control approaches discusses their limitations and delves into advanced strategies such as Model Predictive Control and Sliding Mode Control. Additionally, it explores the emerging field of robotics highlighting how compliance control plays a role in ensuring safe interactions with objects and humans. The paper also provides real world case studies to demonstrate applications. Overall, this research contributes to an understanding of manipulator systems and the integration of robotics enhancing the capabilities of robots, across various sectors.

IndexTerms **- applications, dynamics and control strategy, future aspect, real world challenges**

I. Introduction

INTRODUCTION

The diverse discipline of robotics has made great strides throughout time. Robotics has altered a wide range of fields over the years, from academia to the manufacturing industry. Robots are utilised to increase production, decrease risk to humans, and prolong human life. Artificial intelligence and machine learning developments have made robots even smarter, lowering human labour requirements, and enabling self-driving automobiles, social robots, and medical robots for interaction and surgery.

Manipulator system consists of major three components: links, joints and end- effector. These components of robotic structure are designed to manipulate objects or to perform the required tasks in various application. Links are the rigid segments that connects the joints in a manipulator system. These segments vary in length and shape. Links are responsible for transmitting motion from the joints to the robots' end effector. Links are important in robots as they affect the performance. Joints are the mechanism that allows the robot's links to move relative to each other. Joints must be stronger comparatively to other components of the robot as they must withstand the loads during the operation. There are several joint types but most commonly used are revolute, prismatic and revolute joints. The arrangement and combination of links and joints determine the robot's overall reach, dexterity and workspace. An end effector is a device that is attached to the end of the robotic arm and is used to interact with the environment. End effector can be used for various tasks and it can be designed accordingly on the basis of the design of the manipulator. End effectors are an important part of the robot and play a vital role in various application and fields.

There are two types of end effectors: soft and hard grippers and they can be classified on the basis of their control.

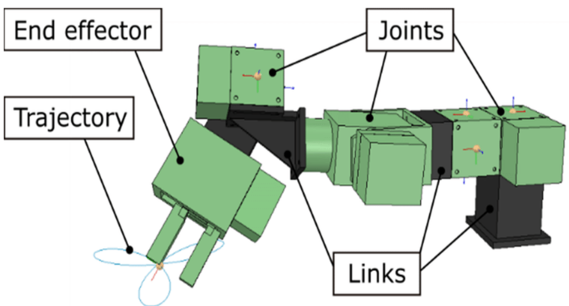


Fig1. Components of a manipulator system [12]

Dynamics and control of manipulator plays a vital role in robotics and can also be considered as the backbone of robotics. This system consists of robotic arm with multiple joints that enable them to reach, grasp and manipulate the objects in wide range of applications such as UR-5 robots, Kinova robot, welding robots or even a simpler word SCARA robot. Understanding the dynamics of the manipulator is crucial stage because a minor mistake can impact the precision and accuracy of the required application. The control mechanisms are integral part of the manipulator as they ensure the safety of both robots and human as well the surrounding preventing accidents and collisions. Manipulator dynamics and control enables smooth and optimal trajectory planning for robots. Through the survey of various mathematical representation, the behavior of the soft gripper's path planning is defined properly and the control methods are implemented to adapt the environment and manipulate the object holding.

This paper aims to provide the comprehensive exploration of the dynamics and control of manipulators, addressing both traditional and advanced techniques. It aims to enhance the understanding in the areas where compliance and adaptability of soft grippers are of utmost importance and bridging the gap between established techniques and innovative, adaptable robotic solutions. It also aims the importance of material properties that can determine the stability of the gripper and be environment friendly making it easier on basis of the cost. The dynamics and control of soft gripper are pivotal and this paper reviews the understanding of the dynamics and control of soft gripper. [1]

II. EVOLUTION

2.1 Kinematics and Dynamics of Manipulators

The kinematics of robotic manipulator deals with the understanding the relationship between the joint angles and resulting position and orientations of the end effector. The forward and inverse kinematics theory of the manipulator deals the same. The forward kinematics deals with the position and orientation of the end effector given the joint angles, it can be solved using the mathematical equations.

$$\begin{bmatrix} cos\theta_i & -sin\theta_i cos\alpha_{i,i+1} & sin\theta_i sin\alpha_{i,i+1} & a_{i,i+1}cos\theta_i \\ sin\theta_i & cos\theta_i cos\alpha_{i,i+1} & -cos\theta_i sin\alpha_{i,i+1} & a_{i,i+1}sin\theta_i \\ 0 & sin\alpha_{i,i+1} & cos\alpha_{i,i+1} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Forward kinematics matrix

The inverse kinematics deals with the joint angles, for the given position and orientation of the end effector. There are various ways in solving the equations either by graphical method or by decoupling method. Forward and inverse kinematics are important tools for robot control and motion planning. The dynamics of the robotic manipulator deals with the relationship between forces and torques involved in the manipulator taking into account of mass, inertia, velocity and joint friction. The Newton- Euler equations of motions theory deal with the dynamics and path planning of the robotic manipulator.

$$I\ddot{\theta} + h + \gamma = \tau \qquad (1)$$

2.2 Mathematical modelling of Manipulators

Mathematical models of manipulators are the process of developing mathematical equations that describe the motion and behavior of a manipulator. This can be done by taking into account of the manipulators' kinematics and dynamics. They allow to simulate and control the movements of manipulator accurately and precisely. The most common modelling technique is Denavit–Hartenberg parameter technique (DH parameter), which describes the geometry and relationships within a manipulator. DH parameter takes into consideration of certain parameters such as rotation (θ and α) and displacement variables (r and d). DH parameter plays a vital role in modelling of manipulator, as this includes the equations of forward and inverse kinematics. There are various mathematical modelling methods but DH parameter contributes a lot in the industries as it contributes efficiency and safety as it includes trajectory planning. DH parameter is and always used in the research and advancements in robotics, automation and manufacturing fields. Mathematical modelling of manipulators is essential tool for designing, controlling and simulation of manipulators as they are capable of performing complex tasks in safe and efficient manner.

2.3 Compliance modelling

Soft grippers as known are deformable and adaptable, it requires controlled forces so compliance modelling is essential for understanding and optimizing their performance. The relationship between applied forces and deformation of the grippers is one of the factors of compliance modelling in the soft grippers.

Through various factors and considerations such as material properties, force-deformation relationship, Finite Element Analysis (FEA), controlled force generation and sensor integration, compliance modelling enables soft grippers to conform diverse object shapes. Other factors such as optimized design and safety assurance predicts the grippers interaction with the objects for pick and placing applications. Material selection and their respective properties play a vital role and it is given an equal importance as control techniques. The soft grippers compliance is determined by the material properties such as elasticity and stiffness of the soft materials used. The gripper's behavior can be described using models which have force-deformation relationship. The selection and engineering of materials is the main and the foremost part of designing of soft grippers with enhanced capabilities. One such material used for soft grippers are elastomers which are easy to fabricate, low toxicity, robustness and low mechanical damping coefficients. [2]

Fig 3. Soft grippers using elastomers [2]

Mathematical relationship between the force applied to the grippers and the deformation following it. Soft grippers exhibit a nonlinear deformation behavior due to the materials used. Various mathematical functions and empirical model are used and are under research to describe the relationship between them accurately. The force-deformation relationship curve is similar to the stress-strain curve and the curve shape depends upon the geometry of the gripper, payload, and the material used. Sensor integration is important for expanding their capabilities and adaptability. Use of sensors make the grippers intelligent as it is used to know and interact with the environment. These sensors provide real-time feedback such as grip force, object properties and environmental conditions. Sensors in soft grippers enhances the safety and efficiency. The changes of the environment and the adaptability of the soft grippers to the environment can be done faster with the help of the sensors. After the compliance model is established with the help of the design parameters such as material selection, gripper geometry and actuation strategies optimized designing is achieved. Compliance modelling helps not only optimized designing but also the safety and reliability of soft grippers. The actuation, design and sensor integration it helps to improve the precision, efficiency and accuracy of the soft grippers. This directly impacts the safety features to prevent the damage the human, environment as well the gripper itself. [3]

III. CONTROL STRATEGY

Control strategy play a pivotal role in controlling the movements and actions and also determines the behavior of the robot. Since, soft grippers require a lot of control techniques to enhance and achieve precision, adaptability and efficiency, various control strategy are used, based on the application and the path that the manipulator system is going to follow. Control strategies are integrated with the soft grippers as to determine the sensing and interaction with the object, then process the information and make appropriate decisions, enabling them to manipulate the objects with dexterity and safety.

3.1 Classical Control Techniques

Classical control techniques are responsible for the control of the majority of system. These techniques are based on the manipulators' kinematic and dynamic motion and they can be used to control the position, velocity, acceleration and torque of the manipulator. The common classical control techniques are PID control (Proportional-integral-derivative control), torque control and PD control. PID control, the most commonly used classical control technique and it operates by calculating the error value and the difference between is the setpoint and measured process variable. The controller adjusts the control inputs to minimize the error proportionally, integrally and derivatively. The proportional controller proportionally controls the error by amplifying the output but the offset error is eliminated, so to rectify that the integral controller is used to increase the control signal for every positive error and decrease for negative error. The derivative controller is included to improve the closed loop stability and transient response of the manipulator. The other classical control technique is, "Computed torque control", which computes the control inputs required to achieve the joint positions, velocities and accelerations. It is useful for achieving precise joint level control. "PD control", a combination of the proportional and derivative controller. This technique improves the transient response of the manipulator and the stability too. This can be used to control the position of the joint or the actuators in the manipulators.

Classical control techniques are important and are proven to be the best for the manipulators as they are reliable and effective in controlling the manipulators in the real time applications, simple and user-friendly and provide stability and ensuring safety and precise control of the manipulators.

3.2 Challenges faced with classical control techniques

Despite their usage for many years and have been proven reliable and effective, classical control techniques do have limitations and faces many challenges during complex applications and are not able to handle large disturbances and uncertainties. Linearization assumptions, classical control techniques often assume the system is linear during dynamics. Manipulators exhibit both linear and nonlinear behavior due to some factors like friction, wear and tear in the actuators. Nonlinearity is complex and requires advanced control strategies. Classical control techniques can be a major problem when it needs to maintain the robust factor during uncertainties and disturbances. Factors such as changes in payload, human interruptions and disruptions can affect the performance and provide invariable errors as well as instability. Proper tuning can be challenging and time-consuming. Finding the right collection of gains and delivering good performance takes time and can be non-trivial. It lacks adaptability and learning capabilities when compared to advanced control techniques. Robots continuously change the conditions according to their environment and classical control techniques is not the right fit as they take time to change conditions or to adapt the conditions.

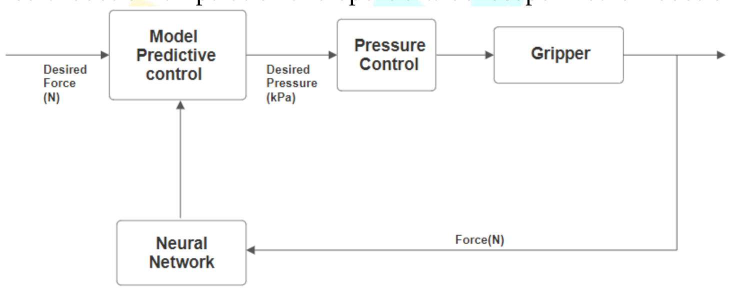
IV. ADVANCED CONTROL TECHNIQUES

Harnessing the full potential of these cooperative robotic manipulators requires sophisticated control strategies in soft grippers. They provide soft grippers more flexibility, accuracy, and adaptability, which makes them useful in a variety of settings. The emergence of new control systems offers promising opportunities for creative research, development, and practical application as soft grippers continue to gain traction in a variety of industries, including manufacturing and healthcare. Soft gripper technology has the potential to completely alter the field of robotic manipulation in the future.

4.1 Model predictive control (MPC)

Model Predictive Control (MPC) is an advanced control strategy used in various fields such as robotics, process control and autonomous systems. It is known for its capability to handle complex dynamics and constraints.
MPC models describes the system's behavior and can relate the current state of the system to its other or upcoming states based on the control inputs. It solves an optimization problem and it minimizes the cost, and it only implements the first control input from the optimal sequence and recalculates the optimal sequence using the updated predictions.

MPC is a sophisticated control strategy that can handle and optimize any complex systems and constraints. It has the capability to adapt, handle and ensure great performance that makes it a powerful tool in various fields. MPC's enhances the safety by enabling grippers to predict and avoid any obstacles as well as any human interventions. This control method is mostly used in rehabilitation robots and personal assistance robots. MPC do have challenges in calibration of the control parameters, the need of accurate predictive models and computational demands of real-time optimization. This can be eliminated by interfacing machine learning and adaptive MPC algorithms that can enhance predictive accuracy and also making it more efficient. The integration of MPC's have a great potential in soft robotic manipulation and opens a wider scope in other robotic application.



Model predictive control flowchart

4.1.1 MPC over classical control techniques

1. It can handle multivariable systems (both nonlinear and linear) with complex interactions. MPC has the capability to adapt to any changing environment including their behaviour and nonlinearities.
2. MPC ensures control inputs remains with the constraints while optimizing the system performance and enhancing the safety and stability of the manipulator or the system.
3. Robust control strategy.
4. It is compatible with Multi Input Multi Output (MIMO) system.
5. It avoids and adjusts the disturbances and control inputs to keep the desired path.

4.2 Sliding mode control

Sliding mode control is a nonlinear control method that alters the dynamics of a nonlinear systems by applying discontinuous control signal instead of a continuous control signal. It is an advanced and adaptable control that enhances the dynamics and control of soft grippers. SMC is known for their robustness against uncertainties and disturbances. This control strategy's adaptability extends to compliance control, permitting the gripper to modulate the stiffness and enabling safe human-robot interaction and object protection.

SMC's control both the joint variables as well as the forces and torques which are even more helpful in controlled force profiles which are more useful in the applications where precise control is most prioritized, for example in medical robots. Medical robots require precise control over cutting tissues and nerves during surgery and the pressure and angle of cutting them should be maintained properly. SMC are more compatible with the soft grippers as they are deformable structures which are suited for more delicate object manipulation. Both SMC and MPC offer advanced control techniques that can adapt to the dynamics and control of soft grippers faster and in easier manner. SMC provides robust control in the cases where disturbances and uncertainties are present. SMC are used in case where precise control over the grippers are required. MPC are used when gripper's behavior and calculation of the control signal for desired grasping position and force is required. MPC is also adaptive and can adjusts its parameters to compensate the uncertainties and disturbances. The control system is chosen on the basis of the application, cost, geometry of the grippers and ease of use. [6]

4.3 Real-time Control

Real-time control is an important factor while designing and manufacturing soft robots or integrating soft grippers as manipulators in the robotic arm. It is because of their adaptability with the objects which have different compliance and shapes. These objects are gripped and manipulated according to the applications, the gripper materials such as elastomers exhibit dynamic deformations and compliance changes. Real-time control enables these grippers' capacity to adapt to their highly variable surroundings and to disruptions and uncertainty. Soft grippers must continuously monitor the real-time data and offer feedback to provide precise control and accuracy for firm and consistent grasping of the objects for variety of sizes, shapes and materials. Using of real-time control minimizes the slippage of the objects, during interaction of the objects the surface characteristics are obtained and the deformation of the gripper's is changed.

The usage of the sensors provides real time feedback that enables the control strategy and the control algorithms to avoid slippage. Precise control and operations requiring a strong grip and minimization of slippage is more important in the material handling, food industries and mainly in the medical fields. Real-time control also enables soft grippers to react to unanticipated outside disturbances. Soft grippers can quickly respond to shock, uncertainties and disturbances to preserve the stability and reduce damages by continuously monitoring the real time feedback data from the sensors and make the changes accordingly. Soft robots or the usage of soft grippers in the robot as manipulators work in a dynamic situations and safety and dependability are enhanced to their quick response and adaptiveness in real-time.

Model Predictive Control (MPC) and Sliding Mode Control (SMC) are two advanced control techniques that are frequently used in the real-time control of soft grippers. There are other control techniques such as fuzzy control method and nonlinear control method. By utilization of real time sensors and their feedback data the control inputs are algorithms are changed accordingly and made sure the object's compliance, slippage and efficiency are optimized and react to the disturbances in quicker manner.

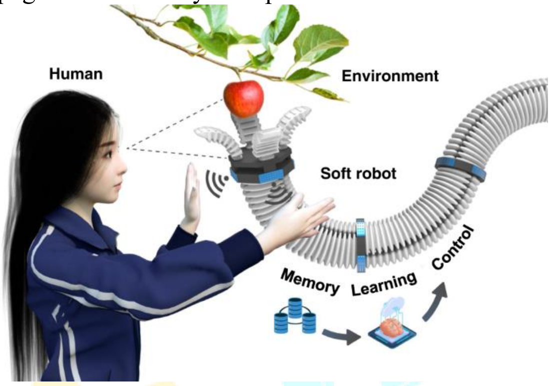
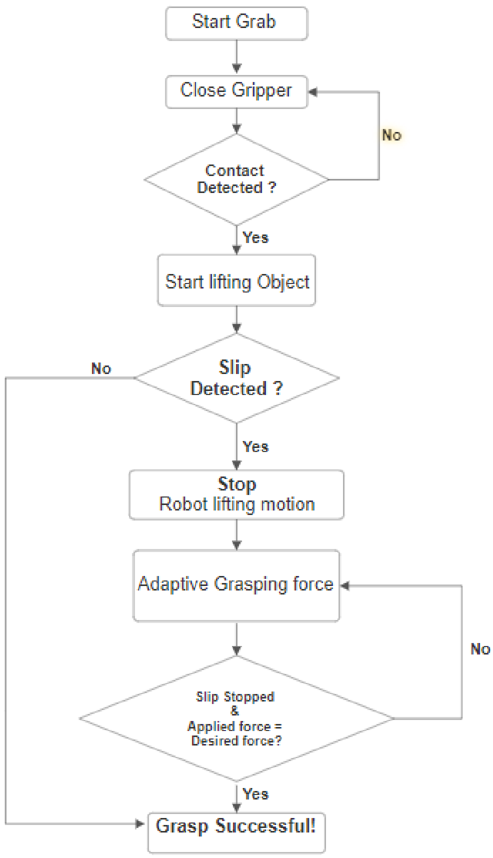


Fig 6. Grasping process with the help of real time control [12]



Grasping algorithm with the help of real time control

V. COMPLIANCE CONTROL IN SOFT GRIPPER

Compliance control is the fundamental principle in design and operation of soft grippers. Compliance is the ability to deform and adapt the shape of the object for firm grasping.

5.1 Control principle

The variable stiffness of the soft grippers is regulated by real time control. The internal pressure of the soft fingers is varied according to the object. Higher the stiffness the firmer the object is grasped, the lower the stiffness the yielding of the object in shape of delicate or irregular shaped objects. Compliance control depends upon the feedback data and control. The data is collected from the sensors and the changes are made accordingly on the basis of the pressure, force, geometry of the object. These data are obtained from the sensors about the objects and interaction with the environment. Control algorithms works and changes the requirements using the feedback data that dynamically adjust the compliance of the gripper. The precision, accuracy and safety of the soft grippers is enhanced by the usage of compliance control. Overexertion and under exertion of the pressure are monitored in the cases where fragile components are held and to avoid damaging the objects. The exertion is monitored and are enabled to reduce the risk of breakage and deformation. This principle is important in applications such as food handling and delicate object handling application industries.

5.2 Actuation techniques

In achieving compliance control in the soft grippers, stiffness and adaptation for different objects and application are changed accordingly with the help of actuators. The three most preferred actuation techniques are pneumatic, hydraulic and electroactive polymers.

Pneumatic actuation, a type of actuation where pressurized air is used to control the movements. The principle of this actuation is the air pressure is controlled for the deformation and stiffness of the gripper. Therefore, the design of the fingers is made in such a way that there are inflatable chambers or bladders using flexible materials that can inflate and deflate easily. The main advantage is it provides excellent compliance control and allows precise adjustment of the gripper's force and shape. They are light-weighted and more suitable for soft and light-weighted objects. When compared to other actuations these are comparatively lower in cost and effective. The main disadvantage is that it is slower in response and they require compressor for pressurized air that restricts the portability of the gripper and maintaining the air pressure is tougher in some cases.

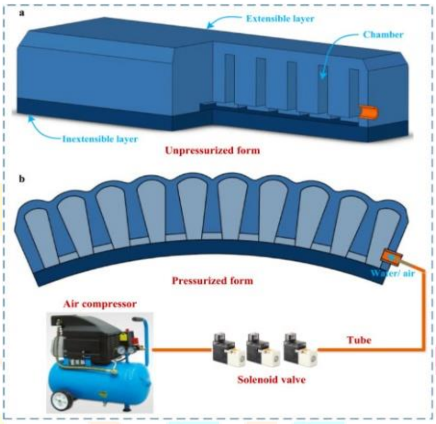


Fig 8. Pneumatic actuated soft gripper [17]

In hydraulic actuated grippers, pressurized fluids (mostly oil or water) are used for control of deformation and stiffness in the gripper. The designed is made in such a way that the fingers have fluid filled chambers or channels. Hydraulic actuators are powerful and precise in control. The fluid is pumped into and out of the chambers for actuation. The adjustment of the fluid pressure inside the chambers allows to deform. The disadvantage of this actuation is not cost effective, require hydraulic supply and dangerous if the fluid leaks.

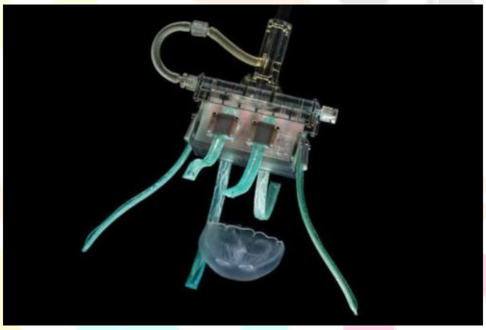


Fig 9. Hydraulic actuated soft gripper [13]

The fig 9. is an example for hydraulic actuated soft gripper, where it is used to grasp and release the jellyfish without harming them, so a mild pressure is sent through the fingers. The actuation of this soft gripper can only be done when it is hydraulic so, the positioning of the fingers can be accurate and the pressure exerted on the object. Therefore, the object is not harmed and there is no deformation.[13]

Usage of dielectric polymers or any conducting polymers are actuated when an electrical field is applied. These materials are directly integrated into the soft gripper's structure. The amount of deformation can be controlled by adjusting the strength of the electric field. EAPs are flexible and light-weighted and also does not require any external sources such as compressor or hydraulic pump. It can generate more forces than the other two and have great precise control. They are bit expensive and require high voltage to generate the electrical field and are sensitive to environmental conditions.

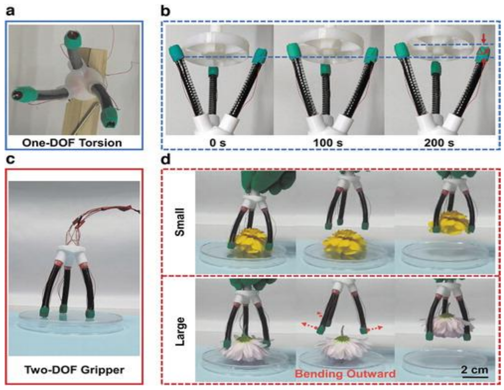


Fig 10. Electroactive polymer soft gripper [14]

The type of actuation technique can be chosen on the basis of compliance, force, portability and cost. These actuation techniques do have advantages and disadvantages but the usage and application decide the best actuation technique.

VI. APPLICATIONS OF SOFT GRIPPERS

Soft grippers or robotics grippers are a boon to humanity in the modern era. Soft grippers generally are inspired from biological creatures such as jellyfish or octopus for its strong yet soft gripping capabilities. With the proliferation in existence and use of cobots in manufacturing industries or the usage of medical robots, soft grippers are becoming immensely pertinent in the modern world.

6.1 Manufacturing

One of the main industries where soft grippers are beginning to be used in the modern world is 'Manufacturing'. Manufacturing industries are often considered to be harsh environments only suitable for standard high-strength robotic gripper working. For many new age processes like 'Micro Molding', a process involved in shaping and forming thermoplastics with dimensions of around a few millimeters, soft grippers are essential to reduce manufacturing process and packaging damages to the product. During quality control, soft grippers can manipulate objects delicately for testing and inspection ensuring the products produced that meet quality standards. In automated assembly and material handling applications, soft grippers are well suited for pick and place of various materials. Their compliance allows them secure fragile components without any damages and deformation of the objects. These grippers are used where precision and gentleness are of most important.

6.2 Healthcare

Soft grippers are widely used in the healthcare sector from advanced healthcare equipment like surgical robots to basic robotic operations like pick and place in medicine production. In all the divisions within the health sector, safety of medicinal equipment, is crucial as it involves the wellness of a living being. With developing technology, soft grippers prove to be a good use in the healthcare sector to assist humans in a multitude of tasks. A clear advantage of using soft robotic grippers over conventional grippers is the uniform distribution of forces over a large area of contact. Soft robotic grippers can also adapt to a wide range of stimuli whilst using minimum sensors as a result of their technology when compared with rigid grippers which generally require multiple sensors to get inputs for pressure or contact. The soft robotic grippers can also be used alongside humans in medicinal procedures to assist humans through time consuming and tedious tasks as they prove to be safe when integrated with compliant collaborative robots.

6.3 Agriculture

Soft grippers are widely used in agriculture. Their compliance and adaptability help them to grasp vegetables and fruits gently without any damages irrespective of their shape and size. Automated harvesting has become popular in agriculture sector where the usage of soft grippers is widely used. They reduce the need of the labor and also reduces the time consumed therefore, the efficiency as well as productivity is increased. The need of customization of the soft grippers are in under research for its capability to grasp any fruits and vegetables of any size. The implementation cost is bit higher so that many people do not consider of buying it.


Fig 11. Soft grippers in agricultural field [16]

VII. CHALLENGES AND FUTURE DIRECTION

7.1 Challenges

There are many obstacles in the field of soft grippers. There is a need of improved materials for greater flexibility and environmentally friendly. Soft grippers in general hold lower load and wear resistance, therefore greater payload capacity and reduction in wear and tear could make it even more rigid like the hard grippers. Enhancing the control algorithm for the soft grippers to provide finer compliance control remains as a challenge, while dealing with complex and more dynamic environment. Soft grippers struggle while handling larger objects which also require to maintain their precision as well the safety.

7.2 Material research

The future of the development of the soft grippers lies in the advancement of the material. There are ongoing researches for the materials that can change their stiffness on the demand of the material with enhanced durability to withstand the load in the industrial settings. Advances in the material science will expand the capabilities and tackle the more challenging tasks across different industries. Materials that have the capability to hold a larger payload, flexibility and reduce the toxicity and making it more bio-degradable for the environment.

7.3 Human-Robot Interaction

Human-robot interaction is an important challenge. This is to make sure the human and robots as well the surroundings around it are safe state. Since, human-robot collaboration is necessary for the setting the robot, the field of soft grippers continue to focus on the compliance control and interaction safety. The control algorithms allow soft grippers to anticipate and respond to human movements and behavior in real-time.

7.4 Robotics tomorrow

In many applications involving collaborative robots for manufacturing and assembly lines, soft grippers are essential to fully complete the system where the usage of normal robotic grippers can nullify the purpose of collaborative robots by posing dangers to humans. Whereas a soft gripper used with a compliant collaborative robot can deliver fruitful outcomes in connecting robotic technologies with human manpower in the manufacturing and assembly sectors. Soft grippers are revolutionary in the food production and processing sectors where a wide array of delicate items from foods like egg yolks to glass beverage bottles are general tasks that need handling. Soft grippers play a pivotal role in the food industry in picking and placing delicate food items without any damage. Soft robotic grippers also play a vital role in general purpose machinery where soft grippers offer better and easier programming and control. Soft grippers are also highly energy and processing efficient in comparison to normal robotic grippers hence proving to be a viable alternative to conventional robotic grippers in developing platforms.

Fig 12. Egg holding using soft grippers [15]

Soft grippers are now playing a vital role in the research field of imitations of animals and under water creatures. The end effectors are designed in a way that, it imitates the creatures such as the octopus' tentacles, gecko behaviour of attachment and detachment on the walls i.e., the gecko effect. Many researches are ongoing as to make the soft grippers more effective as the hard grippers on the aspects of control and manipulation of the objects.

VIII. CONCLUSION

In the field of robotics and automation, the usage of soft grippers has become more popular as they are more adaptable, provide compliance and precision. This paper has provided insights about the soft grippers, dynamics and various control strategies and their usage in other sectors. The dynamics and control of the soft grippers are found but using of the kinematics and mathematical models to find their ability to interact with the environment. Soft grippers have emerged in a captivating field of research in both material selection and movement of the manipulator. They have broken the boundaries of the hard grippers in the aspects of load carrying, adaptability and precision. There are ongoing researches in other unknown fields where soft grippers compete with hard grippers, forging a new path in the world of the robotics.

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