NEXT GENERATION TACTILE SENSING FOR HUMAN-ROBOT INTERACTION IN INDUSTRIAL ROBOTICS

A. Sena, K. Kelly

Department of Mechanical and Manufacturing Engineering, Trinity College, University of Dublin, Dublin 2, Ireland

ABSTRACT

Tactile sensing is commonly viewed as one of the basic forms of sensing [24] – intelligent life is rarely found without some capacity for tactile sensing – and it is a fundamental sense in human perception [24, 29]; however it is a sensing modality which few robots currently benefit from. With robotics gradually becoming more dextrous and intelligent, their application areas are expanding from restricted safety enclosures, to being on the production floor next to human co-workers and leading toward increasingly flexible manufacturing, as is already being seen with the recent rise of collaborative robotics in industry. This paper aims to explore how extrinsic tactile sensing can assist in this progress by being a facilitating technology for developing complex Human-Robot Interaction, and the key engineering challenges behind implementing advanced extrinsic tactile sensing.

KEYWORDS: HRI, Tactile, Collaborative

1. INTRODUCTION

Industrial robotics has traditionally consisted solely of robots confined to safety enclosures, in environments which are built to conform to the robot's capabilities. This has imposed several restrictions on the use-cases for robotics in industry, with safety and space restrictions being the key concerns.

Collaborative robots have ushered in a new breed of robotics for industry, where compliant actuation and force/torque sensing in limb joints have enabled these robots to be taken out of safety enclosures and placed next to humans in many applications, so long as appropriate safety assessments are performed.

While collaborative robots represent a significant step forward toward shared human-robot workspaces and tasks, there is still many ways in which these systems can be improved – for example, these systems must implicitly assess whether a collision has occurred by monitoring their joints for unexpected signals, resulting in the possibility of excessive force being delivered to a vulnerable contact surface [4].

Tactile sensing research can be broadly split into two groups – research which focuses on developing tactile technologies via force estimation in control joints, and research which focuses on developing a close analog to human skin. This paper will largely focus on the latter technologies

This method of implicitly assessing contact forces through monitoring of joint states (position, current draw, torque, etc.) is known as *intrinsic* tactile sensing. The type of tactile sensing which this paper focuses on is *extrinsic* tactile sensing, which is the type of tactile sensing associated with touch, where sensors in a person's skin directly detect pressure/heat/pain etc.

Improvements to tactile sensing in collaborative robots could serve to greatly improve their safety and abilities. Using existing sensing technologies, and previous roadmaps which have been laid out for tactile sensing [29] as a projection for future capabilities, improvements to safety could include detection of minute collisions and detecting pinch-risk scenarios. Similarly, improvements to abilities could encompass a wide range of new functionality, from advanced object manipulation for small parts assembly, to social interaction with co-workers for task guidance.

A driving force for much research into tactile sensor development is their application to personal assistant robots in situations where tactile sensing is key to safety or for providing social interaction, such as providing healthcare to the elderly, and providing treatment to Autism Spectrum Disorder patients [24]. While personal assistive robots that can naturally interact with our largely unstructured environments have many obvious potential benefits for society, the driving technologies could, and likely will, also have a major impact on industrial robotic systems.

Although much work has been carried out in tactile sensing research since the 80's, tactile sensing as an incorporated technology to whole robot systems is largely absent, despite the important role it plays in intelligent perception and social interactions, except for a few notable research systems such as the iCub robot and KASPAR [18, 23, 24], as most tactile sensing development has been focused on development of the low-level transduction methods which would facilitate extrinsic tactile sensing.

This paper aims to discuss notable research which is currently underway, and the engineering challenges which must be addressed for next generation tactile sensing, with an emphasis on the need for system-level design. The discussion will continue on to highlight the potential importance of this under-represented sensing modality for robotic systems in industrial systems and applications.

2. TACTILE SENSING IN INDUSTRIAL HRI

Tactile sensing in robots can be split into two main categories – *intrinsic* sensing and *extrinsic* sensing, which are referred to as *kinesthetic* and *cutaneous* sensing respectively in humans [29].

Extrinsic sensing refers to tactile stimulus directly received to a sensor on the robot's surface; whereas intrinsic sensing refers to an internal sensing system which provides the robot with state information on its joints and motors. A third category of sensing is *haptic* sensing, which relates to how intrinsic and extrinsic sensing interacts.

Current collaborative robots deployed in industry are dependent on intrinsic sensing for both determining their body position (as is the case in traditional robotics via encoders), but also for implicitly determining contact forces (either by measuring the current load at the robot's joint motors and modelling the forces, or having dedicated force/torque sensors). This implicit determination of external forces is a key technology in collaborative robotics, which allows them to estimate contact forces for safety (unexpected impacts), as well as the force experienced at tool centre points for functional reasons (e.g. applying a predefined force to a surface, or for hand-guiding the robot's tool for programming by demonstration).

While this has allowed robots to move out of enclosed guarding and into shared workspaces, allowing workers to use robots more like *tools* than dedicated *machines*, implementing extrinsic sensing is a key step in providing new capabilities which help us progress to a state where robots are truly collaborative *co-workers*.

3. EXTRINSIC SENSING IMPLICATIONS

Extrinsic sensing has the potential to impact many aspects in robotic control – object manipulation, robust operation, safety, and human-robot interaction.

3.1 Object Manipulation

As described in [29] an experiment to show the importance of extrinsic sensing involved anesthetizing the skin on hands of a group of volunteers to eliminate the ability to use extrinsic tactile sensing during object manipulation tasks (analogous to even current adaptive grippers), after which it became difficult for them to maintain a stable grasp on objects.

Understanding an object by touch is not simply a matter of sensing pressure by the immediate contact between object and skin, but is a time-dependent action where we build up the understanding of the object's shape as we move our hands across its surface. An ability to have a highly co-ordinated hand-arm system, which could develop an understanding of an object's shape/texture/material properties, by touch alone, would offer robots much greater capabilities for dexterous tasks, such as small parts assembly.

3.2 Robust Operation

While traditional systems are capable of much faster, accurate and high powered work, they are also typically highly dependent on operating in a well defined workspace – if objects which it must interact with are misaligned, damage to the robot, work piece, or working environment can occur – thus requiring a significant amount of time in planning the robot's motion and structuring it's task environment.

While intrinsic sensing has been shown to help move robots toward working in unstructured environments [26], extrinsic sensing would allow for much greater precision through exploration by touch. In addition to assistive exploration by touch, utilizing extrinsic sensing could serve to greatly enhance the visual capabilities of robots through multimodal sensing – an approach already shown to be effective by [30] with basic touch capabilities in a method described as *interactive singulation*, where touch is used to determine individual objects from a messy pile of objects.

3.3 Safety

While intrinsic sensing can determine impact events, a transfer of force is required which may still result in injury. For example, as discussed in [4], the maximum allowable force for an impact force to the neck is just 35N; however some current collaborative robot's safety triggers can only activate at 150N[1]. In addition to this, due to inertia concerns and stopping distances, collaborative robots need limits placed on their speed and acceleration. Extrinsic tactile systems can incorporate impact-absorbing robot skin surfaces to actually assist the operation of the sensor, as well as to offer additional protection from impacts and

---

1http://spectrum.ieee.org/automaton/robotics/industrial-robots/universal-robots-ur3-robotic-arm - Accessed 30/04/2015

potentially allow faster safe operation when combined with responsive extrinsic sensing [31].

3.3   Human Robot Interaction

Current collaborative systems using intrinsic sensing have enabled new forms of HRI, principally in how they are programmed. In these cases, the system is put into a "teach" mode and it monitors the implied forces applied to its body, moving in the direction of the hand-applied force in such a way that the user has the experience of hand-guiding the robot. This is used to greatly reduce the time it takes to program waypoints for the robot, compared to the traditional method of movement via jogging the robot between waypoints using a control pendant or computer.

HRI in simultaneous and supportive actions is still largely unseen, where the robot and human either work on either different tasks on the same work piece or perform the same task on the same work piece, respectively. This is due to a combination of safety and technical issues, for which extrinsic sensing could potentially offer a solution – e.g. current research on tactile robots for the treatment of Autism Spectrum Disorders (ASD) has shown how extrinsic tactile systems [23, 24] can be used to categorize the type of touch being applied to the robot, which in an industrial setting could facilitate natural ways in which not just programmers, but operators, can interact with these systems.

4.   SENSOR DEVELOPMENTS

Below we have detailed some of the relevant extrinsic tactile sensing developments, which should provide a snapshot of the work currently underway which may soon have an impact on industrial robotics.

Sensor developments for tactile sensing can be considered under 3 main headings, tactile transduction which discusses the actual sensor technology for converting the real-world stimulus to digital information, touch surfaces which discusses how the tactile transduction is deployed to a full system, and tactile data processing which considers how the data produced by the touch surfaces can be processed to guide action decisions without significant latency.

4.1   Tactile Transduction

Tactile transduction is the process of converting a real-world tactile stimulus (pressure/temperature/etc.) to a signal which can be used by the robot's control system.

As mentioned, intrinsic tactile sensing will typically either have force sensors, torque sensors or current sensors at the robot's joints and motors to infer external forces as well as the robot's current position state.

Extrinsic tactile sensing is comparable to intrinsic sensing in the approaches which can be taken for transduction, in that both can be split into 3 general categories of sensing methods: *Electrical* sensing (voltage/current/strain/etc.), *Electromagnetic* sensing (Inductive sensing – Faraday's law.), or *Optical* sensing.

Though both tactile sensing types share similar transduction methods, the primary difference concerns the difficulty of *coverage* for extrinsic sensing compared to intrinsic. In intrinsic sensing, we are just concerned with the joints and motor positions/forces, so for a 6-axis robot we will typically have 6 points of measurement of encoders and force. In extrinsic sensing, we now have the challenge of taking measurements from a continuous surface, resulting in various

infrastructural challenges such as how to minimize wiring or how to make the transduction conform to a robot's surface while being deformable in contact with objects.

Electrical sensing based tactile sensors have been developed at both macro and micro scales; taking the form of voltage-based, current-based or resistance-based measurements.

In [7], hexagonal PCB sensing units embedded in rubber are presented ("HEX-o-SKIN"), which can connect together to form a surface capable of detecting lateral and shear forces, acceleration, proximity, and temperature. These units are developed using standard technologies, and are designed to have redundant interconnects between neighbouring cells where up to 6 connections per hexagon can fail while maintaining operation. This approach builds on the previous similar work in [33], in the use of interlocking geometric shapes, utilizing standard components to provide tactile sensing over large surfaces.

In [10], standard MEMS barometer sensors, as used in mobile devices and based on resistive sensing, are adapted for tactile sensing through the use of a compliant elastomer surface to transfer the applied forces to a pressure in the gel material which can be measured by the sensor. This approach allows rigid-based sensor units to analyse continuous curved surfaces. This system has been tested up to 50Hz and provides a good dynamic range of sensing.

While PCB based approaches allow the developer to use standard technologies to reduce the cost of implementation, their rigid structure results in restrictions in how they can be deployed. The use of flexible PCB surfaces can help in these restrictions; however this introduces concerns over durability for surfaces which may be regularly under shear stresses.

Approaches being explored to facilitate touch in more complex geometries which require finer resolution touch capabilities (primarily in hands and fingers), include shape deposition manufacturing (SDM) methods as featured in [6], where researchers have developed an anthropomorphic robotic hand with tactile sensels (small 4x4 grids of force sensors) embedded in the finger joints and palm. SDM involves embedding sensors in the structure you are producing mid-way through manufacturing such that the sensor forms an embedded layer within the structure. In this example where an anthropomorphic bone structure was used for the robotic hand's frame, this arrangement resulted in the sensor representing a sub-dermal insert between the robotic skin surface and the internal "bone" frame.

Similar work to the previous paper is featured in [32], but with electromagnetic sensing in the form of Hall Effect sensors. Again, sensors are embedded in robotic finger tips for the provision of fine-touch sensing; however through the use of electromagnetic sensing, the researchers are able to place an air-gap between the sensor and a small magnet embedded in the fingertip's skin. This small air gap serves to increase sensitivity of the fingertip, as the movement of the magnet in the fingertip is not limited to the deformation of the material it is embedded in, but of the fingertip skin structure, similar to how the structure of a bridge will flex under load considerably more so than the steel it is made from, but issues might arise in a situation where the system must handle magnetic objects. Additionally, similar to the previous paper, by separating the contact surface from the sensor, this conceivable would make the sensing system easier to

service – worn fingertips could be replaced without modification to the sensor itself.

Additional work exploring fine touch for fingers includes [11], where researchers developed flexible capacitive sensors which can withstand high pressures (250kPa) and high strains (15%), while also sensing light touches (5kPa, equivalent to pressure required for typing). This research is discussed further later in relation to their interesting use of touch for feature abstraction during tactile interaction.

Approaches being explored to facilitate touch over general geometries which require coarse resolution touch capabilities (general robot surfaces), which can adapt to curves and joints include the work in [12]. Here the researchers have developed an electrical impedance tomography (EIT) system for the purpose of tactile sensing, a similar technology as is used for X-ray computed tomographic (CT) reconstruction. In CT scans, penetrating x-rays are passed through the subject from multiple directions and analysed to identify anomalies in the ray's path (indicating the presence of some form of obstruction or void to the x-ray). By performing this analysis in multiple directions, the anomaly can be localised within the subject.

In EIT systems, there is a network of sensors placed around a conductive plane, and the distribution of conductance across the plane's surface can be estimated from the measurement at each node. By having a surface which varies in conductance when pressure is applied, the pressure points can be localized and characterized by the network of sensors – i.e. the location of the pressure point as well as the magnitude can be estimated. This system allows relatively large areas to be monitored by relatively few sensors, with their accuracy depending on how well the variation of conductivity across the surface can be modelled. This also allows the tactile surface to be placed over arbitrary geometries, with the example in this paper being over a mannequin's face.

Power consumption would be of concern with EIT systems, as they require an active current source; however bandwidths of 45Hz or more are reportedly possible.

Finally for electrical based measurements, there is much current work in the development of printable tactile surfaces, which can be adapted to arbitrary surfaces. [8, 13, 34-36]. These printed flexible sensing systems would serve to provide low-cost, low-weight, high-resolution and high-coverage sensing to robotic systems. The printing method employed in these projects ranges from inkjet printed systems [8], to screen-printed systems [34-36].

The alternative to electrical/electromagnetic based measurements is the use of optical sensing. Optical sensing in general has the advantages of being immune to electromagnetic interference (as the sensor signals are carried via light rather than electricity), the ability to bundle a great deal of cables into a small form factor, due to the size of optical fibers, and depending on the type of optical sensing you are able to string multiple sensors onto a single optical fiber – e.g. Fiber-Bragg Grating (FBG) systems.

Optical sensing can take many forms, from using the fiber optic system as miniature camera lenses dispersed across the surface being monitored to directly observe how the surface is being deformed [37], to systems which closely resemble their electrical sensing counterparts in their measurement of strain for

the purpose of tactile sensing except through the use of optical technologies such as FBG systems [38].

A disadvantage with optical sensing systems in general compared to their electrical sensing systems would be the size of the data acquisition system required, e.g. in the case of FBG systems optical interrogators are required which are currently larger than systems which can be made for measuring voltage/current/etc., and the cost per sensor. Additionally, fiber optic cables will typically have limitations on how much they can bend before signal degradation will occur, leading to potential issues in robotics.

4.2   Touch Surfaces

Research into the actual skin-layer of a tactile system varies from its use as a functional layer where it might act as a safety barrier to help protect the user as seen in [31], help with sensor durability as seen in [7], or provide functional improvements, to being an integral aspect of the transduction as already discussed in [10].

Regarding functional improvements, this has been explored in [14] where the researchers attempted to develop a bio-mimetic surface which provides a directional gripping force through the use of micro suction cups.

A further functional aspect to the touch surfaces for a tactile system is the social aspect of touch which this layer can impact on. Research conducted in [15] demonstrated how in human-robot-interactions minor social cues such as hand holding, and the physical temperature of the touch surface played important roles in producing interactions which resulted in comfortable interactions with "emotional warmth". It was also noted however that finding the optimal design for robotic touch that matched human expectations was key to avoiding issues with the uncanny valley problem.

Another aspect of touch surfaces, as previously mentioned in discussion of the hexagonal sensing cells in [7], rigid sensing units (as also featured in) results in loss of coverage over curved surfaces. With robots designed for interaction (collaborative robots, etc.), curved surfaces feature heavily in their design, leading to limitations in how rigid bodied sensing units can be applied, despite their advantage in being able to use standard sensing technologies and off-the-shelf sensors. Progress is being made on this issue with recent advancements in printed flexible tactile sensors, as previously discussed [8, 13, 34-36], and with large-scale flexible sensing such as EIT as discussed in [12] previously.

4.3   Tactile Data Processing

Tactile data processing can be considered from two levels, the data acquisition stage involved with actually managing the low level acquired data, and the data processing stage where the low level data is analysed to provide meaningful information upon which decisions can be made (i.e. detecting a collision and deciding to stop moving, or detecting a shoulder-tap and recognizing this as someone attempting to get the robot's attention).

In acquisition of low level data, consideration for how the bandwidth requirements for the overall system it of key importance, as this will be a key factor in determining the limits to the surface area coverage of the system and the latency in its response. The sensing system presented in [7] operates via local 4-wire communication between the unit hexagonal cells, and gigabit Ethernet UDP

to the processing computer. The researchers have described the theoretical bandwidth upper limit being reached at 1200 unit cells; however this requires the use of a custom FPGA board to assimilate the sensor's values into UDP packets in real-time, indicating the demanding nature of low level data processing. While this number of sensors is adequate for large-scale coverage, fine touch sensing could potentially require more, as described in [27] where over 30,000 sensors equates to an area of $1m^2$.

An aspect to this to consider with geometrically tiled units, whether soft or rigid, is the optimization of their layout to the robot's surface. This has been explored in [25] through the use of Ant Colony Optimization (ACO) methods, a bio-inspired form of optimization which has been applied to problems such as the famous travelling salesman, and one of many approaches to skin layout optimization.

With the large network nature of tactile sensing, infrastructural challenges such as wire routing begin to present an issue. Miniaturization, such as in the printed tactile sensors, and interconnected systems such as in [7] are some approaches to this issue; however [20] explores the use of detachable wireless sensing pads which can be attached to a robot as required. This reduces the wiring requirement and increases ease of deployment; however increases the systems power usage, adds complexity in calibration for tasks beyond collision detection and introduces variability in the form of the wireless link.

Given the low latency requirement in tactile sensing, for both safety and functional reasons, there is a requirement for rapid processing of the continuous stream of data from a tactile system. Based on this requirement, it is therefore necessary to rely on on-board processing of the tactile data, free from the network limitations of off-board processing which introduce determinism issues. While hard real-time is not a requirement for tactile systems, collision forces can reach their maximum magnitude within 40ms [39], so it is beneficial to react well within this time frame (>>25Hz). Attempts at making this sensor data more available to the higher level processes include the middleware software development, Skinware, in [27]; however as of yet there is no definitive solution to bridging the high and low level data.

It is often not enough to simply capture pressure data from the sensors network, but also location and orientation of the applied force relative to the robot's surface. For a full body tactile system this becomes a non-trivial calibration and analysis task. Research in [28] explores this challenge through a novel method by which the robot self-identifies its tactile network through self-touch, where the humanoid robot touches its own arms while observing them and can calibrate the tactile sensor activated with the perceived touch locations. Calibration is further explored in [21] where the researchers attempt to develop an artificial somatosensory map to allow the robot to localize touch on its surface without explicitly telling the robot where each sensor is placed exactly.

Further adding to the complexity of data processing in tactile systems is the many ways in which tactile sensing can be applied, from basic collision detection to advanced social cue recognition. While touch classification has many social applications, it is also relevant to a manufacturing environment where a human worker needs to interact with a collaborative robot; where tactile cues may be more reliable for the environment, e.g. as opposed vocal cues in noisy environments, or interface pendants which may require additional training and be

less intuitive. An example of this could include tapping the robot to indicate the worker is ready for the robot to pass over the work in progress it is holding. Examples of this concept of interaction classification can be found in [23, 24].

A final example (keeping in mind this an inexhaustive list) of data processing is the use of touch for exploration of unknown environments. This has been used in current intrinsic sensing systems to allow useful tasks such as fitting screws where the target hole may be slightly misaligned; however extrinsic sensing would allow a fuller exploration of an unknown environment. In [26] this is demonstrated by a robot exploring its environment by touch, and building up a representation based on the tactile information it acquires. In a manufacturing context, this could equate to a robot feeling in a mixed bin of parts for the correct component, rather than purely relying on its visual system, for example.

5. CONCLUSIONS

Extrinsic tactile sensing has many potential applications in industry, potentially offering additional functionality and safety, in new application areas; however there still remains several engineering challenges to implementing a fully tactile system.

Key challenges identified in this review (albeit inexhaustive) can be summarized along the issues of transduction, sensor placement/ surface coverage, data communication, sensor network calibration, and data conversion (translation of the low level data to high level actionable information).

As extrinsic sensing technologies become more developed, it is expected these sensing systems will become more commonly deployed in full robotic systems, opening the door to a step-change in human-robot interaction possibilities.

6. REFERENCES

[1] M. Fritzsche, N. Elkmann, E. Schulenburg, Tactile sensing: A key technology for safe physical human robot interaction, *Human-Robot Interaction (HRI), 6th ACM/IEEE* , (2011), 139-140

[2] Zanchettin, N. Ceriani, P. Rocco et al., Safety in Human-Robot Collaborative Manufacturing Environments: Metrics and Control, *IEEE Transactions on Automation Science and Engineering*, (2015), 1-12

[3] H. Ding, M. Schipper, B. Matthias, Optimized Task Distribution for Industrial Assembly in Mixed Human-Robot Environments – Case Study on IO Module Assembly, *2014 IEEE International Conference on Automation Science and Engineering (CASE)*, (2014), 19-24

[4] J. Marvel, J. Falco, I. Marstio, Characterizing Task-Based Human–Robot Collaboration Safety in Manufacturing, *IEEE Transactions on Systems, Man, and Cybernetics: Systems,* (2015), 260-275

[5] M. Cheng, C. Tsao, Y. Yang, An Anthropomorphic Robotic Skin Using Highly Twistable Tactile Sensing Array, *5th IEEE Conference on Industrial Electronics and Applications,* (2010), 650-655

[6] Z. Xu, B. Dellon, Y. Matsuoka, Design of artificial skin with integrated tactile sensors for anthropomorphic robotic hands, *IEEE International Conference on Robotics and Biomimetics*, (2011), 2919-2924

[7] P. Mittendorfer, G. Cheng, Uniform Cellular Design of Artificial Robotic Skin, *Proceedings of ROBOTIK 7th,* (2012), 1-5

[8] P. Cosseddu, L. Basirico, A. Loi, Inkjet Printed Organic Thin Film Transistors based tactile transducers for artificial robotic skin, et. al, *4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob),* (2012), 1907-1912

[9] A. Cirillo, P. Cirillo, S. Pirozzi, A modular and low-cost artificial skin for robotic applications, *4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, (2012), 961-966

[10] Y. Tenzer, L. Jentoft, R. Howe, The Feel of MEMS Barometers: Inexpensive and Easily Customized Tactile Array Sensors, *IEEE Robotics & Automation Magazine,* (2014), 89-95

[11] A. Gerratt, N. Sommer, S. Lacour et al., Stretchable capacitive tactile skin on humanoid robot fingers — First experiments and results, *IEEE-RAS International Conference on Humanoid Robots,* (2014), 238-245

[12] D. Silvera-Tawil, D. Rye, M. Soleimani et al., Electrical Impedance Tomography for Artificial Sensitive Robotic Skin: A Review, *IEEE Sensors Journal*, Vol.15 (2015), 2001-2016

[13] B. Nabar, Z. Celik-Butler, D. Butler, Self-Powered Tactile Pressure Sensors Using Ordered Crystalline ZnO Nanorods on Flexible Substrates Toward Robotic Skin and Garments, *IEEE Sensors Journal*, Vol.15 (2015), 63-70

[14] R. Manabe, K. Suzumori, S. Wakimoto, A functional adhesive robot skin with integrated micro rubber suction cups, *IEEE International Conference on Robotics and Automation*, (2012), 904-909

[15] Nie, M. Park, A. Marin et al., Can you hold my hand? Physical warmth in human-robot interaction, *7th ACM/IEEE*, (2012), 201-202

[16] K. Chathuranga, V. Ho, S. Hirai, A bio-mimetic fingertip that detects force and vibration modalities and its application to surface identification, *IEEE International Conference on Robotics and Biomimetics (ROBIO)*, (2012), 575-581

[17] K. Nakajima, Y. Itoh, Y. Hayashi et al., Emoballoon: A balloon-shaped interface recognizing social touch interactions, *IEEE Virtual Reality (VR)*, (2013), 1-4

[18] D. Anghinolfi, G. Cannata, F. Mastrogiovanni et al., On the Problem of the Automated Design of Large-Scale Robot Skin, *IEEE Transactions on Automation Science and Engineering*, Vol.10 (2013), 1087-1100

[19] D. Chathuranga, W. Zhongkui, S. Hirai, Challenges in developing soft tactile sensors for robots that detect incipient slip, *Information and Automation for Sustainability*, (2014), 1-7

[20] A. Lee, D. Kim, Detachable tactile sensor skin module for robotic applications, *10th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*, (2013), 287-288

[21] G. Cannata, S. Denei, F. Mastrogiovanni, A Framework for Representing Interaction Tasks based on Tactile Data, *19th International Symposium in Robot and Human Interactive Communication*, (2010), 698-703

[22] M. Johnsson, C. Balkenius, Sense of Touch in Robots With Self-Organizing Maps, *IEEE Transactions on Robotics*, Vol.27 (2011), 498-507

[23] Z. Ji, F. Amirabdollahian, D. Polani et al., Histogram based classification of tactile patterns on periodically distributed skin sensors for a humanoid robot, *RO-MAN*, (2011), 433-440

[24] F. Amirabdollahian, B. Robins, K. Dautenhahn et al., Investigating tactile event recognition in child-robot interaction for use in autism therapy, *Annual International*

Conference of the IEEE Engineering in Medicine and Biology Society, (2011), 5347-51

[25] C. Nattero, M. Paolucci, D. Anghinolfi et al., Experimental analysis of different pheromone structures in an Ant Colony Optimization algorithm in robotic skin design, *Computer Science and Information Systems (FedCSIS)*, (2012), 431-438

[26] U. Martinez-Hernandez, T. Dodd, L. Natale et al., Active contour following to explore object shape with robot touch, *World Haptics Conference (WHC),* (2013), 341-346

[27] S. Youssefi, S. Denei, F. Mastrogiovanni et al., Skinware: A real-time middleware for acquisition of tactile data from large scale robotic skins, *IEEE International Conference on Robotics and Automation (ICRA)*, (2014), 6421-6426

[28] A. Roncone, M. Hoffmann, U. Pattacini et al., Automatic kinematic chain calibration using artificial skin: Self-touch in the iCub humanoid robot, *IEEE International Conference on Robotics and Automation (ICRA)*, (2014), 2305-2312

[29] R. Dahiya, G. Metta, M. Valle et al., Tactile Sensing – From Humans to Humanoids, *IEEE Transactions on Robotics*, Vol.26 (2010), 1-20

[30] L. Chang, J. Smith, D. Fox, Interactive Singulation of Objects from a Pile, *IEEE International Conference on Robotics and Automation,* (2012), 3875-3882

[31] M. Fritzsche, N. Elkmann, E. Schulenburg, Tactile Sensing: A key technology for safe physical human robot interaction, *6th ACM/IEEE I,* (2011), 139-140

[32] L. Jamone, L. Natale, G. Metta, et al., Highly Sensitive Soft Tactile Sensors for an Anthropomorphic Robotic Hand, *IEEE Sensors Journal, Vol. 15 No. 8,* (2015), 4226-4233

[33] G. Cannata, M. Maggiali, G. Metta, et al., An Embedded Artificial Skin for Humanoid Robots, *IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems*, (2008), 434-438

[34] S. Khan, W. Dang, L. Lorenzelli, et al., Printing of High Concentration Nanocomposites (MWNTs/PDMS) Using 3D-Printed Shadow Masks, *XVIII AISEM Annual Conference,* (2015)

[35] S. Khan, S. Tinku, L. Lorenzelli, et al., Flexible Tactile Sensors Using Screen-Printed P(VDF-TrFE) and MWCNT/PDMS Composites, *IEEE Sensors Journal, Vol. 15 No. 5,* (2015), 3146-3155

[36] S. Khan, L. Lorenzelli, R. Dahiya, Screen Printed Flexible Pressure Sensors Skin, *Advanced Semiconductor Manufacturing Conference*, (2014), 219-224

[37] Y. Yamaha, M. Fukunaga, M. Fujimoto, et al., Soft viscoelastic robot skin capable of accurately sensing contact location of object, *Multisensor Fusion and Integration for Intelligent Systems,* (1999), 105-110

[38] Y. Park, K. Chau, R. Black, et al., Force Sensing Robot Fingers using Embedded Fiber Bragg Grating Sensors and Shape Deposition Manufacturing, *IEEE International Conference on Robotics and Automation,* (2007), 1510-1516

[39] Y. Kishi, Y. Yamada, K. Yokoyama, The Role of Joint Stiffness Enhancing Collision Reaction Performance of Collaborative Robot Manipulators, *IEEE International Conference on Intelligent Robots and Systems*, (2012), 376-381