A Review of the State-of-the-Art of Sensing and Actuation Technology for Robotic Grasping and Haptic Rendering*

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***Abstract*—In this paper, a survey of the state of the art, challenges, and possibilities with sensing and actuation technology for robotic grasping and haptic rendering is presented. To this end, a survey and classification of robotic grippers and grasping methods is first outlined. Then, haptic rendering is surveyed by focusing on different challenges and approaches, such as rigid body haptic interaction, deformable/rigid haptic interaction, fluid haptic interaction, image/video based haptic interaction, and virtual reality (VR) based haptic interaction. Successively, the current sensing technology is reviewed by considering sensor development for robotic hands/grippers, such as tactile sensors, and visual sensors. Finally, the current actuation technology is addressed by considering soft robotic grippers, micro and nano grippers, multi-fingered grippers, and under actuated grippers. The main objective of this study is to boost worldwide efforts toward achieving the vast variety of applications that robotic grasping and haptics may give, as well as to provide an up-to-date reference as a baseline for future research and development in this sector.**

***Keywords*— grasping, haptics, haptic rendering**

I. INTRODUCTION

The ability to grasp is a pivotal feature of intelligent behaviour. Different kind of object grasps are essential in many creative cyberphysical systems, to the point that grasping has been identified as a crucial technology for next-generation robotic systems [1]–[4]. A panoramic survey on grasping research trends and topics was presented in [5] with the aim to draw a broad landscape of applications and current research trends and topics relating to grasping techniques and tools. Applications range from biomedical and surgical to industrial warehouse pick and place tasks, covering a wide range of spatial scales, from micro to macro scales. When considering robotic grasping and human-robot interaction (HRI), the possibility of rendering tactile/force feedback is of essential value. In this perspective, haptic technology, also known as kinaesthetic communication, is any technology that may provide the user a tactile sensation by applying forces, vibrations, or motions [6]. In the last two decades, the field of haptics has introduced a possible digitisation of the sense of touch [7]. The combination of the advancements in sensing/actuation technology with the betterment of haptic rendering represents a promising opportunity towards the achievement of an effective HRI, as shown in Fig. 1.

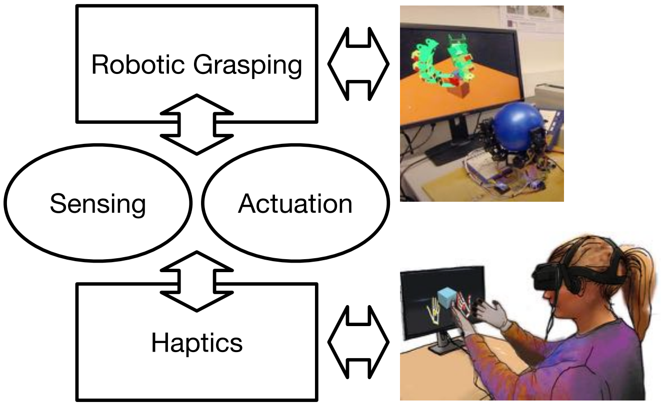

Fig. 1: The combination of the advancements in sensing/actuation technology with the betterment of haptic rendering represents a promising opportunity towards the achievement of an effective human-robot interaction (HRI).

The goal of this study is to increase awareness of the potential outcomes with sensing and actuation technology for robotic grasping and haptic rendering, as well as to provide an up-to-date stepping stone for continued research and development within this field. In this work, we review the state of the art by giving an outline of the current challenges and possibilities within this research area.

The paper is organised as follows. Grasping and haptic rendering methods are surveyed in Section II and in Section III, respectively. Sensing and actuation technology is assessed in Section IV and in Section V, respectively. Finally, concluding remarks are presented in Section VI.

Although the fundamental concepts are provided by these seminal works, an exhaustive and up to date review is still missing to the best of our knowledge.

II. GRASPING AND CONTROL

Technological advancements have led to the development of modern grippers that outperform their older counterpart in terms of strength, reliability and speed. Newer materials, such as piezoelectric, shape memory alloys, carbon fibre and

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many more, are being used to improve the functionality of the gripper design for grasping various objects [8].

This section provides a survey for different state of the art robotic grippers ranging from the very first grippers to the newest advancement in this field and additionally, the grasping techniques and control strategies that have progressed over the years. Figure 5 show the trend and novelty in robotic gripper design produced by researchers for the past two decades.

A. Robotic Grippers

1) Gripper classification: Interactive tasks with the environment for robotics and automation have paved the way towards development of gripper technology. A suitable gripper design compromises of overall system reliability that includes precision, longevity stability and robustness.

Requirement diversity has led to various grippers being developed to cater for the well adapted and reliable systems in many automated applications. The distinct categories in which they are classified today are as follows [9]:

- According to the number of fingers
- According to the actuation mechanism
- According to the mechanism of the gripper
- According to the method of gripping

For the number of fingers, the classification of grippers can be further subdivided into 'n' number of fingers and the anthropomorphic hand; where n = 1,2,3,4. More than 60% of human grasping is achieved with the use of 2 fingers grasping technology [10]. Parallelopiped, cylindrical and pyramidal shapes are a few that only require two contact points for object movement. This is why in many automated industrial spheres two fingered robots are popular. On the other hand, multi fingered grippers can provide a more balanced control and higher precision for objects that are soft and objects that are rigid.

According to the actuation mechanism employed on the device, robotic grippers can be distinguished as being vacuum controlled, hydraulics or pneumatic control and electrically controlled. For high precision and light weight use, electric grippers are used. The vacuum controlled grippers work according to the bernuolli principle by creating high air flow [11]. Hydraulic grippers though offer high grasping force, the heavy mass of the object undermines its everyday use.

The mechanism mode of the gripper design is divided into five categories, namely; screw driven (turning the screw mechanism uniformly with the use of a motor) , Rack and pinion (arrangement of rotational motion to translational motion of the gripper nodes) , CAM and CAM follower, rope and pulley (a tension device to keep rope taut) and worm gear. A robotic gripper with a four bar linkage system was designed by [12] that improved parallel grasping due to the worm gear arrangement.

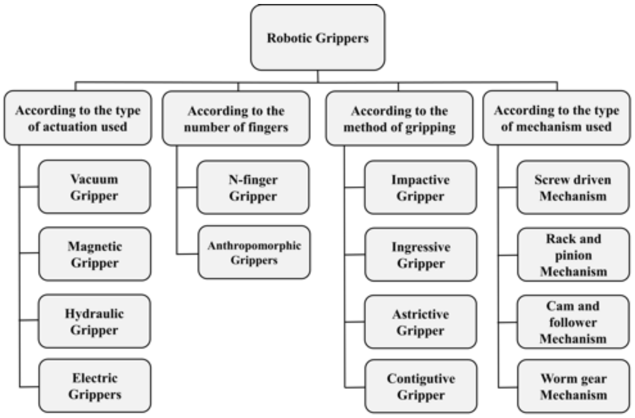

Fig. 2: Grippers classification.

Finally classification according to the physical operations of a gripper, four categories have been developed according to the literature survey conducted [13] namely; ingressive, impactive, astrictive and congigutive grippers. Figure 2 illustrates the gripper classification technology.

2) Gripper Selection: The overall success of the automation engine depends on the correct gripper selection. To determine what an essential gripper would be, the following technical factors are necessary to be studied [14]:

1) Task: The requirement of the task is of paramount importance when selecting grippers. A slow automation process will favour gripper designs of a mechanical mechanism. On the other hand, fast loading unloading requires heavy duty grippers with grasping action attained by magnetic or vacuum suction.
2) Level of precision: Medical use for robotic grippers required very high level of precision, sometimes greater than that of the human hand. Under other conditions, a factory with a part sorting process does not require very high levels of precision.
3) Clamping force: Physical property requirements of the gripper such as force takes into account the overall weight and maximum stresses of the gripper as well as the dynamics i.e. speed and acceleration resulting in impactive forces.

B. Robotic Grasping

Robotic grasping is a very comprehensive process. This complexity can often be underestimated since human grasping motion seems easier to mimic. In truth, grasping objects are depended on certain characteristics such as feeding (previous manipulation), handling, positioning and releasing. These strategies can be based on air, contact, intrusion and many more [15]. Apart from the characteristics, the robotic gripper need to ascertain the environment as well and work accordingly. Accurate positioning and location of gripper with respect to the object is very important for the grasping process at each stage of the operation.

1) Grasping process: A thorough understanding of joint transformations and end-effector manipulation is required for robotic grasping. The process of grasping has been split into six phases for ease of understanding by researchers. The phases have been summarized below:

1) Approaching: The gripper from its initial position (end-effector open and close to the object to grasp) moves towards the object
2) Making Contact: Gripper actuated to close and come in contact with the target object.
3) Grasping force: Suitable forces applied to grasp the object within stable and safe ranges.
4) Securing the object: With the influence of under actuated mechanism, the force stops when the target attains dynamic equilibrium.
5) Lifting the object: The object is moved from its initial position to its new desired position
6) Releasing the object: Unclasping the object and releasing it into position. Then the end-effector is reset onto its initial position to restart the whole process again.

With the use of various sensors and actuators these processes are effectively accomplished and monitored. Fig. 3 shows the different kinds of human grasp gestures need to be mimicked by a robotic hand. A detailed survey of these sensors and actuators have been discussed in this manuscript.

2) Grasping Methods and Control Strategies: In real world applications, grasping methodologies are dependent on physical properties, operative properties, material characteristics and combinational strategies. . The performance of robotic grasping could be evaluated according to the grasping robustness, reliability, and stability [16]. Robustness is used a measure adaptability i.e. resist of change from the stable configuration. Reliability could be used to evaluate how much degree of flexibility is available within the safety ranges. While stability is used to determine the balance of the grasped object subject to external disturbances.

Keeping the characteristics in mind, the methodologies can be subdivided into four categories, namely; mechanical, adhesive, electromagnetic and pneumatic methods. [17]. A majority of gripper design consist of mechanical operation wherein parallel or multi-fingered grippers are used to apply bi-directional force. Haptic feedback, discussed in the next section, is used to control the force applied which is especially important for grasping objects of delicate nature. Pneumatic grippers used vacuum pressure or Bernoulli grippers to achieve high amount of force / torque. High-speed air flow is generated with nozzles creating suction force between nozzle and object plate. On the other hand, adhesive type grasping methods use surface chemical bonding that is in effect temporarily [18]. Malleable grippers are based on electromagnetic grasping. Electric or magnetic field is switched on and off to lift extremely heavy metallic objects providing reliable gripping adjustable to the various shapes and sizes the object without the need for sensory feedback [19].

The human hand is considered a complex and compound gripping system. The brain uses the control of a tendon based design and sensory feedback from the fingers and skin to determine the volume of force to be applied onto different types of objects. Similarly robotic grippers need to to utilize different control strategies to accurately mimic this same action in a very small as well as a very large scale. An interaction of multiple sensors installed in conjunction with each other provide an accurate gripping objective. State of the art sensors used for this purpose are discussed in later sections.

III. HAPTIC RENDERING

In recent years, researchers have put much focus on the haptic rendering technology. Not only does it involve physiological therapy for amputees, it is also useful for other applications, such as the evolution of the gaming industry, the facilitation of dangerous HRI [20]–[22], the simulation and modelling of HRI [23], [24], the monitoring of elderly people [25], the possibility of enabling immersive e-learning experiences [26], [27], and many others. Haptic rendering basically means the process of calculating and estimating the force / tactile feedback to provide the user with a sense of touch or interaction with either a virtual object or a virtual sensing device interacting with a non-virtual object.

Different haptic rendering algorithms have been proposed in the past decade. According to the model of probing objects, haptics can be categorized as point-based, triangle mesh-based, volume based and line-based methods [28]. According to the type of control, they can be classified as impedance-based and admittance-based rendering methods. In relevance to the type feedback, they can be classified into force feedback and tactile feedback rendering. The main focus of this research is the categorization of haptics according the the interaction type which is; rigid body interaction, deformable rigid haptic interaction, fluid haptic interaction, Video based interaction, VR interaction.

A. Challenges

Successful application of haptic rendering devices have been handicapped by several challenges [29]. Firstly, the number of degrees of freedom offered in haptic rendering makes the simulation and feedback complex. Increase in the number of degrees of freedom brings computation cost for real-time detection for collisions and haptic feedback. For example a 2-DoF haptic interaction would support single point based force feedback interaction whereas a 6-Dof haptic render would have to support object-object interaction for force feedback.

Fig. 3: Human grasping gestures.

Secondly, the force models i.e. calculating force or torque feedback based on depth of penetration are impervious to material characteristics. Characteristics like hardness, viscosity, elasticity and anisotropy can otherwise can be rendered closely using physics based models which has become apparent as an accurate albeit not complete accurate approach for force models in haptic rendering. This is because the complexity of the physical laws in such regard is not easy to develop for credible haptic rendering. For example, haptics rendering in medical simulation requires aspects of several components such as human anatomy, cutting speed and cutting angle to determine resultant cutting force models.

All haptic rendering share a commonality that is the haptic probe or the virtual tool (virtual replica of the haptic device). The algorithms devised for the computation rendering technology ascertain the force based on the deviations of the true devise configuration and the virtual tool. Realistic real world accuracy in real-time for rigid as well as deformable objects require complex understanding and implementation of fluid mechanics and Newtonian laws. Shapes with thousands of polygons become more and more complex and hence haptic rendering is still a working field.

Thirdly, the stability and fidelity of haptics is an even greater issue. A high update rate combined with stable haptic interaction is of paramount importance. On the other hand the feeling of force should be similar to that of the real environment [30]. [31] suggests that the optimal frequency for comfortable motor stimulation, one that is least likely to elicit pain fiber stimulation, is close to 10 kHz. Haptic rendering update rate of that value is not only complex but also very costly.

B. *Rigid body haptic interaction*

Rigid to rigid body interactions are classified into four categories; impulse-based, penalty-based, constraint-based and surface-based methods. Penalty based methods of haptics simply measures the depth penetration into virtual objects. [32] extended the traditional mechanism of depth penetration force feedback by including the translational as well as rotational motions instead of just the translational motion. According to the weight values, an adaptive method to adjust parameters of virtual coupling [33] of the simulated environment and tools was suggested by [34].

In contrast, Impulse based response is an haptic interaction approach in which a series of impulses is used to move on a virtual object instead of a constant force depth render. [35] suggested rigid body dynamic solution in which the contact states are represented by separation and impulse contacts. A continuous contact state is represented as a series of micro impulses. This results in high accuracy and efficiency.

The viewpoint of constraint-based haptic rendering is to restrict the position of the tool on the surface of the virtual object. Such stable force feedback provide realistic haptic interacting models. The main problem with these algorithms is the computation for detecting collisions for haptic rendering. The continuous manipulation of such complex scenarios is time consuming which make the response lag resulting in penetration of the tool on the virtual tool. [36] and [37] demonstrated constraint based haptic render for generic polygonal models for 3-DOF and 6-DOF instruments. Fine manipulation in narrow spaces on dental surgery was suggested by [38] which was an improvement on the constraint based methods.

To simplify the complex calculative process, implicit surface-based methods can be considered as a direct haptic rendering method. By converting the general polygonal models into surface representation. The depth perception computation can be simplified in this regard as implicit function values. [39] first suggested the haptic model based on implicit surface values. [40] proposed a method of implicit surface transformation for both 3-DOF and 6-DOF rendering.

C. *Deformable rigid haptic interaction*

Complex polygonal rigid models, as discussed in the previous section, for haptic rendering are difficult to produce, hence deformable objects bring much more intricacy in terms of computational accuracy. Physical simulation are expensive and high update rate is not easily achieved in this regard.

Soft Object deformation has been proposed on many different techniques over the past decade. Finite Element Analysis (FEA) has been the core of the research on deformable haptics. [41] used co-rotational FEA to simulate haptic interaction for soft tissue and light models. [42] offered a solution for real-time collision and haptic interaction between two deformable objects. A sphere tree based method [43] provided haptic collision detection for rigid and soft-deformable objects.

D. *Fluid haptic interaction*

Haptic Interaction for fluidic objects has been disregarded for many years. [44] and [45] made approximations and supposition by focusing on the render of non viscous fluids on the surface with small objects. Therefore efficient algorithms of such haptic rendering still leave a gap on the literature survey. A unified particle model, Smooth Particle Hydrodynamics (SPH) [46], was proposed which defined force feedback with smoothing volume of fluid interaction. When a particle coupled with a haptic device enters the smoothing volume, force feedbacks can be absolutely computed between the two particles based on the sum of pressure and viscous forces. Vibrotactile feedback model method renders smooth solid-fluid interaction. It is based on bubble-based vibrations, which can be divided into three constituents: the initial high frequency impact on the surface of the fluid, oscillation cavity created when body enters the fluid, and bubble's harmonics. However the case remains that accuracy and fidelity of fluid haptic rendering are difficult and more research on this area is required.

E. *Image / Video based haptic interaction*

Image processing technology has come a long way since the first camera was invented. In recent years, image-based haptic interaction research has been intensively carried out. Interaction is carried out by either calculating force directly from the 2D image or by constructing a 3D model of the several 2D images to calculate depth perception and inturn detect collisions and render the haptic feedback. In the field of medical simulation, haptics help create a 3D environment for early prognosis of surgeries [47], [48].

The three force rendering components; contact force, friction force and texture force, which can realistically simulate the image as an actual 3D scene. [49] proposed a similar technique for streaming point clouds i.e. Cartesian space being represented by pixels, from a Kinect depth camera. Force feedback is then calculated using the difference of position of the virtual tool and the configuration of the haptic device.

F. *VR based haptic interaction*

It is importance to understand the human haptic perception for designing haptic devices viable for VR integration. The three keys components required in a VR world is imagination, interaction and immersion [50]. Thanks to the research in computer graphics and sound systems for the past 50 years, today we possess realistic auditory and visual feedback. Haptics on the other hand has not developed as far as the other two perceptions for VR systems. With the boom in medical simulations and the gaming industry, the need for haptic rendering of virtual objects in a VR environment has increased rapidly.

Wearable haptic devices are difficult to put on and adapt since different sizes are required for each users. Contrarily, handheld haptic devices and video based haptic devices have emerged as dominant haptic interaction in VR. Commerical VR devices like HTC Vive and Oculus Rift conjoined with handheld spacial devices with vibrotactile feedback show promising results. A user with a wearable devices would interact with a virtual object in the VR world and the physics simulation inside would determine when and how strong the tactile feedback occur, as seen in Fig. 4. Because of the flaw of wearable haptic devices, many research products have also been created that replace wearable devices with IR image recognition. Leap Motion sensor [51] was used to simulate a 3D environment of the human hand to interact with a virtual tool. [52] used a low-cost robot with a VR platform for rehabilitation games for patients with spinal cord injury. Vibration and pressure feedback was imitated with the use of leap motion sensory system.

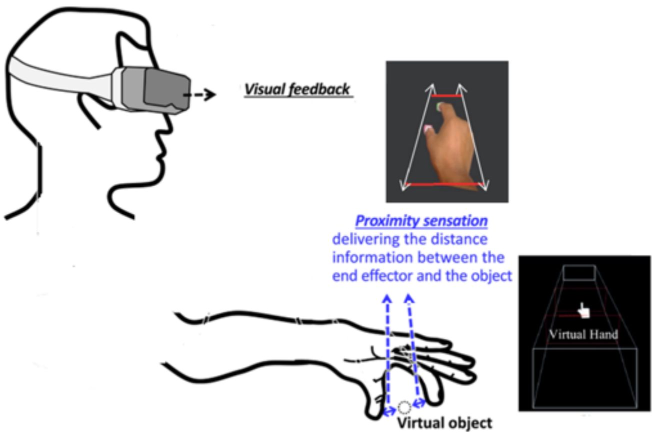

Fig. 4: VR environment: End effector interacts with the object, through teleoperation, as a virtual extension of the hand.

IV. SENSING TECHNOLOGY

Human hands can easily sense and differentiate different surface textures and temperatures, and grasp and manipulate objects of a variety of sizes, weights, and shapes. These capabilities are realized by an efficient integration of sensing, actuation, and gripping functionalities controlled and centralised within the human brain. To mimic such sensation for robotic grippers, researchers have developed many technological marvels over the years. This section presents a review of those sensing devices utilized for robotic gripper design.

A. Sensors Development for robotic hands / grippers

Active development of sensors for robotic hand design started in the early 2000s. [53] provides an overview of fusion sensing technology for robotic manipulation tasks. Most papers on artificial hands and there related sensors are dependent on the platform of study. [54] presented a three-fingered 9 DOF robot hand design and control using SMA muscles. [55] presented a thin flexible resistive tactile sensor consisting of electric, sensitive and protective layers. A matrix of capacitive tactile sensors capable of working in two modes (tactile and proximity) was used in object motion tracking and contact prediction [56].

Emergence of multiple humanoid systems, tailored intensive work on hand development in the area of social robotics. [57] discussed various systems in humanoid robots. It adhered to to the principles of modularization and internal placement of hand components. [58] made a three-fingered robot hand with integrated proximity, slip and tactile sensors. Number of sensor systems was developed accordingly to task-specific requirements and constraints. High-speed hand design [59] furnished a tactile sensor to enable real-time feedback for contact manipulation at high speeds. Such rapid development of sensor technology has to be further subdivided into two categories namely; tactile sensors and visual sensors.

B. Tactile Sensors

Perception of tactile sensation contains a complex array of micro receptors within the human hand [60]. When touched these receptors send signals through the central nervous system and into the brain which are then processed for feedback. Today machines can analyze objects based on their physical properties such as pressure, dynamic strain, surface texture, and shear for recognition and interactive feedback. This section is divided into four types of tactile sensory systems seen in literature and their latest developments in the field have been recorded.

1) Piezoresistive Sensors: These types of tactile sensors use the change in resistance of materials when contact / force is made / applied on them. The phenomena of mechanical to electrical signal is known as piezoresistive effect. Piezoresistor effect can be mathematical expressed using the following equations:

$$\frac{\triangle R}{R} = (1+2\nu)\varepsilon + \frac{\triangle \rho}{\rho} \tag{1}$$

$$R = \rho \frac{L}{A} \tag{2}$$

where R is the sensitivity of the conductor, ν is the Poisson's Ratio of the material, ε is the strain, ρ is the resisitivity while L and A are the lengths and cross-sectional area of the conductor. piezoresistive sensors work based on changing contact area in a microscale or based on volume changes on pressure detection. The application has been used in many fields of various medical and industrial applications [61].

2) Capacitive Sensors: Based on changing the geometry of a capacitor by mechanical effect is another common tactile sensing method. When two parallel plates are charged, they store energy in the form of electrical charge. Capacitance is that ability to store that charge according to the following equation:

$$C = \varepsilon_o \varepsilon_r \frac{A}{d} \tag{3}$$

where ε_o and ε_r is the permittivity in the vacuum and relative permittivity respectively. A is the overlap area between two plates and d is the distance between them. Materials, such as polydimethylsiloxane (PDMS) [62], are mainly used today for fabrication of capacitive tactile sensors.

3) Triboelectric Sensors: Triboelectric mechanism is another type of piezoelectric sensor. The phenomena converts the mechanical effect into electrical signals by inducing a triboelectric potential. The potential can be positive or negative induced at the interface between two different materials. The charge generated is directly proportional to the difference between the triboelectric polarities. When pressure is applied, the effect induces opposite charges in both surfaces. The mechanism has not been widely explored in the research field. Recently [63] integrated a self-powering system with a high-resolution pressure sensor for real-time tactile mapping, done with a signal-electrode generator, and motion tracking.

4) Optical Sensors: The operation of optical tactile sensors is based on changes in light properties to obtain feedback. Optical sensors can be characterized by their response, flexibility and spatial resolution [64]. These sensors exhibit many potential applications which require the features of portability and flexibility [65]. Based on heterocore fiber optics, [66] reported an innovative design structure for optical tactile sensing. The sensors can be used on many biomedical applications.

C. Visual Sensors

Visual / Visuotactile sensation is based on the humans sense of touch and sight. Psychologists remark that 80% of human memory conditioning is obtained through visual stimuli [67]. The Visual sensors convert physical contact that modulates the visible light within the sensor to produce a tactile image. A real-time computer can record and store this data for processing or future analysis.

Use of visual sensors dates back to 1950s and 60s developed by [68]. In [69], design of miniature pedobarograph visual sensors were developed that could be fitted into robotic hands. They investigated various methods of generating optical stress patterns of high contrast for a remote manipulator.

Nowadays, position based visual sensing and image based sensing visual sensing have become suitable for tasks when geometric models are unavailable. Pose estimation of the target object is perhaps the most important topic in visual sensing research. For image based sensing, to determine the law of control in approach, image features of the object are rendered without the necessity for 3D localization. For position based visual sensing, projective geometry applications and genetic algorithms are employed, such as those used for satellite repairing in space orbit [70].

V. ACTUATION TECHNOLOGY

There are numerous applications where robotic grippers are used. A review on recent developments occurring in research of grippers in regards to the actuation mechanism has been discussed in this section.

A. Soft Robotic Grippers

A new paradigm of soft robotics has been widely developed amongst the research community. Soft gripper actuation has become a fundamental area of study. Soft robots are able to find solutions to problems that are not solvable with rigid designs. [71] provides an overview about different designs and materials used for present soft robotic grippers. For these designs different actuation schemes have been developed.

Pneumatic Actuators use positive pressure system to grasp objects. Air chambers are designed inside the soft glove that pressurize resulting in gripper movement such as bending. [72] used a similar technique to move and bend finger like parts. Vacuum actuation, contrary to pneumatic action, exploit the process of negative pressure to bend and move objects. [73] controlled the vacuum input of the soft palm move three fingers and retractable nails. [74] used a cable driven actuation mechanism based soft gripper where thin parts and thick parts were connected with strings and the pulling pattern determine the grasping shape of the gripper.

Electrical stimulation between between two electrodes tend to attract causing deformation. With the use of elastomeric materials this concept of actuation can be used for grasping objects. [75] used a dielectric polymer to create a two-leaf type structure, inspired by the venus fly trap plant, to open and close a gripper. [76] made use of electro adhesion (EA) technology to create a shape adpative soft gripper. The principle behind EA is that opposite charged substrates on a dielectric material created by applying voltage at the embedded electrodes cause attractive forces. A comparison between the soft gripper design has been conducted, shown in Table I, using an arbitrary scale from 1 to 5, 1 being poor performance and 5 being good performance. Using the defined scale researchers can choose relevant gripper design as per required application.

TABLE I: Comparative analysis of types of Soft gripper design on an arbitrary scale according to literature survey. Scale 1(poor) -5(good).

Design type	**Power Output**	**Weight**	**Noise**	**Payload**	**Response Speed**	**Power Consumption**
Pneumatic / Vacuum	4	1	1	5	4	2
Cable Driven	5	2	3	3	5	3
SMA	3	5	5	3	1	1
Di-electric Polymers	1	4	5	1	5	5
Electro Adhesion	2	3	5	2	4	4

B. Micro and Nano Grippers

In recent years, microelectromechanical systems (MEMS) have been widely applied in diverse science and engineering domains. With problem spaces becoming increasingly small, the need for micro manipulation in such delicate and precise manner has become crucial. In literature, in 1991, [77] presented a silicon based electro mechanical gripper design that grasped object of less than 2.7um diameter. Ever since, this field of study has risen exponentially. Micro grippers can today be categorized into several types. Some of them are; electrostatic actuators, electrothermal actuators, micro-pneumatic actuators, electromagnetic actuators. In [78] used thermal expansion technique in actuation beams to micro-grip objects. [79] used micro actuators consisting of pistons that housed by to spring elements to result in displacement of upto 600um.

C. Multi-Fingered Grippers

The main motivation behind such multifaceted gripper actuation schemes tends from the fact that grippers need to be able to adapt to rigid configurations in some moments and similarly also be specially adaptive to soft and fragile objects. [80] proposed a design for a three fingered gripper design that used granular material inside a sealed plastic cover. When negative pressure is applied into the plastic cavity, friction among the inner material particles maintain a rigid-like structure and offer a firm grasp. [81] provided a multi-finger robotic grasping controller actuation design complexity analysis for dexterous manipulation.

D. Under Actuated Grippers

In a non-symmetrical shaped gripping task where multiple fingers need to be utilized for grasping, underactuation is of great usefulness. Force applied and the actuation of the fingers is dependent on the individual fingers coming in contact with the object to grasp at different locations in the state space. The fingers end up automatically enveloping

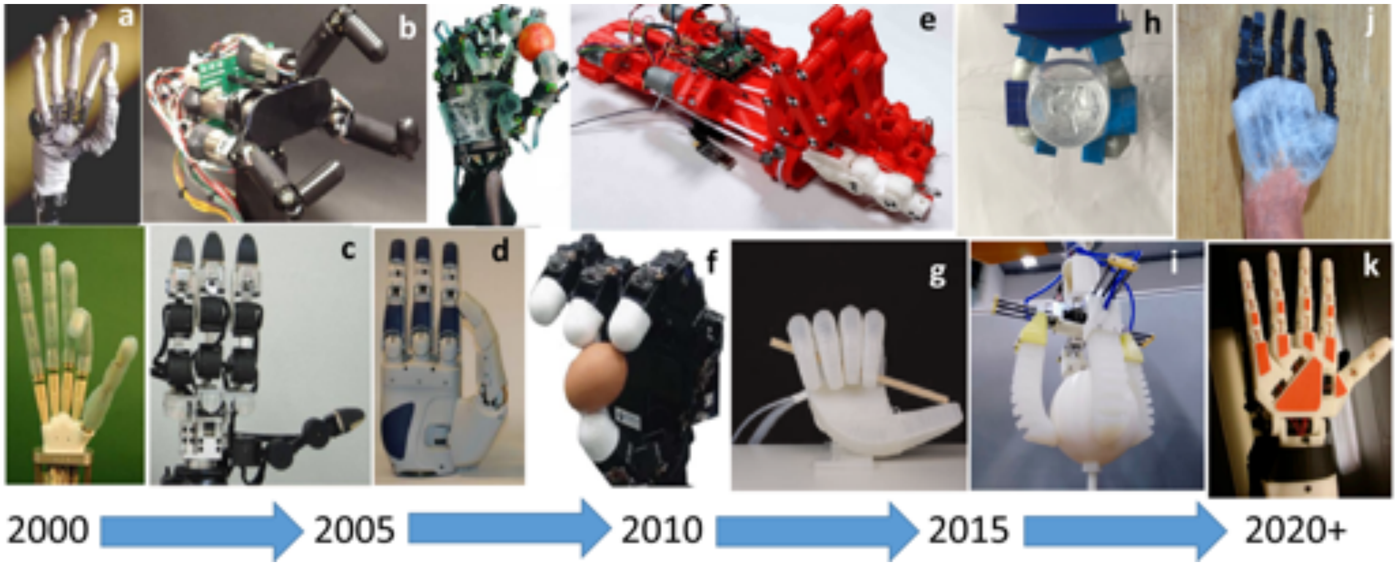

Fig. 5: Trend and novelty of robotic arm design over the past two decades. (a) Ultralight Anthropomorphic Hand [84], (b) High-speed Multi-fingered Hand [85], (c) WENDY Hands [86], (d) DLR/HIT Hands [87], (e) Asymmetric underactuated hand [88], (f) KITECH Hand [89], (g) RBO Hand 2 [90], (h) SMA based soft gripper [91], (i) Flexible robotic hand [92], (j) Asymmetric Bellow Flexible Pneumatic Actuator (ABFPA) [93], (k) Anthropomorphic Multi-finger hand [94].

the object in a power grasp or a pinch grasp involving active coordination of several phalanges or joint links. [82] provides an extensive analysis on the inner working of an under actuated gripper design. [83] presented a tendon based drive that employed underactuation for grasping objective. [95] provided an innovative joint coupling design for under actuated grippers.

VI. CONCLUDING REMARKS

In this work we surveyed and discussed the state-of-the-art, challenges, and possibilities with robotic sensory control and haptic rendering. We also summarised the current research trends related to the actuation technology that can be used to achieve complex artificial movement feedback and manipulation and guide the way for future research lines. The major purpose of this article is to boost worldwide efforts to realise the wide range of application possibilities given by these systems, as well as to provide an up-to-date reference to serve as a stepping stone for future research and development in this area.

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