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Sensors for Robotic Hands: A Survey of State of the Art

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ABSTRACT Recent decades have seen significant progress in the field of artificial hands. Most of the surveys, which try to capture the latest developments in this field, focused on actuation and control systems of these devices. In this paper, our goal is to provide a comprehensive survey of the sensors for artificial hands. In order to present the evolution of the field, we cover five year periods starting at the turn of the millennium. At each period, we present the robot hands with a focus on their sensor systems dividing them into categories, such as prosthetics, research devices, and industrial end-effectors. We also cover the sensors developed for robot hand usage in each era. Finally, the period between 2010 and 2015 introduces the reader to the state of the art and also hints to the future directions in the sensor development for artificial hands.

INDEX TERMS Artificial hands, prosthetics, industrial robotics, robotic hands, robot end effectors, sensors, robot sensing, review.

I. INTRODUCTION

Human hand is a sophisticated mechanism, the product of millions years of evolution, versatile in its functionality and essential for human ability to interact with the world. Major evolutionary transformation steps included formation of five-fingered structure with opposable thumb, development of flat nails from claws and increased sensitivity of the palmar (inner hand) surface [1]. The hand is the part of a bigger system; it is commanded via signals from central nervous system (CNS) and provides sensory feedback through peripheral nervous system (PNS). It is capable of accomplishing a wide range of tasks, which can be categorized as prehensile (activities involving object manipulation) and non-prehensile (articulations and gesture activities) [2]. Of these, dexterous object grasping and manipulation, the fundamental function of human hand, became viable due to number of processes such as development of stereoscopic vision and evolution of musculoskeletal and sensory structures. Additionally, human hand is an important instrument of cognition with the ability to explore through tactile sensing. Hence, it has been both a product and a major catalyst of human body evolution. Skeletal structure of the hand is comprised of 27 bones (8 form the wrist, 5 found in the palm, and 14 constitute finger phalanges). More than 30 muscles in the hand and forearm actuate the hand commanded via signals from three major nerves, radial, median and ulnar, as well as more than 20 identified muscular branches. Sensory innervation is also provided through three major nerves and more than 20 sensory branches.

Skillfulness of the human hand and its essential role in our lives inspired many to reproduce its functionality and structure leading to the emergence of "artificial hands". In the context of this paper, we use the term "artificial hand" for a multi-fingered actively or passively actuated device resembling in function or shape to the native human hand designed to be connected to the end of an actuated kinematic chain. This definition includes artificial hands for various purposes such as prosthetics, industrial, social and humanoid robotics. The origins of artificial hands can be attributed to the upper extremity prosthetics, from where their use expanded to other areas involving dexterous manipulation and interaction. First reported development is associated with the Roman general Marcus Sergius. He lost his right hand in the second Punic War and an iron cast prosthesis was made to replace his amputated extremity providing him with the ability to hold a shield [3]. Subsequent progress in the field was reported in 16th century. Anthropomorphic five-fingered prosthetic device with opposing thumb capable of several grasps was built by Goetz Von Berlichingen [4]. Later military surgeon Ambroise Pare developed a five fingered hand, "Le Petit Lorrain", for his patients with upper extremity amputations [5]. Fingers of this artificial hand were capable of independent motion. Berlichingen hand and "Le Petit Lorrain" not only resembled the appearance of the human hand, but enabled certain prehensile functionality. This provided a solid fundament for further research in the field, where major breakthroughs in actuation and sensing were achieved in the 20th century [6] driven by the increased number of upper limb amputees due to the World Wars.

George Devol created the first industrial robot Unimate and introduced the concept of ''Universal Automation'' [7]. He described it as ''a more or less general purpose machine that has universal application to a vast diversity of applications where cyclic digital control is desired'' [8]. Following this breakthrough, over the course of several decades industrial robots replaced the human workers on the factory floors of the developed countries. Robotized manufacturing also stimulated the development of artificial hands for higher efficiency in grasping and object manipulation tasks. Furthermore, in the eighteenth century mechanical androids, the predecessors of the humanoid robots, accommodated fingers capable of independent movement [9]. In general, the robot hands are either used as prosthetic devices attached to the human body and controlled directly by human input or as end effectors in systems which aim to replace or assist human in a wide range of tasks, such as work in hazardous/dangerous environment, industrial automation, repetitive task accomplishment, social interaction/assistance, etc.

People adjust their habitat in a way that everything they interact with is customized for the efficiency, effectiveness and comfort of use. Customization involves all kinds of objects designed for manipulation and interaction with the human hand. Moreover, anthropomorphism is proven to be an important characteristic expected by people from artificial hands which they interact with independent of the application area [10]. This imposes size and structure constraints, which constitute one of the main challenges of artificial hand development - inability to physically fit hand actuation, sensing and electronics in the amount and quality which would enable natural hand dexterity and control. Another major drawback is the limited interface between human and prosthesis. Except recent research work [11], traditional two-channel EMG control allows for opening and closing of all fingers, which does not accommodate multiple degrees of freedom configurations. Artificial hand development relies on a variety of the fields in anatomy, mechanical design, materials science, actuation, sensing, neuroscience and brain-machine interfaces. Design constraints, conceptual challenges and the multidisciplinary nature of the artificial hand research force developers to make tradeoffs. Examples of such compromises can be observed in prosthetics where hooks and passive hands [12]–[14] for a long time have been the only sufficiently robust, reliable and affordable products on the market. These devices lack the ability to produce the level of dexterity and skill of a natural hand. However, they can implement set of critical grasping and basic manipulation functions, and compensate in the large extent for cosmetic look and sense of upper limb wholeness. Similar design compromises can be observed in industrial robotics. Two and three degree of freedom (DOF) Schunk grippers, which have been delivered for more than 20 years [15], are non-anthropomorphic and offer little dexterity. Nonetheless, they reliably accomplish narrow set of object manipulation tasks in industrial environment, satisfying their main design objective.

Number of survey papers summarize and categorize the field of artificial hands [16]–[21]. Among these, a comprehensive review of design of artificial hands is presented in [17]. Authors define kinematic architecture, actuation, transmission, sensing, materials and manufacturing as six pillars of artificial hand design. Based on this, they provide a broad review of most significant works in artificial hand development since 1960s. Authors confirm the constraints which force developers to find compromises, but conclude that dynamics of development look promising for the area. The breadth of the area necessitates literature reviews on state-of-the-art in subdomains. Fifteen dexterous android hands with various degrees of resemblance to the human hand are discussed in [18]. Authors define the scope of the paper as to present advantages of fifteen advanced android hands which should provide researchers a broader view on the subject. In the subdomain of prosthetics, Belter and Dollar presented a work on the performance characteristics of anthropomorphic prosthetic hands in 2011 [16]. Authors went through a wide array of commercial and research hands (mostly of anthropomorphic nature) primarily discussing their physical performance such as grip force, digit range of motion and grasp speed. In [21], physical specifications are evaluated in light of an anonymous online survey conducted among myoelectric prosthetic hand users (54 adult and child amputee subjects). Based on the concerns and preferences of the surveyed users, the authors list a series of suggestions for the design of upper limb prosthetic devices. The span of the review articles emphasizes the importance of different aspects such as actuation, sensing, materials and user preferences. Mechanical structure of the hand encompasses manipulation capability, physical capacity to accommodate actuation, sensing and embedded system. Hand actuation has been a focal point of the research for decades, and it can be realized through various technologies [19]. Pons et al. compares actuation technologies in the context of prosthetics [20].

On the human body surface, the hand has the highest innervation density and tactile sensitivity [22]. Introduced firstly by Penfield and Rasmussen [23], neurologists and neuroscientists actively employ homunculus diagrams to illustrate functional structure of motor and sensory cortices and somatotopic organization. The process of determining somatotopic organization is realized by providing certain stimuli (usually electrical or vibration) to the hand segments and observing the response within the brain clusters. For example, functional magnetic resonance imaging (fMRI) was used to obtain sensory somatotopic map of the human hand [24]. Cortical homunculus is illustrated as a human figure caricaturized in order to reflect the amount of body parts innervation. Disproportionally large hands, face and lips of the homunculus point out highly innervated body organs. From this the complexity and importance of sensory component in artificial hand development comes apparent.

Thorough reviews on tactile sensing generally and in the context of robotic hands are presented in [25] and [26]. However, the authors are not aware of a survey paper, which focuses on different types of sensors used for robotic hands. In this work, we review artificial hands which were or have been developed since 2000. Specifically, this paper is the survey of hand sensors, and aims at revealing general trends in artificial hand development with respect to sensory design, integration and application. In our study we adopt the chronological approach. Sections II-IV cover a five year period each and intend, individually and together, at reflecting the gradual developments and progress in the area of hand sensors. Section IV thus presents the reader to the state-of-the-art and hints the potential future trends in hand sensor development..

II. 2000 - 2005

Artificial hand development at the turn of the millennium is summarized in the comprehensive work of Bicchi [10]. The author focuses on the three principal functional requirements of the artificial hands: human operability, dexterous manipulation and robust grasping. Between 2000 and 2005, prosthetics was the main driver for technological developments in the area. To the date, most commercial upper extremity prostheses had one or two degrees of freedom (DOF), provided little or no sensory feedback to a user and demonstrated low anthropomorphism. Research mainly focused on enhancing dexterity and grasping capabilities of hand prostheses, which in its turn assumed development of robust control systems of increasing complexity. Subsequently, by the end of the five year period, an emphasis was made on anthropomorphic properties of the devices and creation of capable and mature human-machine interfaces.

A. PROSTHETIC HANDS

One of the most significant contributors of the era has been Scuola Superiore Sant'Anna, which presented several highly capable hand prostheses. Massa et al. developed the RTR II – a three fingered underactuated (similar to the mechanism introduced by Hirose [27]) robot hand capable of performing adaptive grasping [28]. RTR II was developed to solve the problems of low functionality, cosmetics and controllability in hand prostheses. Apart from the mechanical design and the kinematics model, this required development of effective control and sensor systems. Carozza et al. reported on RTR II hand sensors, EMG-based human-machine interface and control system [29]. Strain gauge-based force sensors and Hall effect-based (Model 554968 by Honeywell International Inc.) position sensors were employed in RTR II, which facilitated slippage detection. Additionally, a tactile force sensitive resistor (FSR) was embedded into the thumb tip for exteroceptive sensing [30]. Despite being developed as a prosthetic device, RTR II was firstly integrated into the humanoid robot WE-4RII. The integration of this hand with the humanoid platform occurred under collaboration between ARTS Lab (developer of RTR II) and Takanishi Lab of Waseda University (developer of the WE-4RII). The joint team, ROBOCASA, had the first task of increasing the expressiveness of the WE-4RII, specifically by adding artificial hands. RTR II, equipped with current, pressure, tension and position sensors, was integrated to the WE-4RII under a preliminary study [31]. Analysis of the results contributed to the development of RoboCasa Hand #1 (RCH-1) [32]. This hand was designed to realize basic gestures, several grasping patterns, hardness measurement (two-hand, one-hand and one-finger hardness measurement) and surface recognition [33]. For this, RCH-1 was equipped with 16 contact sensors on the palm and phalanges, two 3-axis fingertip force sensors (for index finger and thumb) and one FSR sensor on the dorsum of the hand. RTR II served also as the base platform for the CYBERHAND project. First report described a design approach for mechanical structure, sensory system and socket for a three finger device with 10 DOF and underactuation mechanism similar to the one found in RTR II [34]. The proprioceptive sensors consist of 8 Hall effect-based position sensors (for each joint of each finger), three cable tension sensors, encoder on each motor and accelerometer incorporated inside the palm. The exteroceptive sensing of the hand was accomplished using two types of sensors: on/off touch sensor (for contact detection) and three axis force sensor. Various design iterations of the CyberHand in the following years will be covered in the forthcoming sections.

Another hand prosthesis of this era was Southampton Remedi-Hand. During the design, Light and Chappell took into account user requirements for higher number of grasping patterns and the availability of enhanced visual feedback during manipulation [35]. The human-like 6-axis hand prosthesis was capable of stable prehension with minimum grip force thanks to Southampton Adaptive Manipulation Scheme (SAMS). The hierarchical control [36] enabled the multiple degrees of freedom prosthesis with the ability to regulate the grasping motion and force by providing required position, force and slip detection sensory feedback. Magnetic encoders and current sensors were placed on each motor for position and force sensing, respectively. Additionally, the acoustic slip sensor was installed in the fingertips of thumb, index and middle fingers. For force sensing, motor current sensing instead of analog force sensitive resistors was employed to leverage the lower delay and higher reliability. Later, in 2005 Cranny et al. reported on a fingertip design with the following sensors integrated: force sensor based on two strain sensitive thick film resistors, slip sensor which utilizes piezoelectric properties of lead-zirconate-titanate operating as a vibration sensor and a temperature sensor [37]. A review of Southampton-Remedi hand sensors along with comparison of natural and artificial neuromuscular systems is provided in [38].

Other notable prosthetic hands of the era are described in [20] and [39]. Schulz et al. introduced a new ultralight anthropomorphic robot hand with five fingers and 13 controllable DOF [39] (see Fig. 1a). Distinct features of this hand include compact flexible fluidic actuators located internally with the hand, low weight of a finger mechanical structure (20 grams), and low time required for full finger flexion and extension (less than 100 ms). This hand incorporates four touch sensors and three flex sensors to each finger. Another underactuated hand of the period, MANUS Hand used two DC motors and a Geneva mechanism to enable three DOF five fingered prosthetic device [20]. The control system of the hand is provided with position (each active finger joint) and force data (in each fingertip) through Hall Effect based sensors. The pioneering projects discussed above in general reflect the state of the prosthetic hand sensor systems. Focused rather on mechanical design, actuation, transmission and anthropomorphism of these prostheses, researchers relied mainly on position, force and/or slip detection as the principal sensations required for grip force control and stable grasping. With appreciation of human hand capabilities as universal instrument, Sigiuchi et al. developed an artificial hand covered with soft rubber skin with 5 fingers and 16 DOF [40]. In order to provide the control system with position, velocity and force information of different points on the hand, researchers implemented a distributed touch sensor with more than 500 points [41].

A major challenge for the robot hand design was (and still to a lesser extent even today is) the limited physical space available for actuation, transmission, sensing and electronics necessary to approach the dexterity and skill of a human hand. One way to overcome the problem is the addition of a forearm unit. This, however, limits the range of applications and portability, which is why many research groups directed their effort into developing intrinsically actuated hands. As a result, developers found the compromise in utilizing various underactuated mechanisms and adaptive grasping techniques [42]. Mechanically underactuated adaptive mechanisms at this period used primarily position and force sensing, as in [42] and [43]. TUAT/Karlsruhe robot hand [44], a 5 fingered hand with 20 DOF actuated by a single ultrasonic motor is worth to mention due to its high degree of underactuation. The Toronto/Bloorview MacMillan (TBM) hand, a prosthetic device for children, focused on increasing prosthesis functionality and cosmetic appearance, while matching performance characteristics of the concurrent devices [45]. TBM hand is actuated by a single motor, and implements passive adaptive grasp. The aforementioned examples are important for our survey, since they represent the design philosophy, which aims to reduce the need for sensors by automatic adjustment of grasp position and posture and thus simplify the control system and/or mechanical design.

B. RESEARCH PLATFORMS

Modularity and simplification were other significant directions. Modular design of fingers and open skeleton structures delivered ease of assembly and maintenance and lower costs. A good example of this is the third version of the University of Bologna (UB) Hand [46] (see Fig. 1c). Authors aimed at decreasing the mechanical complexity while keeping certain amount of anthropomorphism and dexterity. Based on a comparative study to pinpoint the best solutions for these objectives [47], the sensory component of the hand was implemented as follows. Position sensor measures the bending torque of a spring, which is a part of a hinge at each joint, exerted on a compact load cell placed in the lower side of each phalange. Force sensor consists of a pair of strain-gauges for tendon force measurement. Additionally, the actuation module is located in the forearm unit and consists of 16 sensorized motors each equipped with a potentiometer-based position sensor and tendon force sensor.

Despite many shared limitations, research hands were not as constrained as prosthetics in terms of physical space. This allowed introduction of multisensory research platforms for robust control implementation. Over the time of almost two decades, German Aerospace Research Center (DLR) presented a continuously evolving series of artificial hands. DLR introduced the new multisensory 4-fingered robot hand in 1997 [48], [49]. Four years later, a new version of the articulated hand was presented in 2001 [50]. Design objectives for the robot hand included intrinsic actuation and electronics, and reduction of cabling. Additionally, open skeleton structure and some degree of modularity for ease of assembly and maintenance were also employed. From sensory point of view, second version was equipped with force and position, as well as motor speed and temperature sensors. Each of the four fingers of the DLR II has three actuated joints, each equipped with strain gage based torque and potentiometer based joint position sensors. Authors explain that potentiometers presented an advantageous alternative to motor position measurement, as the results provided are more precise and there is no requirement to reference fingers each time. Also, potentiometer was used to calculate the base joint position. To continue, a six dimensional force torque sensor was installed at each fingertip of the multisensory hand. Besides, each of the three motors actuating four fingers were equipped with speed sensors as implemented in DLR Hand I. Subsequently, DLR hand was thoroughly analyzed to understand its capabilities and, more importantly, limitations leading to suggestions for future directions [51]. At the same time, DLR and Robot Research Institute at Harbin Institute of Technology (HIT) started collaboration on development of HIT/DLR hand, a smaller and easier to manufacture device based on DLR II. The prototype of a finger and control system architecture of the HIT/DLR hand is presented in [52]. HIT/DLR hand has 4 temperature sensors less per finger, compared to DLR II. Additionally, the potentiometers used for measuring joint positions in [50] are replaced with Hall-effect sensors, and authors introduced new base joint torque sensor designed to allow the reduction of the finger length.

During the first five years of the millennium, second and third versions of Gifu Hand, a five-fingered robot hand,

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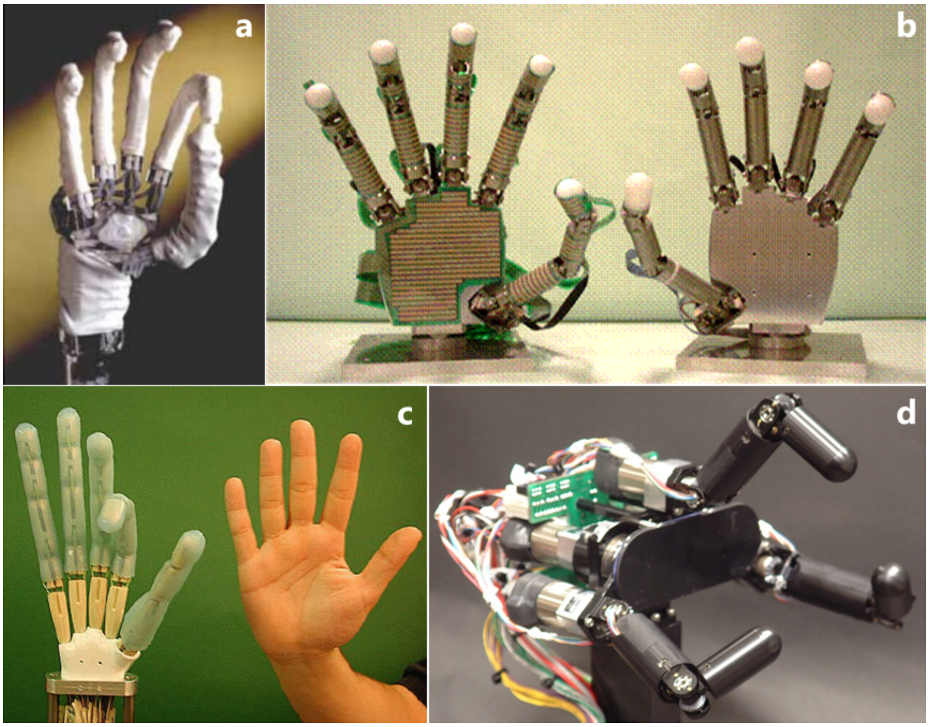

FIGURE 1. Robotic hands of the period between 2000 and 2005: (a) Ultralight Anthropomorphic Hand [39], (b) Gifu Hand III [54], (c) University of Bologna Hand 3 [46], (d) High-speed Multi-fingered Hand [59].

were introduced in Japan [53], [54] (see Fig. 1b). In the second version, researchers focused on reducing backlash in the gear transmission and improve the output torque compared to the first [53]. Gifu II has 16 DOF, is intrinsically actuated through DC motors with rotary encoders. For ease of maintenance and assembly, researchers developed fingers as units and joints as modules. Gifu II contains a 6-axis nano force sensor at each fingertip. To increase dexterity of the hand, researchers equipped it with a tactile sensor with 624 contact points, of which 312 are distributed over the palm, 72 over the thumb and 60 over each finger. The tactile sensor comprised of a grid pattern of electrodes, uses conductive ink and measures the varying electric current in response to the pressure applied to a thin film. Characteristics and design of the tactile sensor along with its output during capture of different shape objects can be studied from [53]. In the third generation [54], researchers focused on enhancing the tactile sensor by increasing the number of detection points to 859 and increasing the width and pitch of constituent electrodes. As a result, the insensitive surface area was decreased to 49.1%. The KH Hand type S inherited many design characteristics from Gifu III, specifically in relation to sensor system. Authors described the master-slave system with robot hand commanded by human operator hand wearing force feedback system, which allowed the user to perceive tactile sensory data from the hand during operations as demonstrated by peg in a hole experiment [55].

Intrinsic actuation stimulated development of non-tendon based transmission mechanisms, which in its turn triggered the move from tendon tension-based force sensors. Rhee et al. presented the mechanical design of the three fingered KIST Hand in the context of door opening control problem [56]. The hand incorporates fingertip force sensors, consisting of 8 strain gauges, as an alternative to commonly applied tendon tension-based contact force measurement. Additionally, a CCD monovision camera is used for doorknob positioning. Authors point out that tendon tension-based sensors introduce maintenance issues and can only provide joint torques. Similar fingertip force sensors were also used in [57]. Moreover, Yamano et al. presented a hand actuated by ultrasonic motors with trimmer potentiometers, where contact is detected by measuring the deformation of an elastic element. Likewise, angular rotation information from potentiometers allows the force estimation without installation of extra force and torque sensors in [58].

High-power miniature actuators and harmonic drives were implemented for the development of a high-speed three fingered robot hand [59] (see Fig. 1d). Researchers focused on mimicking the dynamic fast motion of a human hand in artificial hands. Reconfigurable hand with strain gauge-based force sensors in interphalangeal (IP) and metacarpophalangeal (MP) joints of each finger demonstrated wide range of grasping patterns and performed catching of a rubber ball falling from one meter height.

C. ROBOT HANDS FOR INDUSTRIAL ROBOTICS

In the field of industrial robotics, the programmable end effector, BarrettHand grasper [60], was crafted for tasks

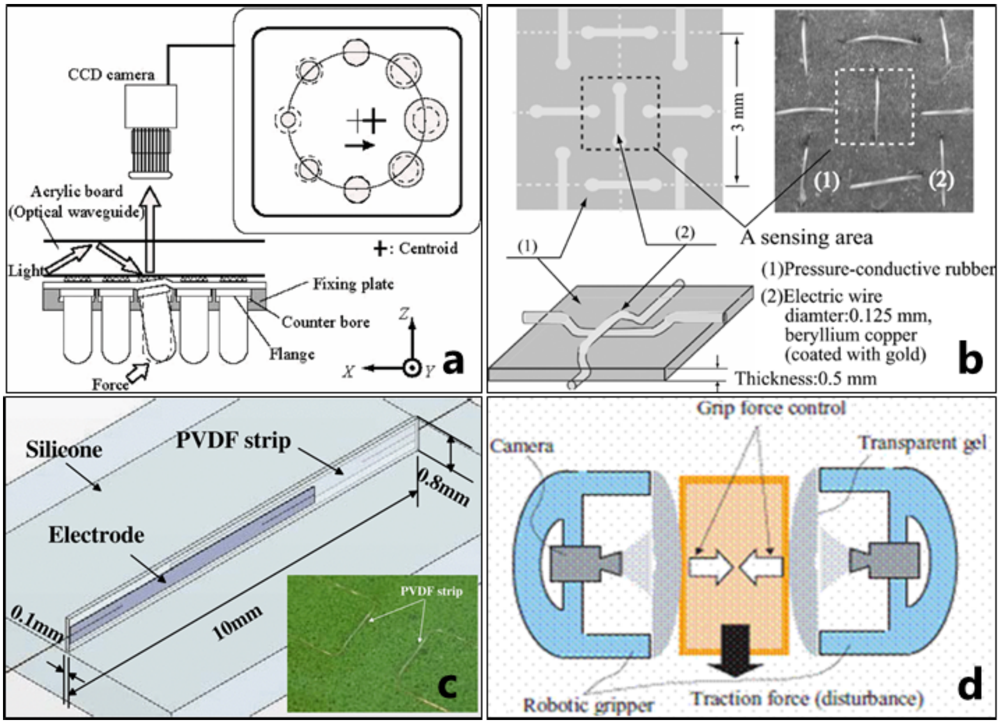

FIGURE 2. Examples of hand sensors developed between 2000 and 2005: (a) Three-axis tactile sensor system [66], (b) Structure of the sensing element of tactile sensor [68], (c) PVDF sensor structure [70], (d) Grasping with vision-based tactile sensor [67].

requiring high degree of flexibility and reconfiguration by adapting to the size and the shape of objects. By default, the BarrettHand includes Hall effect-based position sensors at each motor. As a commercial product, the grasper later obtained the option to be accompanied by additional sensors: fingertip torque sensor based on strain-gages which measure differential tension of tendon for each finger and tactile sensor array of 96 cells spread over three fingers and palm with higher densities on the fingertips [61]. Studying the kinematic model of the BarrettHand, Edsinger-Gonzalez created a three-fingered hand with enhanced force-sensing and passive adaptation capabilities [62]. The author developed the Force Sensing Compliant Actuator which utilized two torsion springs between each motor and the hand chassis, and measured the deflection of these through potentiometers for force sensing. Additionally, the hand was provided with joint angle measurement (through potentiometers) and tactile sensing (through FSRs) [62].

D. SENSOR DEVELOPMENT FOR ROBOTIC HANDS

Another active area between 2000 and 2005 was the development of sensors tailored for robotic hands. An overview of tactile and force sensing technologies for robotic hands is presented in [63]. The author discusses the applicability of these sensors for manipulation tasks with an emphasis on sensor fusion.

Number of light detector-based tactile sensors was developed at the time [64]–[67]. Researchers demonstrated that disadvantages such as computation time and calibration issues can be successfully overcome and the technology offers advantages such as durability, portability, ease of maintenance. Deformable membrane shape reconstruction from image data implemented for tactile sensing is presented in [64]. Kamiyama et al. introduced a tactile sensor consisting of a CCD camera and an elastic body with embedded color markers [65]. The distribution of force vectors applied on the elastic body was measured by calculating the disposition of the markers. An optical waveguide-based tactile sensor consisting of a CCD camera, a light source, an acrylic board and rubber sensing elements was introduced in [66] (see Fig. 2a). In [67], authors present the four fingered intrinsically actuated NAIST hand, which was developed as a testbed for studying vision-based slip margin estimation and grip force control (see Fig. 2d). To continue, Shimojo *et al.* [68] developed a thin flexible tactile sensor by implementing a single-layer composite structure where wire electrodes were stitched into the pressure-conductive rubber (see Fig. 2b). Sensor characteristics along with experimental results of applying the sensor on a four-finger hand for grasping tasks were also presented. In [69], authors review several candidate polymers with emphasis on their advantages and disadvantages presented along with current and potential usage for hand prostheses sensor systems.

This period also has seen usage of various materials for sensing purposes. For example, Choi *et al.* [70] developed a fingertip tactile sensor based on polyvinylidene fluoride (PVDF) and pressure sensitive resistor ink which can detect contact normal force and an incipient slip (see Fig. 2c).

Tada et al. presented a fingertip fabricated using two layers of silicone with different hardness mimicking the cutis structure of the biological skin. PVDF films and strain gauges were randomly distributed within this structure for tactile sensing [71]. The fingertip was designed to enable texture sensing capability (e.g. detecting the difference between paper and wood textures). Furthermore, Heidemann and Schopfer utilized tactile data acquired from 2D pressure sensor (16 × 16 pressure points with 6 mm distance between them) incorporated to the end-effector for object recognition (achieved 81% classification accuracy for seven classes). Additionally, Heidemann and Schopfer [72] developed a sensor system by combining piezoelectric transducers and pressure sensors in order to discriminate the hardness of wide range of objects with potential application in biomedical robotics.

Several significant artificial hands were introduced along with number of outstanding long-term projects having their inception during the described period. In general, many works focused on developing intrinsically actuated, forearm-free, underactuated robot hands with passive adaptive grasp capabilities. Consequently, more hands abandoning tendon based transmission were introduced. While researchers experimented with various actuation mechanisms, electric motors kept the leadership of most commonly implemented method. Additionally, researchers mostly promoted the modular design of hands to simplify the maintenance and lower the costs. This in some extent influenced the development of hand sensor systems. Force and position sensing along with slip detection were prevalent and extensively applied for grip force and stable grasp control. With the progress in mechanical, actuation and transmission components of artificial hands, in addition to an intensifying sensor systems development during the period, researchers invested the effort to develop interfaces for providing sensory feedback to a human operator from robot hands. The hand in [73] is equipped with tactile sensors, and sensory data is transmitted to the user through the microelectrode which stimulates the appropriate nerve. Dhillon and Horch [74] extended this work by also sensing motor neuron activity to translate the efferent neural commands into grip force and limb position references of prosthetic hands. To conclude the review of the time period, the reader is advised to familiarize himself/herself with review works [75] and [76], which were presented in 2004 and 2005, respectively, and present a broad review of state of the art in artificial hands development to the date. Additionally, Tegin and Wikander [77] review the tactile sensing in the context of intelligent robotic manipulation. Next section will cover new developments in artificial hands sensors and will update on novelties presented in long-term projects during the period 2005 – 2010.

III. 2005 - 2010

A. PROSTHETIC HANDS

In upper limb prosthetics, researchers continued the work with the focus on underactuated and adaptive mechanisms, bio-inspired functionality and neural human-prosthesis interfaces. Pushing the limits of underactuation, Kamikawa and Maeno developed a five-fingered hand actuated by a single ultrasonic motor [78]. The hand was designed to mimic the grasping force distribution of the human hand, for which authors applied FlexiForce sensors (Nitta Corp.) on the pads embedded to the phalanges of each finger and acrylic potentiometers for force and position measurements, respectively.

The design of the Cyberhand, a capable prosthetic device providing an effective neural interface for control and sensory feedback to a user, is presented in [79]. The development adheres to the principles of modularity, underactuation, anthropomorphic appearance and kinematics. The hand incorporates a bio-inspired sensory system for proprioception and exteroception, which are instrumental for the two-level control providing general user intent recognition and low level commanding of the hand. The early version of the CyberHand was then used in [80], where a study was carried out to find whether a human user can self-attribute a robotic hand prosthesis. Authors previously demonstrated that rubber hand illusion [81], [82] also evokes in upper limb amputees through experiments involving a rubber life-size prosthesis [83].

Research groups focused on reproducing exact anatomy and structure of the human hand with the aim of contribution to hand prosthesis and neural interface development. In 2004, Weghe et al. presented the design of skeletal structure for an Anatomically Correct Testbed (ACT) hand [84], which imitates the properties of a human hand to enable static and dynamic features in the artificial device. The hand is actuated using DC brushless motors via tendon transmission. Motors are connected to controllers equipped with photo-sensors and encoders; in addition to position sensing, force measurement can be performed through motor current processing [85].

The reported era demonstrated impactful work in neural and human-prosthesis interfaces. Pylatiuk et al. developed a force feedback system for myoelectric prosthetic devices [86]. The presented low-cost and low-weight system contains vibration motor and piezoresistive force sensor. The paper demonstrates good acceptance of vibration feedback and reduction of grasping force in experiments without visual contact. Kuiken et al. described the neural-machine interface for amputees, which implements targeted reinnervation by moving brachial plexus nerves to arm and chest muscles [87]. The interface allows motor control and, importantly, reemergence of sensation capability was observed in some subjects. Experiments involving temperature and electrical stimulation showed that the regeneration of afferents and presence of sensation of amputated limb can serve as basis for implementing prosthetic sensory feedback.

B. DEVELOPMENTS IN ACTUATION AND TRANSMISSION AFFECTING SENSORS

Novel actuation and transmission mechanisms introduced during the period had a major effect on hand sensor development. Maeno et al. used shape memory alloy (SMA) wires for actuation of the miniature hand having strain-gauge based joint angle sensors [88]. In the following year, Price et al. reported on the design and control of a three-fingered 9 DOF robot hand equipped with SMA artificial muscles [89]. In the work researchers suggest flexible bend sensors as ''promising alternative'' to conventional techniques, such as potentiometers, optical encoders and vision sensors, for joint deflection measurement due to their size, weight and low profile. Flexible fluidic actuators were used in 8 DOF artificial hand combining five-fingered anthropomorphic and three-fingered robotic gripper concepts [90]. The FRH-4 hand was developed with consideration of portability between various arm systems, which stimulated modular design without forearm unit. 12-bit magnetic rotary encoders (AS5045 by Austriamicrosystems) and FSR cursor navigation elements (Interlink Electronics) were used for position and tactile sensing, correspondingly. Circular sensing area is made of four sectors, each of which has a rubber actuation layer attached to its middle for force concentration. A new transmission system for artificial hands called ''Twist Drive'' is proposed as a superior alternative to gears in [91]. The mechanism is based on a tendon transmission, where the pulling force and joint motion are generated by twisting pair of strings. String twisting causes the flexion of a finger, whereas the installed spring results in the finger extension during string untwisting. Due to the fact that the ''Twist Drive'' cannot provide relationship between motor and joint angles, authors equipped each joint with a 12-bit magnetic encoder (AS5046 by Austriamicrosystems AG) for angle sensing.

C. RESEARCH PLATFORMS

Most papers on artificial hands and related sensors are associated with research platforms. Kargov et al. extended the modularity principle in hand development by enabling customization in terms of phalanges and finger lengths, number of actuators and active/passive configuration of joints [92]. They implemented joint position measurement through Hall-effect based contact-free 10-bit magnetic rotary encoders (AS5040 by Austriamicrosystems), force sensing based on modified pressure sensors (FSR 149 from Interlink), and piezoelectric relative pressure sensing (Series 1 TAB, from Keller) for fluidic actuators. First and second versions of DLR/HIT hands were introduced in 2007 [93] and 2008 [94] (see Fig. 3c), respectively. The first DLR-HIT-Hand contains set of sensors described in the finger design paper presented in the previous section [52], whereas the second version employs two specially designed potentiometers for angle sensing. In addition, in 2010, Zhang et al. presented a thin and flexible resistive tactile sensor developed for the second version of the DLR-HIT hand [95]. This sensor consists of electric (flexible PCB), sensitive (pressure-conductive rubber and silicon-rubber glue) and protective (silicon-rubber film for protection and increased friction coefficient) layers.

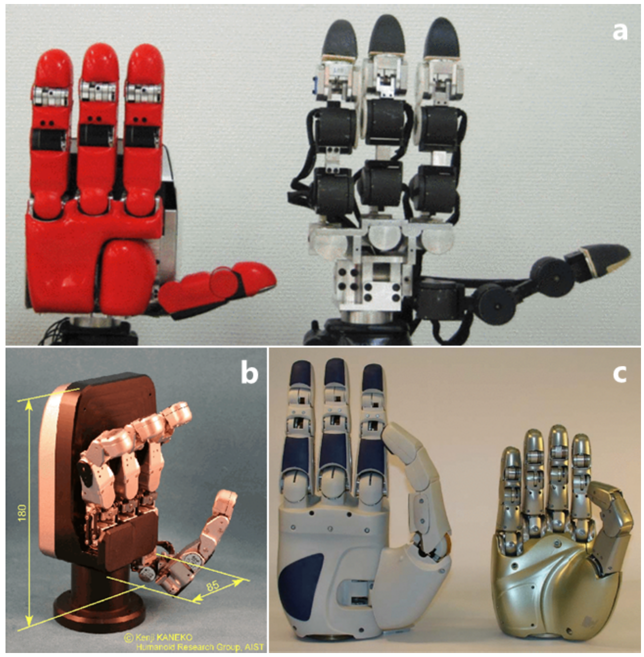

FIGURE 3. Representative robotic hands from the period between 2005 and 2010: (a) TWENDY-ONE and WENDY Hands [97], (b) Multifingered Hand [96], (c) DLR/HIT Hands [94].

Emergence of multiple humanoid systems, especially geared for social robotics, stimulated intensive work on hand development in this area. In [96], authors adhered to the principles of modularization and internal placement of hand components to allow portability between various arm systems in humanoid robots (see Fig. 3b). The device is equipped with incremental encoders for joint position tracking and strain-gauge based 6-axes fingertip force sensors. Iwata and Sugano presented the design concepts and implementation of a humanoid robot TWENDY-ONE [97] (see Fig. 3a). The design of the four-fingered hand of this humanoid included soft fingertips and finger and palm surfaces covered with viscoelastic silicone material. Additionally, fingers are equipped with passive compliance mechanism enabling adaptive grasp capabilities. The hand employs potentiometers to measure joint angles (two per finger), six-DOF fingertip force sensor and distributed tactile sensor with 241 detection points spread over hand and placed under the ''soft skin''.

Hasegawa et al. equipped a three-fingered robot hand with integrated proximity, slip and tactile sensors [98]. Sensor groups were used to maintain reliable grasping, force control, object withholding and arresting if the slippage occurred. Authors used center of pressure (CoP) tactile sensor, where pressure sensitive conductive rubber is placed between layers of conductive film. The sensor provides information on contact position and amount of force applied; additionally, the analysis of the data allows slippage detection. Apart from the tactile sensor, researchers incorporated net structure proximity sensor based on the infrared LED emitter and phototransistors as detecting elements. Importantly, authors encounter the problem of fitting multiple sensors to the limited space available on the surface of the fingers. In this regard, a through-hole was made in the tactile sensor, which allowed exposition of the phototransistor elements. The integrated sensor demonstrated efficient performance for implemented pick and place task carried out in conditions of uncertainty. CoP tactile sensor was also used in [99] where authors equipped the high-speed hand [59] with tactile and slip detection capabilities.

Number of sensor systems was developed accordingly to task-specific requirements and constraints. High-speed hand project introduced in the previous section [59] was furnished a tactile sensor to enable real-time feedback for high-speed contact manipulation. The sheet-like tactile sensor comprised of two layers of electrically conductive coated film and one layer of pressure conductive rubber [100]. This sensor demonstrated response time of less than 2 ms for detection of the finger angle change during a rigid stick grasping experiment. This allowed authors to perform tasks such as dexterous dynamic pen spinning and one-handed knotting of a flexible rope [101]. To continue, Edin et al. focused on developing a tactile sensor consisting of contact and strain-gauge based 3-axis fingertip force sensor which would provide discrete mechanical events critical for performing grasping and lifting operations [102]. The three-finger hand designed for underwater operation incorporates four force sensors (for each finger and wrist), ultrasonic sensor for distance measurement, image sensor providing visual information for tasks like object shape determination, and three sets of Hall effect sensors for finger position limit maintenance [103]. The sensors are used for enabling grasp functionality under control of user operator or autonomously.

D. TACTILE SENSORS

Tactile sensing remained one of the research thrusts during the period. An electro-optical device based on the electron-tunneling principle, which converts stress into electroluminescent light, was reported in [104]. The device allows imaging stress distribution with near human level spatial resolution of around 40 μm. Schmidt et al. presented a sensor comprised of static and dynamic tactile measurement components [105] for enabling human interaction and object exploration capabilities for robot hands. Static module measures the resistance change of a piezoresistive foil for an applied pressure via a second foil with embedded electrodes. The major novelty is the dynamic capacitive tactile module, in which brush of fibers attached to the flexible membrane transmit a force to capacitors on contact occurrence. The sensor consists of two static modules surrounded by 16 dynamic modules and is attached to the jaw of a gripper for experimental sessions. To continue, two piezoelectric materials were used to develop a new tactile sensor with high sensitivity, wide measurement range and pressure resistance [106]. Specifically, authors applied vibration type piezoelectric sensor with high sensitivity and pressure resistance, and developed an elastic body for the sensor to extend the measurement range. Due to the diverse physical configurations of artificial hands, versatility became an important consideration. Goger et al. developed a tactile sensor consisting of resistive component (matrix of electrodes covered with conductive foam), which provides an image of the applied pressure profile, and PVDF polymer embedded into the sensor cover to enable vibration transmission, and hence slip detection [107] (see Fig. 4a). Importantly, the sensor is available as a construction kit, which allows portability and easy adoption across various robot hands.

In [108], Wettels et al. point out that despite recent advances, there is still no tactile sensor which would have characteristics and robustness sufficient for its universal, rather than limited to specific structured environments, applicability (see Fig. 4b). They proposed a bio-inspired tactile sensor comprised of a rigid core, containing sensitive components within, with electrodes distributed over its surface. The sensor is covered with elastomeric 'skin' resistant to wear and biomimetic texture and tackiness. Wettels et al. used the developed sensor, which was from then referred to as 'BioTAC', for developing a grip control in an experiment involving Otto Bock Michelangelo 2 robot hand [109]. At the same time, Fishel et al. developed a micro-vibration sensor with a pressure sensor in the core utilizing conductivity of acoustic frequency vibrations of the liquid surrounding the core [110]. Authors leveraged the hydrophonic sensing of the sound waves propagated from the sensor skin to enrich the tactile sensing information on top of the previous work. Later that year, Lin et al. reported on the development of the BioTAC™ finger sensor module which incorporated both of the sensor components of Wettels and Fishel, and added a thermistor for temperature measurement [111]. Synergistic combination of vibration and temperature information was used to enhance the tactile sensing. The modular design of the sensor allows easier maintenance and high portability. It eventually turned into a commercial product and was used by different platforms, as it will be further discussed in the following section.

Schmitz et al. reported on the development of a fingertip tactile sensor in [112]. A flexible printed circuit board (PCB) and circular, rather than square, sensitive elements (12 of them) were used for a durable and easy to manufacture sensor. Two conductors separated by a dielectric constitute the capacitor. With 12 capacitors used in a sensor, in each silicone foam is used as dielectric, conductive silicon rubber layer as one of the conductors and 12 circular elements serve as a second conductor. Experiments showed the presence of hysteresis and cross-talk between the sensing elements.

E. HAND SENSORS DEVELOPMENT. 'ARTIFICIAL SKIN'

Drawing inspiration from an electric fish, Eigenmannia virescens, Smith et al. utilized electric fields measured by capacitive sensors for pretouch formation in robot hand grasping [113]. It is an alternative to vision and tactile sensing with an intermediate operational range.

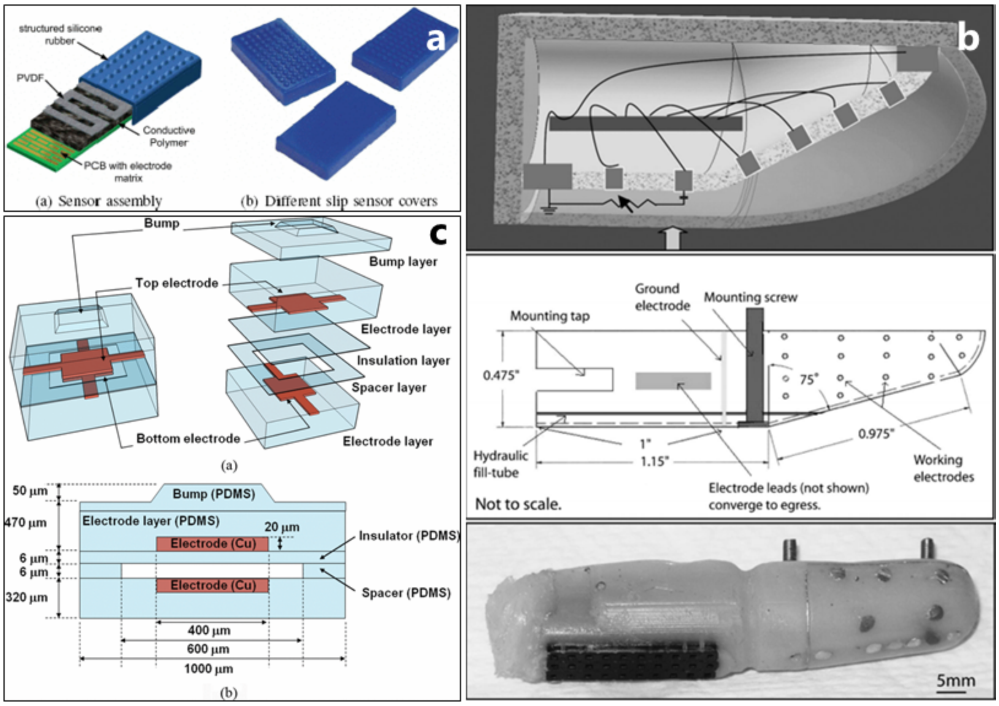

FIGURE 4. **Different tactile sensors for the period between 2005 and 2010: (a) Tactile sensor assembly [107], (b) Structure of the sensing element of tactile sensor [108], (c) Structure and cross-section of the tactile sensor [116].**

Authors carried out several experiments of varying complexity including human hand avoidance, planar manipulator alignment and object scanning using a two-finger gripper equipped with electric field sensors. In the following year, Wistort and Smith reported on experiments where the data from electric fields sensors were used for closed-loop control in pre-shape and robot hand alignment tasks [114]. The sensors consist of two electrodes, transmit and receive, and the proximity of objects relative to the electrodes modifies the capacitance between them (AC current applied to transmit electrode initially induces current in receive electrode). Special 3D-printed fingertips made of plastic accommodated the electrodes and were placed onto the three-fingered Barrett Hand for first experiment, whereas Barrett WAM 7-DOF manipulator with specially designed array of electrodes in place of end-effector were used for the second. Subsequently, the capabilities of this pretouch system were revealed by performing more complex operations such as human co-manipulation (electric field sensors indicated whether an object is also being held by a human) and object grasping procedure [115]. Limitations of electric field sensing with non-conductive materials were noted. Another direction in the area of capacitive sensing suggested development of dual-mode devices. In [116], researchers introduced the sensor with Polydimethylsiloxane (PDMS) mechanical structure and a mesh of copper electrode strips (see Fig. 4c). The sensor is capable of switching between tactile and proximity mode by reconfiguring electrode connections. Five layers of PDMS and two electrodes incorporated into different layers (in a top-down approach) within are used in a single sensor cell. Tactile sensing is accomplished by measuring capacitance between top and bottom electrodes (as pressure results in deformation of top layer PDMS and pushes the top electrode), while proximity sensing is accomplished by sensing capacitance between two neighboring top electrodes. As pointed out by authors, the design allows observing proximity and tactile information during hand operation with the advantage of reducing hardware burden due to mode switching. Alternatively, pretouch system based on fingertip optical proximity sensors presented in [117] allowed grasp adjustment prior to object contact. Authors used four infrared emitter-receiver pairs (Vishay TCND50000) for the fingers of the Barrett Hand engaged for the system evaluation.

Advances in tactile, force and position measurement along with slippage detection, created an auspicious environment enabling development of robust artificial hands control systems. A lot of effort was focused on operation in uncertain conditions. In [118], researchers developed a grasping strategy for unknown objects based on human grasping reflex. The scheme consisting of grasping and withholding actions was implemented on the Gifu Hand III [54]. Takahashi et al. used four 6-axes force sensors (one per fingertip and one for the wrist) in addition to 86 element tactile sensor for robust position and force control in order to grasp objects with unknown mass, friction and stiffness [119]. The method enabling quick and smooth switching between the position and the force controller was tested on a 12 DOF three-fingered robot hand. To continue, Felip and Morales [120] proposed a controller to facilitate grasping under uncertainty by utilizing sensory feedback. They use grasp primitives to perform a single indivisible procedure associated with a specific physical form. In experiments utilizing BarrettHand as an end-effector for a mobile manipulator, the control system utilizes the data acquired from 12 DOF wrist force/torque and acceleration sensor, pressure sensors in each fingertip (Weiss Robotics) and strain sensors in each of the fingers.

Emergence of new sensing technologies and extensive demand for tactile information for complex grasping tasks created a propitious environment for artificial skin development. Cannata et al. introduced a novel skin designed for full-body humanoid robot [121]. The skin is made of flexible interconnected triangular sensor modules, each of which incorporates 12 capacitive taxels (implemented via capacitance to digital converter circuits). The Bionic Hand [122], covered with multiple layer artificial skin capable of sensing strain, demonstrated texture and slippage detection. The artificial skin on each of the five fingers contains four PVDF films and three strain gauges, while the palm skin has six PVDF films and six strain gauges distributed equally over the area. The skin structure is designed to have multiple layers, finger sacks and palm sheet made of polyurethane with varying stiffness to enhance sensing and manipulation. Noise susceptibility and hysteresis were the main technical hurdles to overcome for the capacitive sensors used for artificial skins. Electromagnetic shielding and local signal processing were employed in force sensing capacitors to tackle the aforementioned disadvantages [123]. Specifically, the outer plates of the sensor acted as shielding for the middle layer and the acquired signals were locally digitized by compact NAND multivibrator circuit. Sensor showed mechanical robustness, scalability and low-cost making it a suitable building block for artificial skin sensor arrays.

IV. 2010 - 2015

Pertaining the impactful attainments in tactile sensing between 2005 and 2010, categorization of tactile human-robot interaction (HRI) and associated sensors were presented in [25]. Subsequently, Yousef *et al.* [124] presented an overview of tactile sensing for dexterous in-hand manipulation.

A. PROSTHETIC HANDS

In the area of prosthetics hands, the era starts with the SmartHand transradial prosthesis [125] (see Fig. 5a). The hand is designed to accommodate large-bandwidth neural interfaces and evaluate natural control and feedback. This requirement assumes dexterous manipulation availability along with sufficient bio-inspired sensors. Fingers are equipped with joint angle, tactile and tendon tension force sensors. DEKA Prosthetic Arm uses the foot-based control, where FSR and inertial measurement unit at the foot of the user generate the control reference [126]. To continue, tendon displacement based grasping force and gesture control was presented for a prosthetic hand in [127]. Authors specify

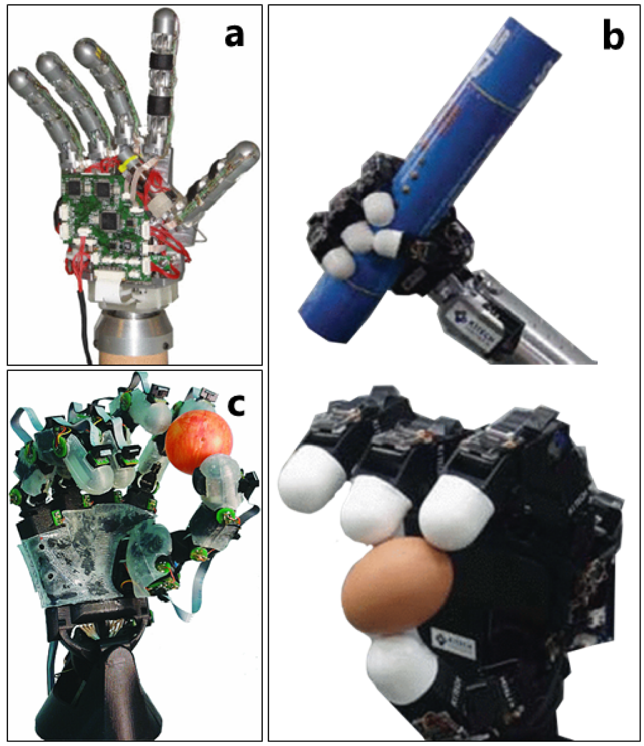

FIGURE 5. Notable robot hands from the period between 2010 and 2015: (a) SmartHand transradial prosthesis [125], (b) KITECH Hand [142], (c) UB Hand IV [146].

the method for determining the occurrence of a contact, and subsequent grasping force measurement. The tendon displacement is mapped to the grasping force of the multigrasp prosthesis utilizing the stiffness of the series elastic elements. Commercially available force sensors (FSR 400, Interlink Electronics Inc.) were customized to enable tactile sensing along with a thermistor (NTC, Panasonic) for enabling thermosensitivity in SMA-actuated hand prosthesis [128].

In this period, researchers focused on effective neural interfaces for the control and the sensing of dexterous prosthetic hands. In a four week long study, electrodes implanted to the stump nerves of the amputee subject recorded neural signals while subject was imagining one of power or pinch grips, or flexion of little finger [129]. Offline classifier demonstrated 85% recognition of grip type, which was increasing gradually, hinting the learning effect. Concurrently, for ten days three of four electrodes were stimulated to provide sensory data. This resulted in discrete tactile sensation from different stimulated sites of the median and the ulnar nerves. Authors noted that pressure stimulation outperforms vibrotactile stimulation in multi-site feedback discrimination in [130]. This study involved eight transradial amputees divided into groups A (full phantom map present) and B (partial or no phantom map), as well as ten healthy subjects. Subjects with full phantom map demonstrated better discrimination compared not only to subjects of group B, but also to healthy subjects. Additionally, the study concluded that possession of a full phantom map allows better sensational discrimination, independent of the feedback modality. The following year, Raspopovic et al. used transversal multi-channel intrafascicular electrodes to reach near-natural sensory feedback in amputees [131]. This allowed the real-time user intention translation to the prosthetic device. For instance, the user could effectively perform grasp control without visual and audio information. Follow-up experiments reveal a significant progress in sensory feedback based object property recognition. Specifically, in object stiffness classification, a subject reached 78.7% accuracy in three-category problem (high, medium and low stiffness). Moreover, 88% recognition was demonstrated in classification between cylindrical, big and small spherical objects.

B. RESEARCH PLATFORMS

Humanoid robot torso, Robonaut 2, was developed by NASA and General Motors to be installed to the International Space Station in 2011 [132]. To satisfy the strict functional requirement of this assistant platform, the hand module was designed to work with tools [133]. The inclusion of the forearm unit vacated the hand module for accommodating three types of sensors. Firstly, joint angle measurement is realized using Hall-effect sensors with a novel ''ellipsoidal shaped'' magnet (as found in [134]), which allowed linear relationship between the angular position and change in magnetic field. Secondly a tactile load cell, a six DOF force and torque sensor [135], which uses eight pairs of semiconductor strain gages, is incorporated into the phalanges. Finally, tendon tension sensing is placed in the actuation system, where the measured compressive forces in the conduits used for tendon routing implies the amount of tensile load on a tendon [136]. DLR hand-arm system can be considered as the state-of-the-art in this period [137]. Grebenstein et al. emphasize the HRI aspects and introduce the variable-stiffness actuated system with over 100 sensors located in the hand and arm modules.

Concurrently, Kim et al. introduced four-fingered bio-inspired robot hand which employs eight encoders and one potentiometer for position measurement, and 24 tactile sensors distributed to the fingertips (four on each) and the palm (eight) [138]. Similarly, position and force feedback were enabled in a three-fingered robot hand by installing potentiometers in finger joints and FSRs in the finger segments, covered by soft pads [139]. For the similar purpose of position and force control, Fukui et al. used tactile arrays on finger pads and fingertip multiple-axis force/torque sensors in Universal Robot Hand II [140]. The tactile sensor is a three-layer structure comprised of an electrode pattern seat, pressure sensitive rubber and urethane gel, which was used in [141] in 2008 for shape classification during in-hand rotation. Physical space limitations and complexity issues are frequently restated as fundamental problem of artificial hand development. In 2012, KITECH hand leveraged a compromise between performance and complexity [142] (see Fig. 5b). The hand contained off-the-shelf RC servos with angle and feedforward current based torque sensing. In 2013, Endo et al. presented second refined version of the Waseda Soft Hand (WSH-1RII) designed for humanoid service robots [143]. 14 sheet force sensors (FlexiForce) were distributed over finger pads and covered with soft ''skin''. The skin made grip force control possible in addition to preserving anthropomorphic features and sense of hand touch (evaluated with human users in a handshake experiments).

Modularity and simplicity of mechanical design remained popular design objectives in the period. Adhering to these, Martin and Grossard developed a backdrivable robot hand [144]. They point out that, given tendon forces are not degraded by low mechanical impedance of transmission (as seen from motors), backdrivability enables measurement of the contact forces by the resistive torque induced onto the DC actuators. This gives the ability to estimate joint torques, which can provide the measure of contact forces if the contact position is supplied via tactile sensing.

There also can be seen a shift towards commercial off-the-shelf sensors, which were used either as-is or with some customization. Along with the simplicity of usage and maintenance, off-the-shelf products lower the price of devices by eliminating the nontrivial sensor design and manufacturing. The iRobot-Harvard-Yale hand incorporated tactile arrays (on fingers and palm), flexure deformation sensors (on fingers distal joints), magnetic encoders (on finger proximal joints), and accelerometers (in fingers distal links) [145]. Except the 3D deformation of distal joints flexure sensors, the other sensors were used as is or customized from commercial products. The optical flexure sensor uses two phototransistors and optical fiber delivering light onto them, which are used to measure the curvature of points at the two sides of a joint. Linear regression on the data obtained with the numerical integration of the interpolated bending profile along the length of the joint enables detection and measurement of flexion, twist, combination of both, and shear.

In this period, numerous highly skillful robot hands were developed leveraging the advances in related fields. The UB Hand IV was introduced in 2013 [146] (see Fig. 5c). The authors list conservative design methodologies inherited from industrial robotics and conventional mechanics as one of the main hurdles for rapid evolution of the field. Indeed, the UB hand series propagates on innovative ideas on the design, actuation and sensor systems. For instance, UB Hand IV shifts the system complexity from the mechanical design to the control and sensing. Researchers propose the design of the hand with LED-based optical sensors with wide and narrow field-of-views for joint position [147], [148] and force [149] sensing, respectively. Additionally, tactile sensing is provided through a two-layer sensor, where optoelectronic components are located below a silicon layer for deformation-based force measurement [150]. The optoelectronic-centered sensing achieves low susceptibility to electromagnetic noise and eases requirements of conditioning and amplification electronics.

C. TACTILE SENSORS

Teshigawara et al. continued their work [99] on slip detection based grasp force control, and proposed a thin and soft sensor made of electrodes and pressure conductive rubber [151]. The new sensor eliminates mechanical noise due to hand operation and allows change in grip force. A broad overview on slip detection and prevention can be studied in [152], where authors presented two robust adaptive sliding mode controllers for slip prevention in hand prosthesis manipulation. The integral sliding mode slip prevention controller smoothly increases the grasping force when the slippage is detected, and causes less object deformation while keeping the object from being dropped, when compared to alternative controllers.

Lack of computational power and unavailable or limited tactile information for curved surfaces pushed the researchers to investigate biomimetic approaches. Bio-inspired hand motion generated using human recorded data was used for accomplishing unscrewing and screwing tasks [153]. This approach reduces complexity of hand motion planning and provides an anthropomorphic solution to rolling contact problem requiring no force feedback (which conventionally requires a network of tactile sensors).

Each of the tactile sensor technologies, should it be piezoresistive, piezoelectric, capacitive or optical, has certain disadvantages, e.g. low resolution, non-flexibility, susceptibility to noise, or hysteresis. One of the recent materials used for realizing tactile sensing is quantum tunneling composite (QTC). This material turns into conductor from insulator, when compression, twisting or tension is applied. In [154], QTC is used as the base material to develop flexible four-layered tactile sensor capable of detecting normal and shear forces (see Fig. 6c). The four layers of the 3D sensor contain bump (force transmission), two layers of electrodes between which the QTC pills and elastomer functioning as protection. After all, researchers characterize the fabricated sensor and demonstrate that for the x, y and z directions the detectable forces are 20 N, 8 N and 8 N, respectively, whereas sensitivities of a cell array are 0.47 V/N, 0.45 V/N and 0.16 V/N, correspondingly.

The authors of [155] point out that robot tactile sensors with the ability to detect dynamic phenomena spanning a frequency band in tens or hundreds of Hz started resembling to the mechanorecepters of the humans with the similar ability. The achievements in hand manipulation and sensation thanks to the advances in tactile sensing are presented in numerous studies as follows. A machine learning approach of classifying materials based on their texture without any prior assumption demonstrated positive results across several classifiers in [156]. An effective online in-hand object localization method based on particle filter and custom collision checker detects inaccurate finger positions or faults during grasping using integrated tactile sensing, hand kinematic data and initial object pose acquired from a vision sensor [157]. A novel piezoresistive rubber based tactile sensor demonstrated notable improvement in household object classification through palpation procedure [158].

A comparative review of tactile sensor technologies is presented in [159]. In this work, Wettels et al. introduce three sensing modalities of the BioTac®, namely force, vibration and thermal sensing. Thermal and vibration sensing is used to discriminate between object properties, such as thermal properties, geometry and texture, as well as for slip detection. Importantly, BioTac®is available as a commercial product and is installed on several robot hand platforms, which enabled number of research projects using the sensor. For example, the gripper of the PR2 robot was equipped with the sensor in the study which demonstrated that learned haptic properties of objects can be generalized over unknown objects, and also related to certain labels in the form of haptic adjectives [160]. Concurrently, Xu et al. integrated BioTac®into the Shadow Hand and used Bayesian exploration [161] for identification of objects through tactile data [162] (see Fig. 6a). Experiments demonstrated 99% accuracy in ten class identification problem over 100 trials. Importantly, authors performed ranking of the exploratory movement to identify that, for instance, compliance and thermal test were the two most effective procedures.

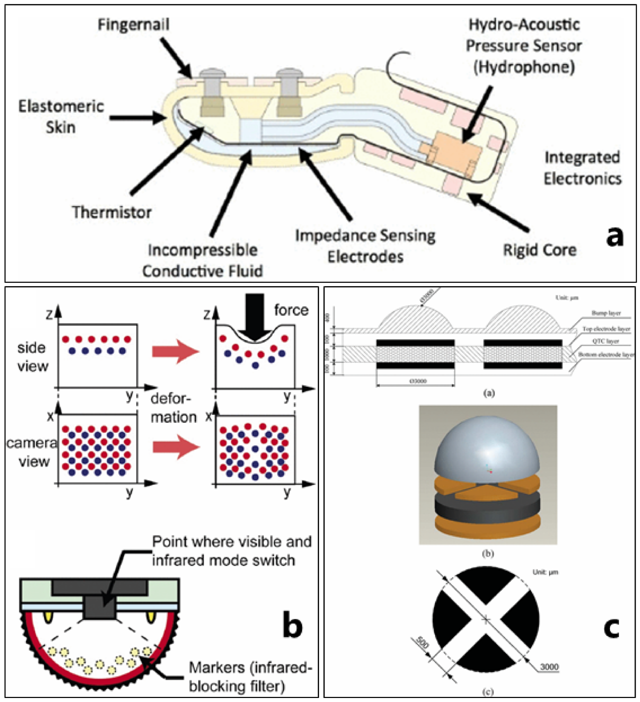

FIGURE 6. Various sensors for robotic hands developed between 2010 and 2015: (a) BioTac sensor structure [162], (b) Vision-based force sensor [167], (c) Outline of the three-axis tactile sensor [154].

In the "Roboskin" project, the developed artificial skin was integrated into four robotic platforms (iCub, NAO, Kaspar, and Schunk robot hand) to achieve the project goal of improving safety and efficiency in HRI [163]. Soft amorphous artificial skin leaves the sensor node size and spacing between elements as the only constraint for humanoid robot installations [164]. The microphone based vibration analysis capability of the skin is utilized for texture recognition. The sensor performs local signal processing and can transmit data to external devices. Each node is incorporated into neoprene rubber mesh and subsequently embedded into silicone rubber

(Ecoflex Supersoft 30, Smooth-On). The robot skin was used in 15 class texture recognition problem with Baxter robot, where it demonstrated 71% accuracy in classification and one centimeter precision in localization.

An unprecedented ultra-high sensitivity was achieved in a novel piezoresistive sensor [165]. The performance is by virtue of both conductive and elastic active layer of the sensor. This was afforded by the development of elastic microstructured conducting polymer (EMCP). EMCP consists of interconnected hollow-sphere structures of polypyrrole (PPy) and allows structure based elasticity. The pressure sensor was capable of sensing subtle pressure, specifically less than 1 Pa, and had short response time, good reproducibility and temperature stability.

The reader is referred to [166] for a review of bio-inspired electronic and sensing device development in the context of the robotic skin. Authors mention how various natural skin properties are achieved in different projects. Two important trends in synthetic skin development are the multi-modal sensing and the active matrix addressing with signal amplification achieved through integrated transistors.

D. HAND SENSORS DEVELOPMENT

Emphasis towards multimodal sensing in robot hands shifted the focus of the developers to the concurrent measurement of several stimuli and sensor fusion. Sato et al. introduced a vision-based thermal sensor for robot fingers [167] (see Fig. 6b). The sensor consists of a CCD camera, heat and light sources and elastic seat with thermo-sensitive paint covering inner side. It resembles the shape and compliance of a robot finger and can transmit surface temperature facilitating both deformation and temperature measurement.

The effect of ''hearing a sea'' from putting a seashell next to an ear served as inspiration for developing a microphone based proximity sensor [168]. The system consists of two microphones collecting sound inside and outside the cavity placed into a robot finger, and analyzes the spectrum of ambient noise to detect proximity to an object surface. Another simple and easy-to-install sensor, the Resistor Network Structure Proximity (RNSP) sensor, consists of LEDs, phototransistors and resistors [169]. The sensor measures the photocurrent in the network and central position of the current distribution. This allows measurement of the center position of affordable sized objects and estimation of the object posture, if the object size exceeds sensor field of view. The authors showed effective grasping with preshaping using only rough information on objects obtained from RNSP and tactile sensors. A matrix of capacitive tactile sensors capable of working in two modes (tactile and proximity) was used in object motion tracking and contact prediction in the context of HRI [170].

A new class of stretchable devices based on single-wall carbon nanotube films is introduced in [171]. This new electric nanomaterial paved the way for a strain sensor, which is capable of measuring and withstanding strain of up to 280% - 50 times the amount for a conventional metal strain gauge. Additionally, the sensor demonstrated high durability, fast response and low creep during the tests, which included twisting and compression along with standard mechanical strain. The paper studies the use of the sensor as a wearable human motion detector, and we believe in the future the sensor will find extensive use in artificial hand applications. Another soft strain sensor based on hybrid ionic and metal liquids conductivity used to decouple signal transmission from sensing was developed for a hand prosthesis [172].

Vision systems, specifically RGB-Depth cameras and stereo pairs, providing both intensity and depth images, were actively used for robot hand applications throughout the time. Cameras were applied not only for object recognition and position estimation, but for number of various tasks including in-hand object localization and modeling as well as shape, texture and deformation analysis [173]–[176]. Physically these vision systems were installed external to their end-effectors due to the size. This, however, is subject to change [177], [178] due to the developments in various range imaging techniques, which result in more compact depth sensors.

V. CONCLUSION

In this paper, a survey of artificial hand sensors has been provided highlighting the main trends in the area since 2000. The growing emphasis on sensor development between 2010 and 2015 hints that sensors will be one of the major research thrusts in robotic hands. We believe that the challenge of fitting actuation, sensing and computation in highly constrained volumetric envelopes will continue to be the main challenge in the future. In the next decade, we foresee the following trends in artificial hand sensor development:

- Advances in the miniaturization of sensors and electronics will accelerate development of artificial skins for robotic hands with denser spatial resolution and a multitude of sensor modalities.
- The use of artificial hands as end-effectors for social and industrial robots will become widespread. Customizable and stand-alone sensor units will be employed by the robotic hands in order to tailor them for different needs. This will potentially spur the development of common communication protocols and operating systems for artificial hands and various hand sensor units.
- Thanks to the rapid advances in the mobile device technologies, sensors employed in smartphones will be employed by the artificial hands driving costs down and increasing reliability. These sensors include MEMS based inertial sensors in small form factors and also vision based sensors such as RGB and depth cameras. In order to process the data from the vision sensors locally, robotic hands will also employ stronger computational units, presumably also the ones used for advanced mobile devices.

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