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SURVEY

A Non-Contact Manipulation for Robotic Applications: A Review on Acoustic Levitation

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ABSTRACT Robots play an important role all over the world in the industrial field in terms of handling various materials and performing duties quickly with high accuracy. Product handlings in the pharmaceutical/chemical field are carried out by robots without contamination due to its specific superiority as compared to human. Robotic manipulation is the term used to describe how robots deal with many objects. This article reviews the contact and non-contact manipulation with their most common robotic applications and focusing on the non-contact manipulation since it can do specific tasks which contact manipulation cannot do. Reviewing of the robotic non-contact manipulation which include the metal-based robotic manipulation such as magnetic and electrostatic levitation and the non-metal-based robotic manipulation method such as aerodynamic and acoustic levitation have been made in this article. The main core of this article is acoustic levitation which considered one of the most important levitation and manipulation method due to the recent advancements that made it proper to deal with any kind of materials. Here, we review the renowned three methods of acoustic levitation that already using in robotic non-contact manipulation which are standing wave, near-field and single-beam acoustic levitation. Then, we present a performance characteristic of the reviewed methods and the summary of controlling strategies, followed by conclusion and future recommendations for acoustic levitation methods as a non-contact manipulation.

INDEX TERMS Robotic manipulation, acoustic levitation, non-contact manipulation.

I. INTRODUCTION

In context of the Fourth Industrial Revolution, robotics are employed to raise productivity, manufacture goods of superior quality at competitive prices, and fulfil client expectations. As shown in Fig. 1, handling or manipulation is ranked the topmost robotic application installed in industry. Robotic handling plays a milestone role in industrial field in terms of handling products used in automotive industry [1], textile industry [2] and aerospace manufacturing industry [3]. The handling is often repetitive and arduously prolonged for an extended period deemed unsuitable for a human worker. Roboticized operations can guarantee accuracy for a long period without exhaustion. Certain operation which demands complex cognitive decision may still require human presence in the loop of the handling control system and so, the concept of Collaborative robot or cobot by which human and robot co-exist in the operational safe working space is introduced [4].

Robotic handling or manipulation describes how robots deal with the things around them, such as when they grip an object, open a door, pack an order, or fold laundry. These tasks require manipulation motion of robots to be planned, managed and controlled in order to fulfil the handling objective. Robotic manipulators grip and move things in their environments by applying contact forces. Contact manipulation allow fixtures to hold work pieces in place. In some applications, objects need to be handled without making the direct contact due to some reasons such as delicate, avoiding

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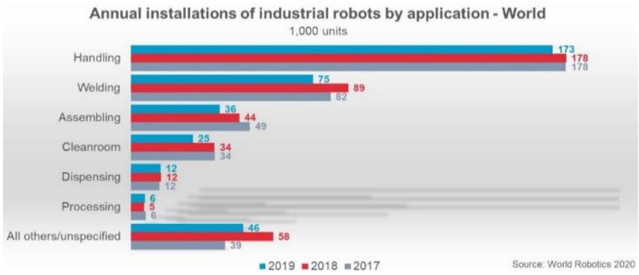

FIGURE 1. **Handling (manipulation) as the main robot application in industry [5].**

contamination, and other physical constraint. Such special application may be motivated by industrial and pharmaceutical needs for instance. We shall give a brief description of a robotic manipulation firstly, on contact manipulation before discussing the non-contact manipulation at a greater detail. Different non-contact manipulation methods are discussed in this study starting with metal-based robotic manipulation like magnetic and electrostatic levitation. After that, the non-metal-based robotic manipulation method covering aerodynamic and acoustic levitation (the focus of the paper) will be reviewed in Section 2. Acoustic levitation methods for the robotic non-contact manipulation with applications and its performance characteristics shall be given in Section 3. Different control strategies for acoustic levitation shall be presented in Section 4. A conclusion and possible future recommendations will be presented in Section 5.

II. ROBOTIC MANIPULATION

Contact and non-contact manipulation are the two basic subcategories of robot manipulation. The bulk of the reviews will be mainly focusing on non-contact manipulation. Fig. 2 shows categorization manipulation by manipulation types.

A. CONTACT MANIPULATION

Contact manipulation [6] means a direct interact between the robot arm or gripper and the object itself to be manipulated.

Fig. 3 shows the robotic hand in a contact manipulation mode where an object is carefully gripped. Manipulation in contact is regarded as tasks where explicit or implicit control of interaction forces is required. Tasks such as polishing [7], [8], [9], [10] could be done with implicit control of the forces whilst tasks such as peg-in-hole [11], work piece alignment and articulated motion can be performed without any control of the forces under perfect knowledge. Contact manipulation can be categorized into mainly three types: environment shaping, work piece alignment and articulated motion [12]. Environment shaping comprises of wiping [13], polishing and engraving [14]. Workpiece alignment includes tasks found in industry assembly of which task such as peg-in-hole can be improved by means of compliance. Articulated motion involves opening task such as jar [15] and valve turnings [16], [17]. Table 1 shows the review summary of common application carried out by contact manipulation.

TABLE 1. **Common applications of contact manipulation.**

Contact Manipulation	Surveys
Grasping	[18], [19]
Grinding	[20], [21], [22]
Scooping	[23]

A comprehensive look by [12] describing the types of in-contact duties that have been carried out by robots, demonstrating how to operate robots during these duties, then outlining the models used to encode these tasks, and finally outlining techniques for properly utilizing the representations. The main and first important requirements for a robot to present functions in contact manipulation is to choose a proper controller. The controller must be chosen between implicit or explicit control of the forces. In the implicit control of contact manipulation, forces are referred to as compliance. In order to establish this compliance feature by virtue of a software, impedance control is adopted [24]. Deviation from desired trajectory is allowed which means in-contact motions without switching the controller and free space as well. In the explicit control when a desirable level of force is set, a traditional controller force is a popular choice such as PI controller with a high frequency update to keep the applied force by the robot at its demanded level [25].

In the contact manipulation, a robot can do its tasks successfully for example gripping an object, transferring the gripped object from one place to another in the working environment but sometimes it may face a problematic challenges such as releasing the gripped object correctly into the desired place due to the sticky force between the gripped object and the ends of the gripper itself [26]. Not all objects have regular surface morphology and adequate friction which permits sure grip of the object without slippage. In context of decontamination, some objects may need to be handled or manipulated without physical contact to prevent contamination. Certain objects which are extremely delicate, may need to be handled without least or non-contact at all. This kind of issues which appears when applying contact manipulation can be resolved by finding a special kind of material. However, the solution incurs cost on the fabrication as well as time. However, assuming arguably that this problem can be easily fixed, the following problem cannot be solved by contact manipulation due to the nature of the materials it serves to be manipulated. For example, contact manipulation can cause damage to micro materials used in electronic industry, living cells in surgical field, small living animals and the most importantly not to forget the possibility of an interaction between the manipulated materials and the ends of the gripper when dealing with a very sensitive chemical material.

In the next subsection we provide an overview of non-contact manipulation with four different methods with special highlighting for the acoustic levitation method.

B. NON-CONTACT MANIPULATION

Non-contact manipulation [27], [28] means the robot interaction with the object without touching it. Non-contact manipulation is considered as the solution to the handling issues aforementioned. When physicists studied this

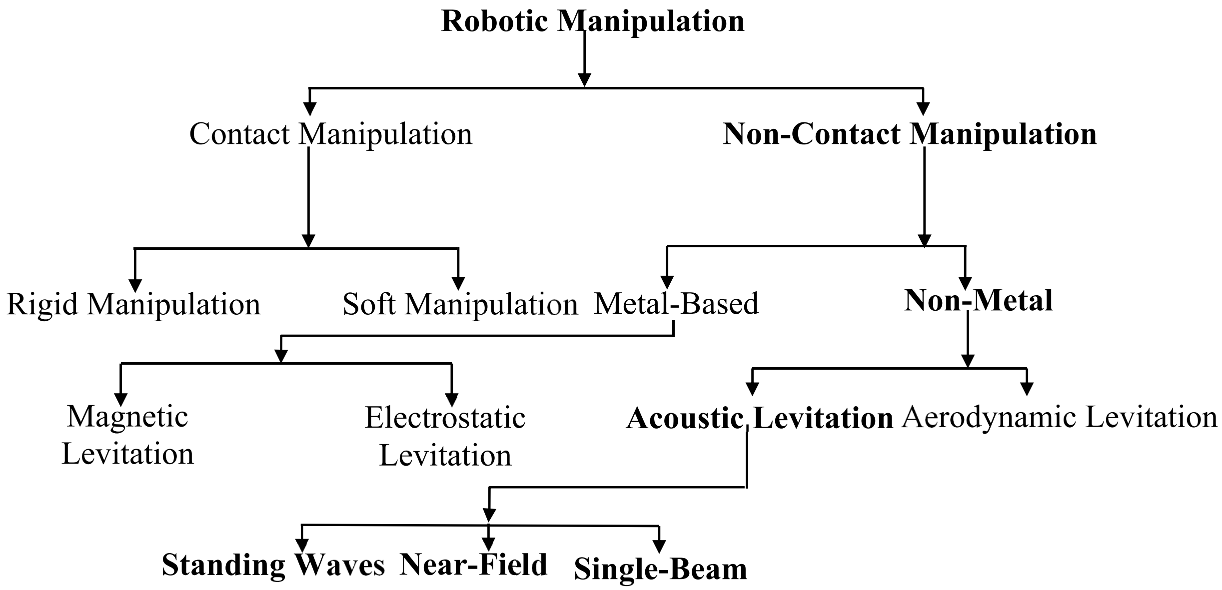

FIGURE 2. Robotic manipulation types.

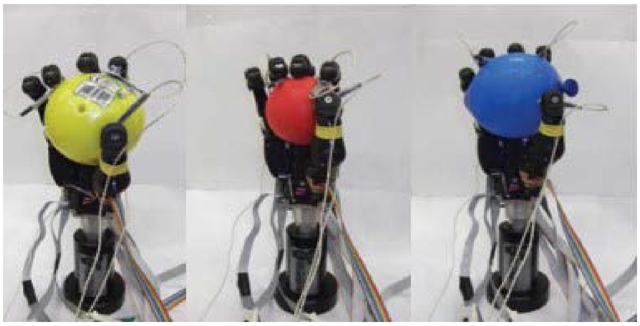

FIGURE 3. Robotic Arm in contact manipulation mode [18].

phenomenon, they noticed the presence of invisible forces that levitate solid and liquid objects. They were able to identify it and work out the method to levitate different types of materials.

The problem faced by the physicists is to maintain the stability when lifting the objects. The challenge is how to ensure that the lifted objects do not deviate from the intended position. There is an interesting physical problem to consider in finding systems that exhibit a stable levitation in a vacuum. According to [29]. Earnshaw demonstrated in 1842 that it is impossible to levitate objects stably in a medium containing attractive or repulsive forces since these forces and distance are directly related to the inverse square law. Main examples of Earnshaw's theory are the forces between electric charges, Monopolar magnets and gravitational masses. Hence, the reader can conclude that the process of levitating magnetic objects or charged objects is absolutely not possible according to Earnshaw's theory, but fortunately this is not true at all. Similarly, stable levitation can be applied to charged objects in a four-pole oscillating electric field. Earnshaw's theorem applies only to individual objects, as analysis of magnetic and dielectric objects consisting of two poles shows that the possibility of levitation to be stable for magnetic and superconducting objects in a static magnetic field [29]. There are other types of levitation used in non-contact manipulation which found in literature as indicates in the following points.

1) MAGNETIC LEVITATION

The magnetic levitation or maglev is a very sophisticated technology, which has diverse usage. The non-contact feature and thus no friction is the most popular point in all of its applications, and this leads to increasing efficiency, reducing charges of maintenance and increasing the beneficial life of the system. The diagram of magnetic levitation system is shown in Fig. 4. Maglev can be used as an efficacious technology in different industry fields. The work principle of maglev is to make an object suspended in the air without any type of assistance but only by magnetic fields. These magnetic fields are capable of counteract or reverse the counter accelerations and the force of gravity in order to keep the object in the desire levitation level. Maglev is well known for over a century, but despite the fact that maglev trains have garnered most of the attention globally, while maglev is not only limited for levitated trains. The decoupling controller which includes two parts, the master decoupling part which is used to counteracts the major linear interactions between the actuators and the slave intelligent nonlinear compensation part which used to inhibit the nonlinear interactions of each channel, then the stability of the maglev system will be ensured according to such a controller and also removing most of the interactions between ip/op channel [30]. A maglev system introduced in [31] used the Neural Network (NN) to approximate the electromagnetic parameters. The developed NN controller was compared with two stage controllers (Two stage controller is a combination of NN and SMC) for tracking trajectory of the maglev system. It was found that the (NN controller) improved the (Two stage controllers) because the signal of

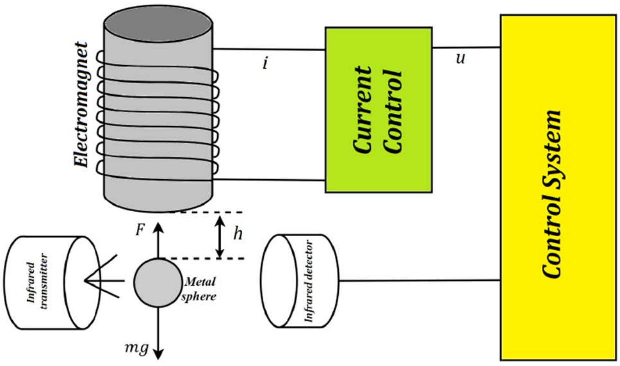

FIGURE 4. Diagram of a magnetic levitation system [39].

the first one followed the reference signal better than the second and the root mean squared of the first one is very small compared to the second controller [31].

According to [32], a PID-based controller outperforms the PD controller because the steady state error was lowered to zero when two feedback control systems (PID & PD) were used to levitate a magnet disc utilizing the lower magnet of the Maglev according to however the PID control system need to exert more control effort during the initial two seconds of operation. In terms of robustness handling of noises and uncertainties, the integrated PID and adaptive sliding-mode controller are employed in a number of experimental findings [33]. The performed maglev system with three types of controller which are (Linear–quadratic regulator) LQR, PID and Lead compensation, then controller's types have been compared in term of three parameters which are peak overshoot, rise time and settling time, the results showed that LQR controller showed higher stability and response in comparison with classical controller types used for all the system parameters utilized [34]. The design of an adaptive sliding mode control law based on (Radial Basis Function) RBF neural network minimum parameter learning method (RBF MPL-ASMC) for maglev train, the RBF neural network with minimum parameter learning method is applied to the sliding mode control of maglev system in order to solve the problems of slower response speed, a large overshoot, and chattering, which reduces stability and robustness when the parameters of the maglev system change [35].

In order to address disturbances, nonlinear uncertainty, and mismatched uncertainties in the system, an adaptive neural-fuzzy sliding mode controller (ANFSMC) using a sliding surface, an adaptive-fuzzy estimator, and a neural-fuzzy switching rule is proposed. The proposed nonlinear robust controller has a non-overshooting, robust, fast dynamic response and can effectively weaken chattering while addressing the issues of unmatched disturbance and parameter perturbations with fast regulating speed, which satisfies the control quality requirement of the low-speed maglev train which is in contrast to the linear PID and SMC controllers [36]. A comparison of all other nonlinear controllers demonstrates that the ST-SMC provides the overall best dynamic response with barely any chattering and is robustness against external disturbances in controlling Maglev systems. The presented super twisting SMC not only eliminates chattering but also is robust against external disturbances to the plant. [37]. The radial basis function (RBF) network was utilized in the modification of parameters in the controller to increase the control performance because the PID control method with fixed parameters may have pauper control effect owing to external interference and changes of internal parameters [38], so the RBF-PID technique has a better control effect in dealing with external interference and internal parameter altering in the maglev system, and the combination of the RBF network and the PID control can handle the control problem of the non-linear system more effectively. A new robust control technique that tracked the trajectory of an uncertain maglev system with high accuracy, fixed-time convergence, and robust stabilization [39].

A functional link artificial neural network (FLANN-TLBO) model which improves the detection and running of the Maglev system through teaching-learning-based optimization proposed by [40], the outcomes show that the actual system and the detected model have better response matching. Furthermore, the statistical experiments confirm the FLANN-TLBO network's superiority to other networks. Three nonlinear controllers are provided by [41], to control a maglev system, the first one is adaptive terminal sliding mode (AT-SMC), the second one is adaptive integral back stepping sliding mode (AIBS-SMC) and the third one is adaptive back stepping sliding mode (ABS-SMC), then the results shows that for both the overall dynamical response and transient reaction the AT-SMC controller gave the best performance compared with the other two controllers. A prototype micro robot that can be remotely controlled with three degrees of freedom in an enclosed space by sending magnetic energy and optical signals from the outside is presented in a quite recent study in [42] that uses magnetic levitation. This micro robot can lift and manipulate particles up to 1.5 g in mass. The most popular applications of a magnetic levitation in non-contact manipulation in handling [43], biomedical [44], [45], [46], disease diagnostic in [47] and [48], environmental management in [49] and [50], and single-cell studies in [51] and [52].

2) ELECTROSTATIC LEVITATION

In order to lift a small, charged object and resist the effects of gravity, a mechanism named as electrostatic levitation is being used. For about quarter of a century since the first electrostatic levitator was found by [53], electrostatic levitation has been utilized to study bulk high temperature materials. Fig. 5 shows the block diagram of the electrostatic levitator.

Electrostatic levitation is non-contact technique which can be used in the analysis of high temperature and/or undercooled materials because it is carried out in a vacuum or high-pressure gas [54]. One of the applications of electrostatic levitation method is to control the Micro-Electro-Mechanical system (MEMS) switches as provided by [55].

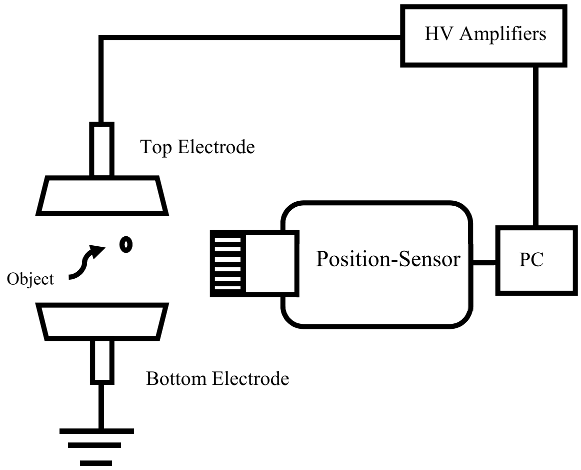

FIGURE 5. A Block diagram of electrostatic levitator.

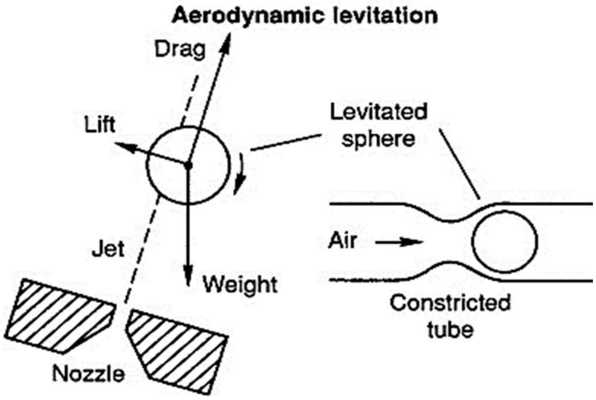

FIGURE 6. Aerodynamic levitation of a spherical object [29].

Metals, ceramics, glasses, and semiconductors have all been subjected to electrostatic levitation from room temperature to more than 3800 k. The advancement of electrostatic levitators helped in using on beamlines, such as synchrotron sources as well as used in the investigation of nucleation and glass formation [56]. A very recent study of three-dimensional droplet manipulation via electrostatic levitation in [57], demonstrated that through the adjusting the local electrostatic force acting on the droplets in carrier oil between needle plate electrodes, one may regulate the vertical motion of the droplets, including droplet levitation at the carrier oil and air interface.

3) AERODYNAMIC LEVITATION

Gas pressure is employed to lift objects, so that they are not in direct contact with any container through the process of aerodynamic levitation. Fig. 6 shows the aerodynamic levitation of a spherical object.

This eliminates pollution and nucleation issues in scientific studies that arise from direct contact with a container. When nucleation and growth may easily take place at a container interface, the aerodynamic levitation approach permits the production of novel glasses, amorphous phases, and metastable crystalline forms that are not readily accessible. aerodynamic levitation is frequently used to study semiconductors, metal oxides, metals, and alloys [58]. The aerodynamic levitation elements' compact size makes it possible for them to be linked with a broad range of non-contact diagnostic techniques. aerodynamic levitation needs a gaseous atmosphere; therefore, process gases can be used to change a sample's chemistry in real time [59]. A planar manipulator for flexible and contactless handling based on the aerodynamic levitation concept was described and tested in [60]. For various types of objects, a model of the system has been created, and the parameters have been determined. for one degrees of freedom position control and tracking, an effective controller has been tuned.

4) ACOUSTIC LEVITATION

For decades, scholars have explored technology which can be utilized to challenge gravity force. thanks to studies that began years ago, the pressure generated by sonic waves can nowadays give a path to levitate objects and to keep them in stable mode against gravity force. although the concept of acoustic levitation emerged in the 1930s, the technology of standing waves had been investigated long before then. a sound field will have a force affected an object exist in it. august kundt [61] was the first to pay attention to the effect of acoustic levitation during his measurement on the dust particles motion in a resonant tube. l. v. king presented a detailed theoretical understanding of acoustic radiation forces with his experiment on a rigid sphere [62]. acoustic levitation is a phenomena/method which is used to suspend objects in air/medium based on sonic radiation from the sound waves in the medium itself. acoustic levitation using sound moving into and out of air in order to balance the gravity force. acoustic levitation which is also called acoustophoresis is a method that uses sound radiation to hanging objects in a medium. the major use of this method is for noncontact processes of objects, allowing the manipulation of all substances, solids, liquids, and even small animals and this method is free of any pollution and contact noise. the most important advantage of acoustic levitation to make it suitable for a wide range of applications is the ability to levitate any material and this is what distinguishes it over other methods like magnetic and electromagnetic levitation which can only be applied to a specific kind of materials like magnetic materials and electrostatic levitation which can only be applied to conductive materials. non-contact processes of objects shows many benefits, like the manufacturing of micro-electronics systems where handling the components is very difficult because of their sensitive and fragile characteristics [63], also in the biological/chemical industry when handling hazardous and high purity materials [64].

Most applications of the acoustic levitation nowadays are in the field of biological/chemical research area which include investigation the fundamental physical features of solids or liquids samples in crystallization and titration experiments, solidification and melting, features of molten materials, equilibrium shape and stability of liquid drops, generation and characterization of organic surface layers at air-water interface, evaporation and raman spectroscopy [65]. The evolution of a robotic gripper (acoustic levitation gripper) can provide non-contact gripping technique serving as an alternative handling method. presently, during the handling in the production, small electronic components are susceptible to damage due to electrostatic discharge or esd and stresses due to surface tension forces (van der wal).

This is the case as reported in [66] when micro grippers are used. if the small electronic components can be handled, manipulated or transported using acoustic levitation technique, some of the aforementioned adverse effects can be avoided in the first place. Acoustic levitation had only one remarkable limitation which is an object can only be levitated through a standing wave when its diameter is half of the wavelength and this limitation is known as rayleigh scattering limit [67]. This will not be considered as a problem if the acoustic levitation gripper priority is to transport tiny and fluffy particles. Objects are levitated at the nodes in a standing wave acoustic pressure field because of the radiation forces which gather at these nodes [68]. the radiation force seems to act like a restoring force (spring) whilst the drag force (due to air) seems like a damper when an object is displaced from a node [67]. The german physicist august kundt tested with the manipulation of sonic waves to initiate nodes and antinodes in the mid of 19th century. Kundt's tube is a requisite/basic model which examines for nodes in standing waves employing a closed glass tube. after that, the american physicist charles rey was privileged with the first successful use of an acoustic levitation. nowadays, scholar's test and use acoustic levitation in technology and medicine. also, acoustic levitation will make a revolution in industry field through packaging and transportation by making it much easier to deal with and handle small, sensitive, fragile objects and corrosive materials. since there are many possible improvements to be made on acoustic levitation, this leads to consider the acoustic levitation as a field of great opportunities that can be achieved. defying the gravity force acting on an object, the object need to be stabilized and all forces need to be balanced in other directions as well.

The concept of ''acoustic levitation'' mentions a special technology/method that using sound waves generated in a special environment to levitate different kinds of objects instead of any other means. This article shows the recent research for the acoustic levitation technology in the last five years up to now, its five different types according to the classification of acoustic levitation methods by [69], fig. 7 Shows the five types of acoustic levitation. Focusing on the relationship of the dynamic behavior and the rheological features in drop dynamics in acoustic levitation and then discussed the possibility of developing a new rheometer based on acoustic levitation [70]. An ultrasonic robotic system was developed by [71] to manipulate small objects via noncontact operation by building up a dynamic acoustic levitation, to detect human gesture a motion sensor (kinect) is also connected and then controlling the manipulation stage. Gain-scheduled controller was created by [72] utilizing a single, second order ordinary differential equation to capture the slow dynamics of a near-field acoustically levitated objects. An object can be acoustically levitated even if this object is larger than the acoustic wavelength itself and this new approach was presented by [73] through creating an acoustic standing wave amid the object and the vibrating plate and this new standing wave can generate a vertical acoustic radiation force which will be able to counteract the gravity and keep the object suspending in air. A review of the theory of acoustic levitation was presented by [69] and showed the various acoustic levitation techniques which have the ability to hang objects in air. A new approach of using an ultrasonic phased array, contactless coalescence and mixing methods for droplets in the air are possible was submitted by [74].

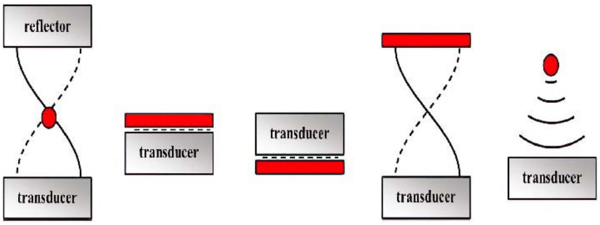

FIGURE 7. **Acoustic levitation methods. From left to right. Standing waves, Near-Field, Inverted Near-Field, Far-Field and single beam [69].**

A new approach based on acoustic levitation which could appropriately levitate and manipulate a micro particle inside a polyimide tube in addition to being able to do so with a micro particle on a culture plate and a mylar film was presented by [75]. A study about some of the recent advances in acoustic levitation provided by [76] which mention a few technical obstacles that need to be overcome in order to improve the ability of present levitation devices to be manipulated. An ultrasonic noncontact manipulator which designed by [77] to add millimeter scale object control to general purpose robots, like the pr2. Also, for the control of an ultrasonic manipulation the acoustic field is changed via manipulating the phases of each transducer output channel by increment, decrement or phase angle set command sent from pc to fpga which decoded the commands and the new phase values of each transducer output channel will be stored in a buffer, this can be controlled manually or via pc program. Using of four counter directed arrays located along the faces of the cube made the operation possible to control levitating particles in three-dimensional space was presented by [78].

A novel ultrasonic array structure based on the fpga was submitted by [79] when the embedded system decreases the complexity and cost of ultrasonic suspension technology equipment and enables container-less operation thanks to the phase control algorithm, which makes it possible for particles to be levitated and travel in both horizontal and vertical directions. A novel near-field acoustic levitation-based non-contact rotating handling technique for disk-shaped objects powered by ultrasonic energy was successfully presented by [80]. Next, acoustic levitation is further discussed in context of non-contact manipulation or handling. In the next section. 3 we present a general view of the acoustic levitation methods for the robotic non-contact manipulation, applications and performance characteristics.

III. ACOUSTIC LEVITATION METHODS FOR NON-CONTACT MANIPULATION APPLICATIONS AND ITS PERFORMANCE CHARACTERISTICS

A non-contact manipulation idea based on acoustic levitation is seen to be the best answer for avoiding the issues of damage, scratching, and contact pollution produced by traditional physical contact operations on high-precision materials or parts [80]. As mentioned earlier that acoustic levitation includes five methods according to [69] but here in this article we shall focus on the methods that have been already used in non-contact manipulation which are:

A. STANDING WAVE METHOD

Standing wave levitation is the most used method for acoustically suspending particles or objects in the space. In this technique, particles suspended in pressure nodes of a standing wave field are much smaller than the acoustic wavelength. An article in German [81] describing the first empirical detection of tiny particles being trapped at standing wave pressure nodes. In this experiment, the resonating rod at one end of a horizontal, transparent tube was used to create an auditory standing wave. A movable stiff piston was employed at the opposite end to change the length. At the pressure nodes, tiny dust particles gathered based on the generated standing wave in the tube. Although, this acoustic levitation experiment was not the first, as we would like to believe because the agglomerated particles continued to be in touch with the tube walls, the experiment did show that a standing wave field exerts an acoustic radiation force on microscopic particles. A standing wave created by a vibrating quartz rod and a reflector were able to hang alcohol droplets in the pressure nodes as reported in [82]. This is credited as the first application of acoustic radiation force for levitation. Since then, numerous standing wave-based acoustic levitation systems [83], [84], [85], [68] have been created. A lead shot and the small coin were levitated by just a high-intensity standing wave field in an experiment which St. Clair [86] described (The levitating coin can be seen in a picture of another article by St. Clair [87]). Just several years later, Allen and Rudnick [88] created an acoustically suspended system for small objects by combining a loud high frequency siren with a reflector.

Many more researchers produced standing wave levitators having comparable features in the ensuing decades. In the 1970s and 1980s, novel standing wave devices were developed in response to the possibility of exploiting acoustic radiation force for the non-contact placement of materials in microgravity [89], [90], [91], several studies being carried out under National Aeronautics and Space Administration (NASA) grants. In order to arrange molten materials in space, Taylor Wang and coworkers [89] developed an acoustic cave in rectangular shape. Three orthogonal speakers working at a detectable frequency aroused the 4 in. × 4.5 in. × 5 in. chamber. The apparatus was able to levitate and rotate a water droplet, soap bubbles and an expanded polystyrene ball, during laboratory experiments. Wang used a comparable acoustic rectangular cave to explore the dynamics of acoustically rotated free drops in a microgravity condition while travelling aboard the Challenger NASA Space Shuttle (mission STS-51B) [92]. The acoustic radiation force was utilized to place drops in the acoustic chamber, and acoustic viscous torques were employed to rotate the drops [93]. The advancement of acoustic locating systems for aerospace implementations has been financed by the European Space Agency (ESA) simultaneously with the research NASA financed in the 1970s and 1980s [94]. The positioning tools which originally founded for space uses, have since been altered to permit the objects levitation in terrestrial conditions. In this procedure, the German researcher Ernst-Güenter Lierke played a key role to lift both solid objects and liquid drops because he sophisticated a vast range of acoustic levitation devices [94], [95], [96], [97]. Commercial acoustic levitators [95] have been produced as a result of Ernst-Güenter Lierke's research on aural levitation and have been used in a variety of tests [98], [99], [100].

In the literature, standing wave levitation are largely divided into two categories. The first kind is referred to as the single axis [68], [84], [85], [86], [87], [95], [101], [102], [103], [104], [105] and it is consists of a reflector and a transducer (or two opposing transducers), where the standing wave field is produced between them. The second type creates a standing wave field in one of the cavity's acoustic modes using a closed resonant chamber [89], [106], [107]. Resonant and non-resonant devices are another way to categorise single-axis acoustic levitators. In the resonant type, one of the resonant modes of the acoustic chamber must be taken into consideration while determining the distance between the transducer and reflector. When the distance between the transducer and the reflector is set to a multiple of a half wavelength, resonances happen specifically in the case of a plane standing wave. Small living creatures [108], [109], soapy bubbles [110], pharmaceuticals [111], solid materials [85], [101], [112], and liquid droplets [98], [113] have all been levitated using resonant single-axis levitators. Resonant levitators provide a number of benefits, including the ability to produce high acoustic pressure amplitudes, which enable the acoustic levitation of high-density materials such liquid mercury or iridium [114]. A plane transducer and a plane reflector make up the simplest single-axis acoustic levitator setup [86], [87], [101].

However, it has been discovered that the use of concave surfaces enables the axial and radial stresses on the levitated items to be greatly increased [94], [102], [115]. Due to this, many single-axis levitators [85], [94], [95], [104], [116], [117] or [102], [115], [118] are made of a plane transducer and a concave reflector, or both. The employment of reflectors with peculiar properties has also been documented in the literature [119], [120], [121] in addition to levitators using concave and flat surfaces. For instance, Melde et al. [120] created a reflector using a holographic approach and printed it out using a 3D printer. Using the created reflector and a 100 kHz ultrasonic transducer, two water droplets were levitated at the same height with a 3 mm distance from the levitator main axis. Hong and coauthors [119], [121] described another sort of reflector with an interesting property, using a surface of liquid reflecting as opposed to a conventional solid reflector. Later on, Foresti et al. [122], used a related kind of reflector to transport and levitate high-density materials. A transducer and a reflector or two opposing transducers can be used to create single-axis acoustic levitators that are non-resonant [123]. In a non-resonant levitator, the standing wave is primarily created by the superposition of two counter-propagating waves as opposed to a resonant levitator, where the standing wave is created by the superposition of several reflected waves. The ability to change the distance between the transducer and the reflector (or two transducers) is the primary benefit of non-resonant levitators.

A single-axis, non-resonant acoustic levitator made of two concave arrays of tiny, 40 kHz transducers and their levitator are inexpensive and easy to make were recently demonstrated by Marzo and coauthors [68]. The levitator uses low-cost 40 kHz transducers with its mechanical components created by using a 3D printer. The transducers are driven by virtue of an H-Bridge driver controlled by an Arduino-based microcontroller. Fletcher et al. [124] provided an acoustic-based method for non-contact manipulating of objects in a rectangular resonant chamber as shown in Fig. 8. Three orthogonal speakers create an acoustic standing wave, similar to the resonant chamber produced by Wang et al. [89]. The chamber has just one movable wall and the pressure node is just located midst of the chamber itself. The resonance of the acoustic chamber is maintained by moving the movable wall while concurrently altering the frequency of the opposing speaker. This technique uses the force of sonic radiation to manipulate the object. The object is moved by a distance that is equal to the moveable wall's half-distance. In 1986, Trinh et al. [106] presented a technique termed mode switching, sometimes known as frequency switching, for manipulating a levitated item inside a rectangular chamber. Trinh's method [106] makes a switching between various acoustic cavity modes. This technique achieves a 1D manipulation without the use of moving parts. Manipulating materials from a lower temperature area to a higher temperature area within the chamber was the aim of this method which provided in [106]. A non-resonant acoustic levitator made of a sound emitter and a small reflector is another method suggested for manipulating objects in microgravity [123]. The object can be levitated at a pressure node that is situated at a distance from the reflector surface of about a quarter of a wavelength when an acoustic standing wave is created by the superposition of the incident and reflected waves. High order reflections are reduced by the reflector's small size [123], and as a result, the force of the acoustic radiation acting on the object is essentially independent of the spacing between the emitter and the reflector. Moving the reflector will allow you to control the levitated object in this situation. A non-resonant acoustic levitation system based on this manipulation mechanism manipulates the levitated particles by moving the reflector in respect to the transducer [125].

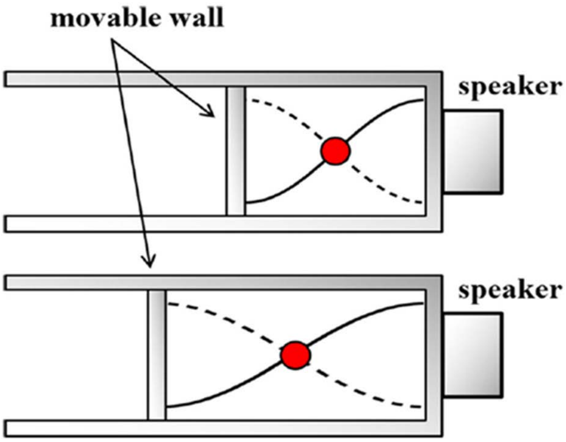

FIGURE 8. Method of acoustic levitation via moving the moveable wall and adjusting the frequency of the speaker on the other side made the contactless manipulation possible in horizontal direction [69].

The action of acoustic viscous torques allows the acoustic waves to spin objects in addition to translating particles that are levitating [93], [126]. Within the rectangular resonant chamber, two perpendicular standing waves can produce acoustic viscous torques on the levitated particle [91], [127]. When there is a phase shift of 90° between the perpendicular waves, the torque on the object is at its greatest levels, as theoretically shown by Wang and Busse [93]. Acoustic viscous torque experiments have already been done in microgravity [92], [128] as well as on earth [126]. Creating a standing wave by superimposing the travelling waves emitted by two opposing transducers is another method for acoustically manipulating levitating objects [129], [130]. According to this method, changing the relative phase between the transducers affects the positions of the pressure nodes, which in turn affects the levitation positions. The travelling wave that one transducer emits should ideally not be reflected by the opposing transducer since reflections can impair manipulation as discovered by Grinenko et al. [131].

According to [131], when the opposing transducer's reflection coefficient is less than 0.5, the manipulation by counter-propagating waves is possible. In reality, decreasing the reflections below a particular threshold will result in a successful manipulation. Many researchers have proven the translation of the levitated particles by altering the relative phase between transducers. Matsui et al. [132] reveal that a set of two opposing 20 kHz transducers may translate microscopic particles vertically. Two slanted transducers were employed by Kozuka et al. [133] to control expanded polystyrene particles in midair. A single-axis acoustic levitator made of two 22 kHz transducers with a radiating face measuring roughly 70 mm in diameter was built by Weber et al. [134]. The method employs a method of bonding an absorbing substance in front of the transducers, helping to eliminate undesired reflections. Scholars also noted that shifting the relative phase between the transducers allowed for vertical displacement of the levitating particles. A recent single-axis levitator that can move levitating particles both upwards and downwards as presented by Marzo et al. [68].

A new set of acoustic levitation device for moving small items and liquid droplets was proposed by Koyama and Nakamura which consists of linear [135] and circular [136] transporters and can be used to move objects over long distances. The non-contact transfer of levitated objects was shown by Bjelobrk et al. [137] utilizing a system made up of a transducer tied to radiating plate of aluminum and a reflector with a cylindrical concavity. With increasing the space between the reflector and the radiating plate, the minimal Gor'kov potential's horizontal locations change, according to Bjelobrk et al. [137] numerical analysis of their device. It shows that the horizontal transmission of a tiny particle of polystyrene across a 37 mm distance can be achieved by changing the reflector height. The same tool was used by Bjelobrk et al. [138] to move and combine liquid droplets in the atmosphere. Foresti et al. [139] proposed a flexible sonic levitation device capable of moving and combining numerous droplets in the atmosphere. Four arrays of transducers are used in the acoustic levitation system created by Ochiai et al. [140], [141], [142] to manipulate objects in three dimensions in 2014. Two arrays of 40 kHz ultrasonic transducers placed in opposition to one another constructed a modular levitation system which was developed in [143], via adjusting the transducers' amplitudes and phases, this device is able to manipulate object in 3-dimensional direction. Two 40 kHz arrays have recently been employed to lift and carry food, providing a novel gourmet experience [144].

B. NEAR-FIELD METHOD

Unlike the standing wave method where the levitated particles hanging in the pressure nodes are very small compared to the acoustic wavelength, Near-Field acoustic levitation method has the ability to lift objects reaches to few milligrams and heavy planar objects [145], [146], [147], [148]. With a tiny air layer separating them, a sizable planar item levitates in the near-field levitation, also known as the squeeze film levitation. The object itself serves as a reflector in the near-field approach, as opposed to a traditional standing wave method which has a transducer and a reflector. As a matter of fact, the examination of the acoustic radiation force shown in Fig. 9 realized that it significantly increases since the reflector gets closer to the surface of the transducer. Thus, the acoustic radiation force can be used to levitate a planar object on top of transducer when replacing the reflector with the object itself. A study provided by [150] demonstrated that near-field method has the ability to levitate objects of some kilograms in weight from tens to hundreds micrometer over the transducer surface. A levitation device created by Reinhart et al. [145], was utilized to lift and transfer a 200-mm silicon wafer using near-field acoustic levitation. A transducer with a surface that vibrates uniformly in amplitude and phase can be used to achieve near-field acoustic levitation [150]. Flexural mode vibration of a plate is another popular method [151]. Usually used to float planar items over a vibrating surface [149], [150], [152] this method of levitation can also be used to lift nonplanar objects including, cylindrical objects [153], spheres [154], and L-shaped beams [155]. The ability of the near-field concept to regulate the friction between human fingertips and vibrating surfaces has also been proven [156]. A vibrating cylindrical stator and two circular plates enable an air bearing based on the NFAL mechanism to position and lift items as discovered in [157]. Ran Gabai et al. [158], proposed a near-field acoustic levitation-based non-contact stage for item handling and positioning that created an acoustic field with improved pressure able to hold the object without any contact. A very recent study in [159] proposed a measurement method of the holding force acting on a levitated object which has a large displacement from the vibration source during near-field acoustic levitation.

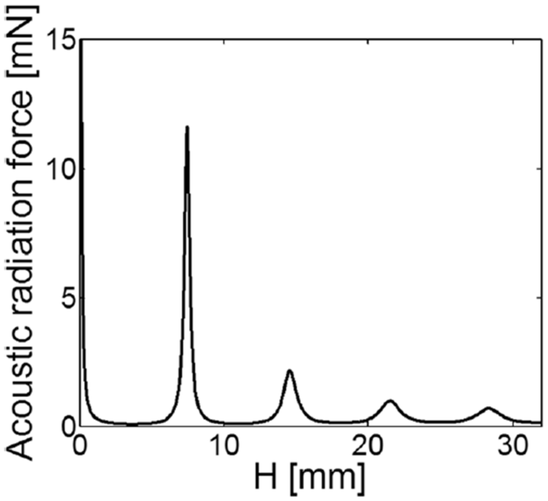

FIGURE 9. Examination of acoustic radiation force [69].

C. SINGLE – BEAM METHOD

A brand-new technique for acoustic levitation, known as single-beam levitation or single-beam trapping, has been presented in [160] and [161] which levitate small objects using one sided emitter. Using a transducer array powered at 1.15 MHz to trap polystyrene beads in aqueous medium, Baresch et al. [161] demonstrated the simultaneous axial and transverse trapping. Marzo et al. [160] reported the first single-beam levitation in air empirical proof to handle small objects and levitate them acoustically. They used single-sided arrays of transducers where 40 kHz transducers of 10 mm in diameter were arranged in 8 × 8 array as shown in Fig. 10 and they were able to do the phase control of each transducer by utilizing a specially constructed electronic board.

They employed an optimization technique to discover the best phase delays for each transducer in order to maximize the trapping forces in the targeted place. They could produce the twin, vortex [162], and bottle [163] traps, three different types of acoustic traps, depending on the phase distribution. Although other scientists have previously studied the acoustic

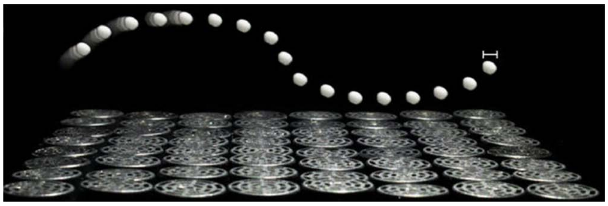

FIGURE 10. Acoustic levitation and non-contact manipulation using 40 kHz transducers of 10 mm diameter arranged in 8 × 8 Array [160].

radiation force created by vortex and bottle beams and it was the first time these fields were used to lift small objects. A twin trap generated successfully by [160] using twin beam to levitate small particles. Two approximately cylindrical, high acoustic pressure amplitude areas around the item define the twin beam. The object is moved to the location of minimum acoustic pressure amplitude by the acoustic radiation force generated between the twin beams. According to [160], the velocity gradient is responsible for the forces in the other two axes, whereas the pressure amplitude gradient is responsible for the horizontal force between the two cylindrical regions. Few research organizations are able to apply the single-beam acoustic levitation technique reported by [160], because each transducer must be individually stimulated by a complex electronic circuitry. Shortly after, a simpler single-beam device was introduced in [164]. The scientists developed the twin trap to achieve the phase delays in the new device, which used the same transducer array via an Arduino board and acoustic delay lines rather than using complex electronic circuitry. The novel single-beam apparatus is transportable and may be put together using components that are widely available to the general public. A recent work in [165], manipulated the acoustic field by placing a set of metamaterial bricks in front of an 8 × 8 array of 40 kHz transducers. In 2018, the work in [166], demonstrated, that the single-beam acoustic tweezer (SBAT) had powerful lateral trapping forces that could levitate red blood cell (RBC) aggregation. A levitation method using two pairs of focusing ultrasonic transducers set up in confocal mode was proposed in [167]. It was demonstrated that the sonic pressure at the geometric focus will always be stable at 0 Pa when the paired transducers are activated in the inverse phases, indicating the presence of a potential well.

From what has been presented in this section so far, we can summarise the main key points of the performance characteristics of each of the acoustic levitation methods which are involved in robotic non-contact manipulation.

1) Standing wave acoustic levitation: The main structure of this method can be created by a transducer and a reflector or two opposed transducers, closed resonant chamber and two opposing arrays of transducers. According to this structure the standing wave can be classified into two main types, the first one is resonant levitators which can be structured from transducer and reflector and the second one is non-resonant levitator which can be structured from two transducers or transducer arrays opposing each other. In the resonant levitator the standing wave can be formulated by the overlap of the reflected waves between the transducer and the reflector when the distance between the transducer and the reflector are adjust to a multiple of a half wavelength and when this distance is set to a higher order of resonance many nodes will formulated in order to freely levitate more than one object at same time. In the non-resonant levitator, the standing wave can be formulated by the overlapping of the propagated waves (the waves emitted from the two transducers or the two arrays of transducers opposing each other), and the advantage of non-resonant is that the distance between the two emitting sides set freely. The material to be levitated and hanged in the pressure nodes of the standing wave via this method, the size of the material itself must be smaller than half-wave of the sonic wavelength.
2) Near-Field acoustic levitation: The main structure of this method can be created by a transducer whose surface vibrates uniformly in amplitude and phase or a plate vibrating in a flexural mode and the object (planar and non-planar objects) (acts as a reflector) to be levitated with a very small distance between them in order to keep the acoustic radiation force at high level as shown in Fig. 9. The material to be levitated and hanged via this method, the size of the material itself can reaches some kilograms between ten and one hundred micrometers on top of the transducer.
3) Single-Beam acoustic levitation: The main structure of this method can be created by one sided transducer having the ability to trap particles in three dimensions. Due to their ability to draw particles toward the source and produce opposing forces along the beam's propagation direction, these beams are also known as tractor beams. This method can be classified into three major categories according to the type of sonic traps which are vortex, twin and bottle sonic traps and they are used in the process of levitation and manipulation of micro-particles.

The most common non-contact manipulation applications via acoustic levitation are shown in Table. 2 below.

TABLE 2. Applications of non-contact manipulation via acoustic levitation.

Non-Contact Manipulation	Surveys
Handling Hazardous Materials	[64]
Micro Assembly	[66]
Liquids	[70]
Material Sciences	[84]
Small Living Animals	[108], [109]
Solids	[168]
Pharmaceutical Industry	[169]

IV. CONTROL STRATEGIES FOR ACOUSTIC LEVITATION

The control of acoustic levitation process in all of its stages had seen some traditional control strategies which applied to achieve the desired performance, but it has not yet been proven that an object can be rotated in three dimensions under control.

A comprehensive control over the orientation in three dimensions for a non-spherical object only by accurately aligned the acoustic trap using a devised algorithm, and a phased-array transducer (PAT)-based levitator was created specifically for this study demonstrated by [170] which would allow implementations in spectroscopy, photogrammetry, and contactless placement. Up to now, the orientation has only been controlled in one dimension according to [139], [160]. Additionally, due to their symmetries, spherical objects cannot have their orientation modified. Although levitated spheres can be given angular speed as provided by [171], [172], and [173], control over static orientation has yet to be proven. The most common control strategies within literature which had been applied to control the objects manipulation and orientation based on acoustic levitation are PID gain-scheduled controller in [72] and H_∞ in [158].

V. CONCLUSION

Robotic manipulation was reviewed from the perspective of industrial, pharmaceutical and aerospace application. Two categories of object manipulation were discussed namely, contact and non-contact manipulation. The importance of magnetic levitation is highlighted via presenting its most common applications so far as one of the major levitations approaches due to efficiency, low maintenance cost and increment of the beneficial life of the system as well as the stability during the levitation process itself without any consumption of energy, but it's limited to a specific kind of materials to be levitated, i.e., only ferrous metallic material can be levitated or manipulated. Then, the electrostatic levitation is reviewed as a proper levitation method used in the analysis of high temperature and/or undercooled materials in the vacuum or high-pressure gas but it is limited to charged objects only. The aerodynamic levitation is reviewed which uses gas pressure to lift objects by countering the gravity force and eliminates the pollution and nucleation issues in scientific studies that arise from direct contact between the materials and the container. The last levitation method was the acoustic levitation which promises new dimension in context of non-contact manipulation, offering new opportunity in industry application. The following can be inferred from our review of the acoustic levitation techniques, particularly those techniques that are currently employed in non-contact manipulation:

1) The type of manipulation to be used depends on the task the robot is intended to carry out and the nature of the object being manipulated. For instance, gripping and moving things are contact manipulation activities that can be accomplished by non-contact manipulation, but the contrary is not true.
2) Standing wave method of acoustic levitation could be applied to objects of certain size in where the size of objects should not exceed the half of the acoustic wavelength itself.
3) Near-Field method of acoustic levitation could be applied to objects where the size of objects can exceed the half of the acoustic wavelength itself, so that this method could handle the objects that already standing wave method dealing with.
4) Single-Beam method of acoustic levitation could be applied to a very small objects for a certain type of applications in which the first two methods cannot be applied.

From the review, there are many opportunities in the aspect of control of acoustic levitation, some of which can be further investigated according to a specific type of industrial application. Manipulation techniques for acoustic levitation not only involve single axis levitation. There are as briefly mentioned in Section 4, PID Gain-scheduled controller and H_∞ are employed to control the either or both translational and orientational motion. The use of non-linear control which may consider the model-free approach can be potentially applicable.

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