applied sciences

MDPI

*Systematic Review*

# In-Plane Material Handling: A Systematic Review

**Edoardo Bianchi *, Francisco Javier Brosed Dueso and José A. Yagüe-Fabra**

Department of Design and Manufacturing Engineering, I3A, University of Zaragoza, C/ Maria de Luna 3, 50018 Zaragoza, Spain; fjbrosed@unizar.es (F.J.B.D.); jyague@unizar.es (J.A.Y.-F.)
* Correspondence: ebianchi@unizar.es

**Abstract:** With the dynamic nature of today's market demands, industries increasingly require flexible and adaptable systems to navigate through variable operational needs. In-plane manipulation systems, characterized by their ability to handle objects over an active surface, have emerged as promising solutions to address these challenges. This systematic literature review (SLR) investigates the landscape of in-plane manipulation systems, focusing on their classification, technological aspects, and emerging trends. Drawing upon a comprehensive search strategy, this review identifies and synthesizes relevant literature on the topic. Through structured data extraction and analysis, the review categorizes these devices based on their fields of application, employed technologies, common characteristics, advantages, disadvantages, and existing gaps in research and development. The main technologies identified for material handling include MEMS, vibrations, cilia, pneumatic surfaces, variable-morphology surfaces, the use of rotors, and mobile platforms. These technologies are described based on their primary features and fields of application and are compared to highlight their unique advantages and limitations. Accordingly, this SLR aims to provide insights into the current state of the art, identify areas for further investigation, and inform future developments in in-plane material handling. Additionally, the findings of this review contribute to a deeper understanding of the capabilities, limitations, and potential applications of this kind of manipulation across various industries. Furthermore, the identification of gaps in existing literature, particularly regarding the complexity and efficiency of rotor systems, serves as a foundation for future research aimed at advancing the field and addressing the evolving needs of industries in an increasingly dynamic market landscape.

**Keywords:** in-plane; material handling; feeding; distributed manipulation; systematic literature review



**Citation:** Bianchi, E.; Brosed Dueso, F.J.; Yagüe-Fabra, J.A. In-Plane Material Handling: A Systematic Review. *Appl. Sci.* **2024**, *14*, 7302. https://doi.org/10.3390/app14167302

Academic Editor: Jose Machado

Received: 29 May 2024
Revised: 25 July 2024
Accepted: 9 August 2024
Published: 19 August 2024



## 1. Introduction

In today's dynamic market landscape, the request for flexible and adaptable systems to meet constantly fluctuating demands has become imperative. Industries are increasingly seeking solutions that can efficiently maneuver through variability while ensuring optimal performance [1–3]. In response to this pressing need, the development of in-plane (2D) multi-directional manipulation systems has attracted significant attention [4].

These devices represent a category of systems designed to operate within a surface and are equipped with programmable functionality. They embody the evolution of feeders and conveyors [3,5], as they transport material, but their movement capability is omnidirectional in the plane. Additionally, they often include functions for orientation, positioning, and sorting, which, in older systems, were achieved with additional independent devices (like robotic arms or bowl feeders) [6,7] or manually [7,8].

Therefore, in-plane manipulation systems offer a versatile approach to handling objects over an active surface, enabling precise control and maneuverability [9]. Their applications span a wide range of industries, including manufacturing [10], logistics [8], biomedical [11], and beyond. For instance, in the manufacturing industry, these systems are employed for tasks such as feeding and positioning of parts on assembly lines, which enhances production efficiency and precision. In the logistics sector, they facilitate activities like sorting, orientation, and palletization of packages, significantly improving the speed and accuracy of material handling processes. Meanwhile, in the biomedical field, in-plane manipulation systems are crucial for handling delicate and microscopic parts, such as during the manipulation of biological samples, where precision and gentle handling are paramount. Overall, these systems show several advantages, such as enhanced efficiency, flexibility, and adaptability [3] and reduced manual labor [8].

Recognizing the diverse range of surface manipulation systems and their potential applications, there is a growing interest in classifying these systems. Such classification efforts aim to delineate the various fields of application, employed technologies, and common characteristics, as well as advantages and disadvantages, associated with each system. Moreover, identifying gaps and unresolved developments among these systems is crucial for driving future research and innovation in this field.

Despite the interest in in-plane manipulation systems, there remains a notable gap in the literature, namely a comprehensive systematic literature review (SLR) that collects and analyzes the various systems exhibiting these characteristics. This paper seeks to fill this void by providing a comprehensive review of existing literature on these handling devices, with a focus on their classification, technological aspects, and emerging trends.

The remainder of this paper is organized as follows: Section 2 provides an overview of the methodology employed in the review, presents the research questions, and outlines the paper selection process. Following that, Section 3 explores the answers to these research questions in detail. It begins by discussing the various handling systems, proceeds to classify them, and concludes by examining a specific group for package manipulation. Additionally, this study highlights the main features of the technologies, along with key applications and emerging trends in the field. Finally, Section 4 concludes the paper with a discussion of the identified gaps and the main outcomes resulting from the research.

## 2. Methodology

Various systematic review methodologies have been reported within the literature, despite sharing common objectives, i.e., being a structured, comprehensive, and clear synthesis of existing knowledge [12,13]. In this paper, the 10-step methodology proposed by Fiedler et al. [13] was selected, in addition to adopting the PRISMA method [14] for a complete documentation report.

The 10-step methodology provides a systematic framework for conducting a comprehensive literature review. It begins with formulating precise research questions (step 1) to define the scope and objectives of the study. Researchers then identify relevant sources and select appropriate databases for a literature search (step 2 and step 3). Key terms and search filters are carefully chosen to ensure the retrieval of pertinent articles (step 4 and step 5). The process involves aggregating search results, removing duplicates, and applying inclusion/exclusion criteria to filter relevant papers (step 6 and step 7). Following this, researchers review and extract information from the selected articles (step 8), synthesize the analysis to answer the research questions (step 9), and identify any gaps in the literature (step 10). The PRISMA method complements this approach by providing a detailed flow diagram and checklist to ensure a transparent, systematic, and reproducible review process. This includes documenting the search strategy; the number of records identified, screened, and included; and the reasons for exclusions.

The following subsections describe all the mentioned steps, first presenting the research planning, followed by a description of the paper selection process.

### *2.1. Research Planning*

Starting with the research plan and according to the chosen methodology, the first step (step 1) results in the formulation of the research questions. This phase permits the refinement of the areas covered by the research [15], as well as the formalization of the goals of the review.

On this subject, the research questions are listed as follows:

RQ1 What kinds of manipulative systems have been studied to increase flexibility and adaptability concerning in-plane (2D) material handling along transport lines?
RQ2 How are manipulative surfaces categorized in the literature based on the employed technology, transportable material characteristics, and fields of application?
RQ3 Which are the latest in-plane systems focused on package handling/feeding/conveying along transport lines?

The first question was motivated by the industry's interest in more flexible systems to adapt rapidly and efficiently to the constant changes in the market [1,3]. Therefore, an analysis of the studied solutions and technologies within the literature could help to spot missing or unfinished approaches and applications.

The second question is focused more on the formalization of the retrieved information, as it could be interesting to distinguish the various technologies according to working principles, field of application, advantages, and other main features.

Lastly, the third question concentrates the spotlight on a specific subgroup of systems and the latest research. Specifically, the selection of package handling was motivated by its massive and still increasing use in the transport, logistics, intralogistics, and storage industries [8,16].

Moving on, the second and third steps of the procedure concern the main sources of the research. Specifically, the second step (step 2) suggests an overview of where the research is focused, e.g., among the literature, experts, registries, etc., while the third is the actual selection of the database and sources for the research. To address these points, the current work is focused exclusively on the literature in English using the Scopus and Web of Science (WoS) databases for the automatic research, while Google Scholar (GS) covers manual inquiries. The mentioned databases were chosen for their extensive coverage of various journals and disciplines. JabRef (Version 5.1) served as the reference management software, while MATLAB (Version R2022b) facilitated data extraction and evaluation.

### *2.2. Paper Selection*

In order to conduct a systematic search of documents, a selection and filtering process must be established. First, key words have to be selected (step 4), followed by the design of a series of filters and Booleans (step 5).

Specifically, the following search logic and terminology were implemented in the databases: TITLE-ABS-KEY(((*surface* OR *actuators array* OR *non-prehensile* OR *planar* OR *in-plane*) AND ((*material* OR *packages* OR *parts* OR *material flow* OR *object*) AND (*handling* OR *manipulation* OR *conveying* OR *conveyance* OR *feeding*))) NOT (*gripper* OR *robotic hand* OR *fingers*)).

The selection of terminology occurred following an initial phase of manual screening. During this first stage, various attempts were made to collect an initial set of papers on the topic, thereby identifying the most commonly used keywords. Starting from the oldest and most cited publications, such as those by Will and Liu [6], Konishi and Fujita [17], Bohringer et al. [18,19], and Frei et al. [20], terms and expressions such as *conveyance* [17], *surface* [6], *actuator array* [18,19], *parts manipulation* [6], *distributed manipulation* [19], and *planar transport* [20] emerged. Consequently, other keywords were retrieved based on these publications. In contrast, terms like *gripper*, *robotic hand*, and *fingers* were excluded, as an initial search attempt showed they were abundant even though they were not relevant to the analysis of this work.

Additionally, some more internal filters of the databases were added to limit the research area to engineering, e.g., in Scopus, terms SUBJAREA (engi).

Figure 1 summarizes the search process with a PRISMA-based flow diagram, taking into account the number of papers aggregated, screened, and excluded. This fulfills both step 6 and step 7, which concern the combination and removal of papers (step 6) and the inclusion/exclusion criteria (step 7), respectively. On this subject, as visible from Figure 1, in the identification phase, the removals were based only on duplication. Secondly, during the screening phase, record exclusion was established by the relation with the topic, exploiting the title and abstract information. Finally, the second screening process, which concluded after a more accurate reading of the papers, left 85 articles to analyze. This last process contemplated the relevance level and the full-text availability of articles as exclusion criteria.

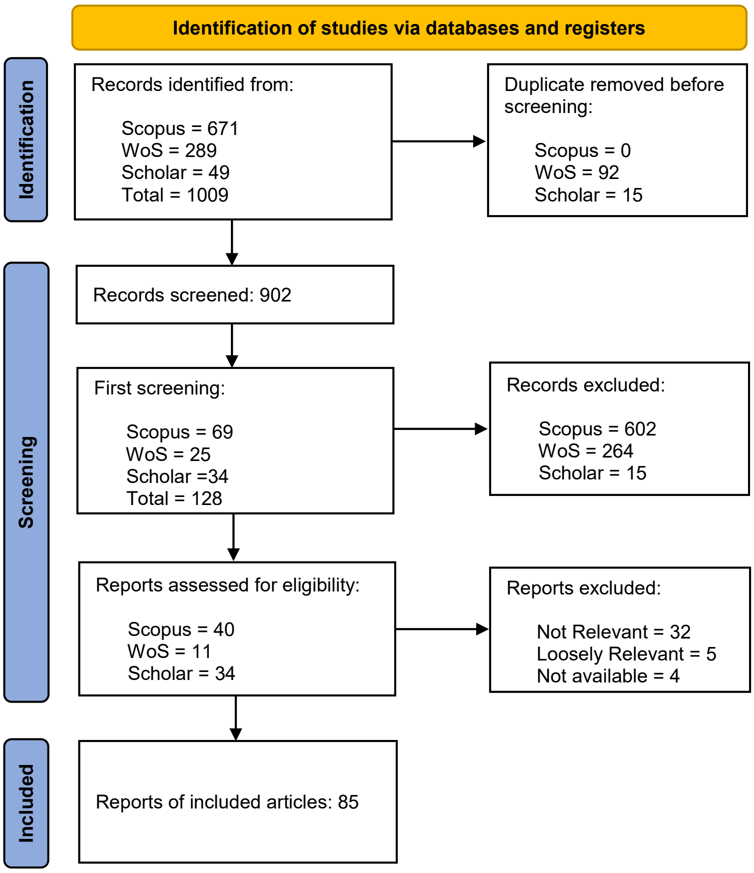


**Figure 1.** Search process and results chart adapted from PRISMA flow diagram [14].

At this point, the following steps of the methodology relate to paper review and information extraction (step 8); the synthesis of the analysis (step 9); and, finally, an overview and identification of research gaps (step 10). For this subject, the research questions have to be considered, as the analysis is focused on finding their answers. Eventually, these topics are covered in the following section.

## 3. Results

The current section first analyzes the publications retrieved from a bibliometric point of view, concentrating on general information. Subsequently, the interest shifts towards the research questions and their answers, delving into each one thoroughly.

### *3.1. Bibliometric Analysis*

This first subsection concerns the bibliometric data, specifically the years of publication and the types of literature artifacts.

On this matter, Figure 2 illustrates the articles released on the topic over time. No filters concerning the year of publication were applied; thus, the resulting numbers represent the entirety of research outcomes in the field. Attention began to be focused on these devices in the last decade of the 20th century [21], increasing gradually with the variability of the market and interest in more flexible and adjustable systems [3,10,22,23]. Moreover, the development of this class of equipment was promoted by the introduction of computers in machines, which also increased over the years [22].

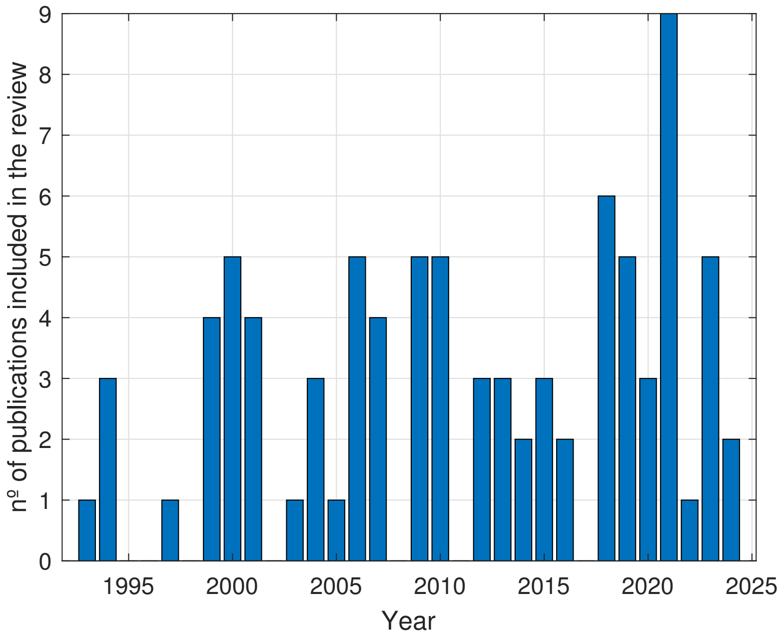


**Figure 2.** Papers published per year.

Moving to the typologies of publication, Figure 3 introduces the retrieved categories, namely article, conference proceedings, book chapter, and review article. As visible from the figure, the majority of the included material consists of journal articles, followed by conference proceedings, which, together, account for nearly the totality of publications on the subject. In fact, outside of these two categories, there are only four book chapters and just two review articles. This information further justifies our research, as it confirms the hypothesis of a lack of review literature on the topic.

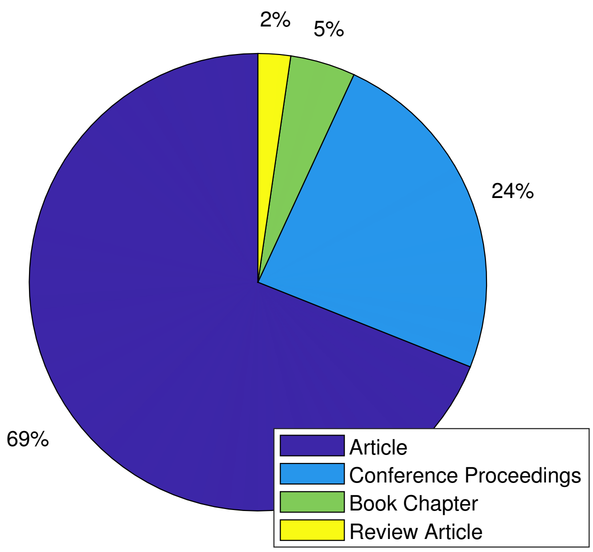


**Figure 3.** Types of publications retrieved.

### *3.2. Answer to RQ1*

After an introduction of general information about the review, the focus can finally move to the research questions. The answer to the first research question (RQ1) is presented in the following paragraphs.

This research focused on which in-plane transport and manipulation systems have been studied to enhance their flexibility and adaptability for typical handling tasks. Upon initial examination of the literature, it became evident that numerous solutions have been explored over the years, encompassing various technologies, fields of application, and handled material sizes.

Examining its evolution in the literature, the concept of in-plane multi-directional manipulation for enhanced flexibility originated with microscopic applications and the advancement of Micro-Electro-Mechanical Systems (MEMSs) [21,24]. Specifically, Ataka et al. [25] were among the first to propose an MEMS to move parts in a 2D space using ciliary motion. Their research, followed by that of many others, such as Bohringer et al. [18,19,26], Will et al. [6], and Bourbon et al. [27], aimed to exploit grids of actuators realized on semiconductor plates to control object motion (Figure 4a). Practically, their idea was to use the friction forces created by tilting cantilevers to transport and handle a part on top.

At the same time, Bohringer et al. [28] and Frei et al. [20] also worked on similar surfaces with distributed manipulation but used vibrations to handle micro parts. In their approach, they aimed to control the vibration frequencies of one [28] (Figure 4b) or more plates [20], utilizing the attraction of parts towards the plate's vibration nodes for manipulation.

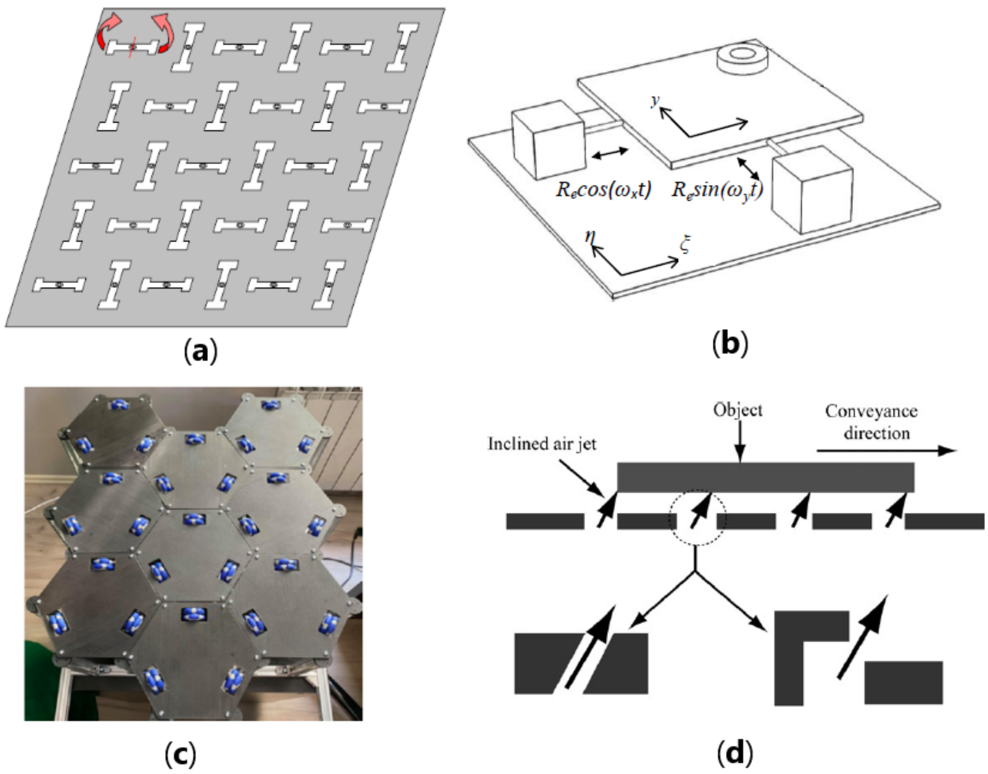


**Figure 4.** Some in-plane handling technologies used over the years. (**a**) MEMS surface based on [27]; (**b**) vibrating platform [29]; (**c**) cell with rotors [2]; (**d**) pneumatic solution [30].

In the same line of interest for distributed and programmable handling, different technologies emerged in the literature during that period. For example, Luntz et al. [9,31] proposed the use of actuated rotors to move macroscopic objects (packages) (Figure 4c), while Konishi et al. [17] promoted the use of air jets for contactless micro-conveyance (Figure 4d).

Starting with the rotor solution, Luntz et al. created an array of cells, each containing two perpendicular, motorized, omnidirectional wheels. A planar object placed on top of this array was supported by many cells, each able to generate an oriented friction force resulting from the two wheels' speed control. On the other hand, the pneumatic solution exploits MEMS, but in this case, the mobile cantilevers open or close valves to regulate air jets (Figure 4d). As a result, the surface is made up of smart modules created with this technology, acting together to achieve contactless object motion.

Among these initial studies, investigations also extended to the types of force fields that surfaces can generate. Approximately between the years of 1997 [32] and 2006 [33], interest was focused on automatically orienting and conveying parts [19,26,32–35] using sensorless solutions [28]. Later, with advancements in sensors and computing power, interest shifted to refined control strategies to accomplish more complex tasks, such as position or trajectory tracking [4,36,37]. In this regard, cameras [5,38] or distributed sensors [39], regardless of the actuation method employed for handling, are preferred, as they provide information over wider areas.

As control technologies evolved, the involved technologies progressed as well. Consequently, MEMS solutions once employed for micro-conveying were replaced by pneumatic surfaces [30,40–43] and electromagnetically actuated moving platforms [10,44–48]. Alternatively, other studies have utilized vibrating [29,49–51] and non-MEMS ciliary [36] solutions for micro-conveyance. However, for these applications, pneumatic surfaces still employ MEMS-based hardware, as seen in [17], to direct and control the air jets. On the other hand, such platforms exploit coils and magnets to achieve very precise positioning and feeding. Vibrating solutions have been proposed that use a saw-tooth vibrating surface [49,50] or a smooth surface [29] to rearrange parts' positions and orientations. Moreover, a ciliary device was utilized for micro-displacements, employing rotating eccentric masses to replicate a specific cilia bio-inspired movement of the *P. caudatum* organism [36].

Moving to macroscopic transport, the initial rotor solution proposed by Luntz et al. [31] was subsequently explored in numerous other studies over the years, including those by Krühn et al. [52], Overmeyer et al. [53], Uriarte et al. [3], and Keek et al. [4]. Additionally, distributed in-plane manipulation of macroscopic parts has been introduced into other technologies, such as novel pneumatic systems [33,54–56], variable-morphology surfaces [37,57–60], mobile platforms [61–63], vibrating surfaces [20,28], and ciliary surfaces [11,64]. These new solutions aim to improve handling skills and surface control capabilities.

Based on the literature research and identification of the size of material and handling speed as key parameters for the effectiveness of macroscopic transport, the rotor solution is recognized as the most effective. These designs employ different modules and a variable number of wheels, along with a camera, to manipulate packages. Specifically, Krühn et al. [52] and Overmeyer et al. [53] suggested the use of one swiveling rotor with an integrated spin drive per module. The device proposed in [3], which is currently used in industrial applications under the name *Celluveyor*, includes three fixed wheels per module with axes oriented at 120° and controllable speeds to direct the total friction force (Figure 4c). Meanwhile, Keek et al. [4] used even more wheels, alternating between modules with five and seven wheels, all actuated to move objects placed on top.

Regarding pneumatic surfaces for macroscopic material transport and manipulation, as outlined in [56], there are two main types, namely air-flow manipulators and air-jet manipulators. Air-flow technology uses pressure fields to move and orient parts, while air-jet technology employs directed air jets to push an object supported by an air bearing [56]. For the first technologies, two different examples of pressure field generation are provided. The first, as proposed in [54,55], uses an array of modules capable of blowing or sucking air, and the second, as proposed in [33,56], utilizes an extensive air cushion capable of creating local air sinks.

Proceeding with variable-morphology surfaces, several solutions to manipulate light and small objects have been studied. Oyobe and Hori [57] first introduced a "Magic carpet" design (Figure 5b), i.e., a grid of vertical linear actuators used to create unevenness in the surface and move parts with them, followed several years later by the solutions proposed in [58,60]. In contrast, instead of simple vertical cylindrical actuators, Robertson et al. [58], employed soft ones with variable stiffness, while Raptis et al. [60] connected the vertices of the actuators with planes to achieve a continuous surface. Other interesting proposals include studies such as [37,59,65–67], where a caterpillar-inspired table was examined for object manipulation, and the work reported in [68], which explored the use of a deformable sheet containing ferrofluid to convey parts through its ripples.

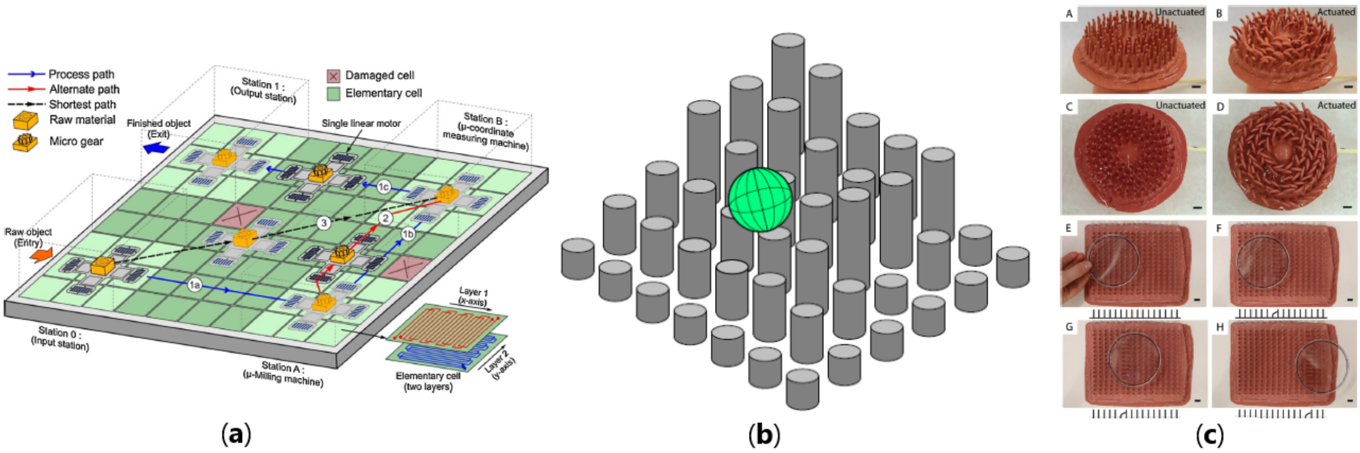


**Figure 5.** Other in-plane handling technologies used over the years. (**a**) Electromagnetic smart platform [10]; (**b**) "magic carpet" based on [57]; (**c**) cilia surface [11].

Conversely, the mobile platforms studied for macroscopic handling, unlike microscopic ones, can not only carry an object on top, as in [61], but also around, as in [62,63,69], with small robot platforms surrounding the part to complete handling.

Lastly, vibrating and ciliary systems for macroscopic motion have evolved similarly to their microscopic counterparts. The main difference in vibrating systems is primarily with respect to the dimensions and power of the active plate [28]. Conversely, for ciliary systems, variation has been introduced in terms of the size of the cilia, as demonstrated by the brush feeder described in [64].

Several other solutions employing the same technology described in the retrieved papers are not reported in the paragraph above. The intention, in fact, was to provide an initial overview of the most common solutions and generalize the characteristics they share. Furthermore, since the objective of the subsequent research question was classification, the authors considered it more appropriate to include all relevant solutions in the subsequent section.

On this subject, a pattern of working principles and features emerged among the analyzed devices. In particular, flexibility and adaptability have been achieved through the use of programmability and distributed actuation. These two characteristics enable the creation of controllable force fields that act on the transported object, either directly or indirectly through a platform.

Programmability allows one to decide on and implement a task virtually without it being predetermined, unlike in more classic systems such as conveyor belts or vibratory linear feeders [3,23,36]. Distributed manipulation has a positive effect on handling flexibility [19], improving manipulation skills [9]. This permits not only linear transport, such as via conveyor belts, but also simultaneous orientations and multi-directional displacements (2D conveyors). Moreover, the programmable nature and distributed placement of actuators on a plane allow a system to easily adapt to changes in tasks and transported materials.

In addition to these two primary system characteristics (programmability and distributed actuation), other commonly encountered features can also be identified. One such feature is modularity, which involves the system being composed of elementary units (modules) that can be assembled into surfaces. This property further enhances system flexibility and adaptability [3], as the modules can be assembled and disassembled arbitrarily according to the desired layout. Among these solutions, there are a few exceptions where the design is not modular; therefore their flexibility and adaptability are limited, but they are still superior to those of classic transport systems.

Several names have been given to this class of manipulation devices over the years, such as “Distributed Micro Motion Systems” (DMMSs) [17], “Modular Distributed Manipulator Systems” (MDMSs) [31], “Advanced Distributed Manipulator Systems” (ADMSs) [5], and the most common “active surfaces” [10,54,55,70] and “smart surfaces” [10,21,27,36,39,41,44,71–73].

Despite the use of “smart surface” or another of the aforementioned terms to name a device, e.g., emSS (electromagnetic modular Smart Surface) [41], generally speaking, these are not formal definitions [10,39]. However, drawing from interpretations by both Barr et al. [39] and Dang et al. [10], all the mentioned types and technologies fall into the “smart surface” class. This is because they all exploit a distributed conveyance system, which, whether sensorized or not, is capable of the most common handling tasks, such as positioning, orienting, sorting, and feeding.

In summary, a group of systems sharing common characteristics and specifications has taken shape. Some repetitive features, such as the technology used, which provides direction for clustering, have already emerged. However, there are still more sub-classes within them to investigate. At this point, the analysis shifts to the second research question (RQ2) and formal classification.

### 3.3. Answer to RQ2

This subsection focuses on the answer to the second research question (RQ2), i.e., the resulting categorization of these manipulative systems.

Considering what has already been said in the previous subsection (Section 3.2), the classification of these devices can be realized based on the following features:

- Employed technology employed;
- Transportable material (geometry, size, weight, and contact sensitivity);
- Field of application.

The first term of distinction is one of the most evident outcomes from RQ1 analysis, i.e., the employed technology or, in other words, the physical working principle applied in each implementation. The possible variations identified for this technology cluster are MEMS, vibrations, cilia, pneumatic, variable morphology, the use of rotors, and mobile platforms.

The second and third differentiation features are strictly related to the first one and to each other. The transportable material is affected by geometry, size, weight, and contact sensitivity, depending on the limitations of the technology. Specifically, the geometry differs between bodies with at least one large, flat face (“planar”) and bodies with a more curved shape (“curved”) when in contact with the device. The sizes of spaces between micro-, meso-, and macroscopic dimensions are referenced as follows: micro < 10 mm, 10 mm < meso < 10 cm, and macro > 10 cm [73]. The weight is distinguished as heavy (>1 kg) or light (<1 kg), while contact sensitivity refers to contactless transport capability (“yes” means contactless transport allowed, and “no” means contactless transport is not allowed).

Similarly, the field of application is based on the previous two characteristics and differences between the intralogistics, biomedical, manufacturing, and research fields.

With regard to this topic, the illustrations presented in Figure 6 schematize the different technologies and working principles. Under each device’s representation, we summarize the main features of the transportable material and the field of application.

As a result, the following paragraphs present the features and the corresponding research for each technology, one by one.

The first devices illustrated in Figure 6 are MEMS devices, which, given their intrinsic dimensions, are suitable for micro and lightweight applications [74,75] on planar objects, like for the micro-assembly of electronic components [6,27]. Transport is achieved using contact friction, while the main implementations, in addition to micro-assembly, are micro-manufacturing and research. Among the retrieved publications on the subject, the majority propose a repeated pattern of four cantilevers made of polyimide [25,38,76] or silicon [6,18,19,27] to manipulate parts, mimicking the ciliary motion of some living organisms [25,38]. On the other hand, a few researchers [74,77] did not specify the actuators' layout, as they focused on the module's novel self-assembly [74] manipulation control [77].

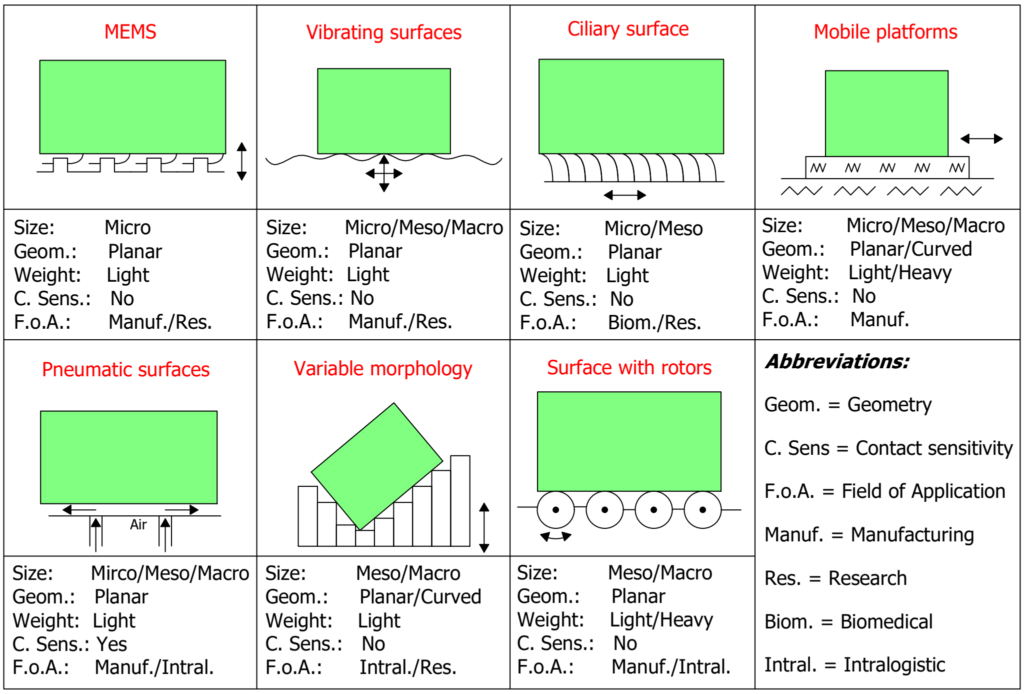


**Figure 6.** Smart surface classification (adapted from [73]).

The vibrating surfaces presented in Figure 6 appear to span a wider range of transportable dimensions according to the specific solution employed. However, planarity and lightness remain essential for the correct manipulation of the object. Additionally, contact is fundamental for motion, and the main fields of application are manufacturing and research, as as for MEMS. Other key distinctions between the analyzed solutions include the types of vibrations, i.e., longitudinal or transversal to the plane, and modularity. Referring to these attributes, many studies have presented a single plate (not a modular solution) driven by rotary [51,78] or linear [19,28,29,79] actuators to move mesoscopic and macroscopic objects through longitudinal [29,51,78,79] or transversal [19,28] waves. In [20,80], two modular solutions using transversal waves were presented. The first [80] exploits ultrasonic piezo-actuators to move microscopic and mesoscopic parts, while the second employs distributed cell plates, also with longitudinal vibrations, to handle meso- and macro-scale objects. Finally, in [49,50], a longitudinal wave-saw tooth vibrating surface was used for micro-part displacement, while in [81] the two types of vibrations were combined in a parallel mechanism-based platform to manipulate mesoscopic parts.

Thirdly, ciliary surfaces are suited for light microscopic and mesoscopic parts with at least one major planar surface. They exploit a step-by-step contact motion achieved d by the bending of flexible cilia [11,64] or the combined rotary movement of eccentric cilia-inspired bodies [36]. Their use is directed more towards biomedical applications, e.g., manipulation of fluids [11] and research.

Moving on, the fourth technology presented in Figure 6 is mobile platforms. Like vibrating surfaces, this class of devices is employed for different sizes of materials, and in some specific cases, mobile platforms can also deal with heavier objects. These systems mostly work with planar parts; however, there are a few solutions that can also move curved items [62,63,69]. Specifically, such devices have the common characteristic of being composed of swarms of mobile robots that can cooperate to surround and handle components. Therefore, given this capability, requirements with respect to the shape of the object are less stringent, and planarity is not required. Additionally, these solutions excel in handling heavier parts, especially considering that most of the other platform solutions identified in the review primarily consist of electromagnetic stages designed for micro-conveyance. On this subject, in [10,44,46–48], similar driving coils were assembled into platforms capable of micro-displacements on top of arrays of permanent magnets. In [45,72], grids of tiny collaborative platforms confined in shaped housings worked together to move planar objects on top by micro-steps, similar to ciliary motion. Finally, in [61], controlled platform accelerations and tilting were used to move a small (mesoscopic) object on top.

Continuing with the technology categories outlined in Figure 6, the next one involves pneumatic systems. This class of devices is employed for contactless transport of different sizes of light planar objects. The fields of application include manufacturing and intralogistics, especially concerning small (micro/meso-scale) and fragile parts [75] like silicon wafers [82]. The majority of the retrieved solutions involve the utilization of MEMS technology to develop modular grids of nozzles with adjustable openings, allowing for control of the direction of air jets. Main research on the topic includes the *Smart Surface* Project, which involved five French teams and one Japanese team building on studies initiated by Konishi and Fujita [17] and Mita et al. [83]. This project is referenced in several works [21,24,30,41–43,71,75,84]. Similarly, another solution with air jets but without MEMS, was presented in [40], where the array for the distributed manipulation contained modules with a central electrode that can open and close the nozzles with electrostatic actuation. As an alternative, other research has focused on different techniques exploiting pressure fields. In [33–35,85], a manipulator for planar parts comprising platforms was studied. In practice, the bottom platform serves as an air bearing, while the top one is capable of creating air sinks to generate flows and, thus, handle forces. In [54,55,86], a similar concept but with only one plane was developed. Specifically, the manipulator comprises an array of tubes used to both blow air to support an object and to produce a vacuum to move it. Lastly, in [82], researchers employed modules with inlet and outlet holes to create local air flows, and in [87], the authors used acoustic pressure fields made up of ultrasonic transducers.

After pneumatic technology, it is the turn of variable-morphology surfaces. This class of devices exploits punctual changes in altitude in some areas of the surface to move light mesoscopic and macroscopic parts. The shape of the object does not prevent functioning but may require different motion rules. The main fields of application include research and certain intralogistics tasks, such as sorting [59]. Among the retrieved solutions, the oldest of the group is the "magic carpet" [57], i.e., a grid of vertical linear actuators capable of creating a deformed surface for material handling. Along the same line but connecting all the actuators with planes, a similar version was studied in [60]. Additionally, in [70], air jets were incorporated into the design. Conversely, in [10,37,59,66,67], a modular surface was used, exploiting four inflatable air chambers per module to manipulate objects with a bio-inspired caterpillar motion. The researchers also suggested that their device is a soft table and can be an alternative to contactless conveyance for fragile parts. Similarly, in terms of soft conveyance, in [58] a smaller modular version of the magic carpet using soft pneumatic actuators was proposed. Lastly, in [68], a ferrofluid-based sheet was employed to handle objects through the use of controllable magnetic fields.

The last group shown in Figure 6 consists of surfaces with rotors. These systems are the only of the investigated technologies capable of transporting significantly heavy and large objects for intralogistics purposes. Their development was tailored to this task, alongside other applications, such as manipulation for flexible manufacturing [5]. The handled objects must have a planar surface to be supported simultaneously by multiple rotors on the same plane without getting stuck. The solutions retrieved within this research propose two main approaches for the manipulation of material flows, namely fixed-axis rotors and swiveling rotors. As mentioned in Section 3.2, the first approach was initially proposed by Luntz and Messner [5,9,31,88]. Their proposal consisted of an array of modules, each containing two motorized omnidirectional wheels positioned with their axes perpendicular to each other. Subsequently, other solutions emerged; in [89], eight wheels per module were arranged in a square layout, alternating the direction of their axes. Similarly, Refs. [7,90] featured nine and four rotors per module, respectively.

More complex designs still following the fixed-axis approach were developed in [4,23]. The first introduces an E-pattern layout for the rotors in each module, alternating between three smaller horizontal rotors and a large vertical one (with the axes in the surface plane). The second employs a single module that interchanges rollers and pulleys with elastic bands to control actuation in two perpendicular directions. The bands primarily serve to divert the material on top, while the rollers convey it in the desired direction. The most industrialized solution with this approach is the *Celluveyor*, which was analyzed in [2,3,8,91], featuring three omnidirectional wheels per module, each oriented 120° apart.

On the other hand, the second approach uses swiveling driven wheels either in packs [53] or individually arranged for each module [52,92]. Our own proposal also features a surface with rotors and adopts a similar "swiveling" approach [73,93]. However, it uniquely embraces certain characteristics. For instance, it lacks spinning actuation (i.e., is underactuated), and the continuous swiveling of the axis is replaced by discrete temporary positions.

Having now presented all the classes with their characteristics, it is possible to make comparisons and determine which solution is most suitable depending on the application. In Figure 6, systems are grouped by their field of application. Particularly interesting are the cases of manufacturing and intralogistics, which appear most frequently. Biomedical applications are only related to ciliary systems and are, thus, omitted from the comparison. Regarding the "research" field, comparisons do not seem relevant, as the goal is greater knowledge rather than practical application.

Starting with the manufacturing sector for microscopic objects, the included systems are MEMS, vibrating surfaces, mobile platforms, and pneumatic surfaces. As previously mentioned, these technologies do not compete at the same level, and among them, MEMS systems remain more prominent within the field of research. This technology, if used directly, due to its working principle, is particularly slow in movement [30] and, moreover, complex to realize and maintain [79]. Given this, to manipulate small, light, and flat surface components, e.g., silicon wafers or generally in microfactories, it is preferable to use pneumatic systems for contactless applications [30,43,94], vibrating surfaces for a less complicated design [79,80], or mobile platforms for more precise positioning [10]. However, this does not preclude the employment of MEMS technology in the construction of other devices, such as the microscopic valves of pneumatic modules themselves [30].

When increasing the size of the handled materials (meso and macro scales), still within the manufacturing sector, for the feeding of non-delicate materials or their positioning when high precision is not required, vibrating surfaces [28,81] and rotor surfaces [31] are most effective. Pneumatic surfaces are used when contact with the object must be avoided (e.g., if fragile, clean, or dangerous), as well as for precision positioning [43]. Meanwhile, mobile platforms for macroscopic applications predominantly utilize a swarm approach [62,63] and can even move bodies with curved geometry, adapting by employing more or fewer collaborative modules depending on the object size.

For intralogistics applications, the most commonly used technologies are pneumatic surfaces, variable-morphology surfaces, and rotor surfaces. Analysis of their behavior for one of the main intralogistics applications, i.e., the transport and handling of packages, is the subject of the last research question (RQ3). However, some general comparisons can be made here. These three technologies are distinguished by characteristics that determine their choice depending on the task at hand. Specifically, pneumatic solutions are the only ones suitable for contactless conveyance and feeding applications. They find outlets in the food industry, LCD industry, and solar cell manufacturing [43]. In some cases, even for delicate materials, soft variable-morphology surfaces can be indicated [59], generally for feeding tasks and especially sorting [60]. Their use in industry, even for non-soft versions, is not yet as widespread as the other two classes but is gradually increasing, since their application is not limited to bodies with flat geometry and rigid bodies [68]. Ultimately, rotor surfaces remain the preferred choice for all intralogistics activities involving non-delicate materials, both in terms of heavy weight and high volumes of transport [3,8,91].

Finally, Figure 7a,b report the number of publications retrieved per technology class (Figure 7a) and their distribution over the years (Figure 7b). The purpose of these figures is to complete the bibliometric analysis started in Section 3.1 with the new information about the technology classification that was just collected.

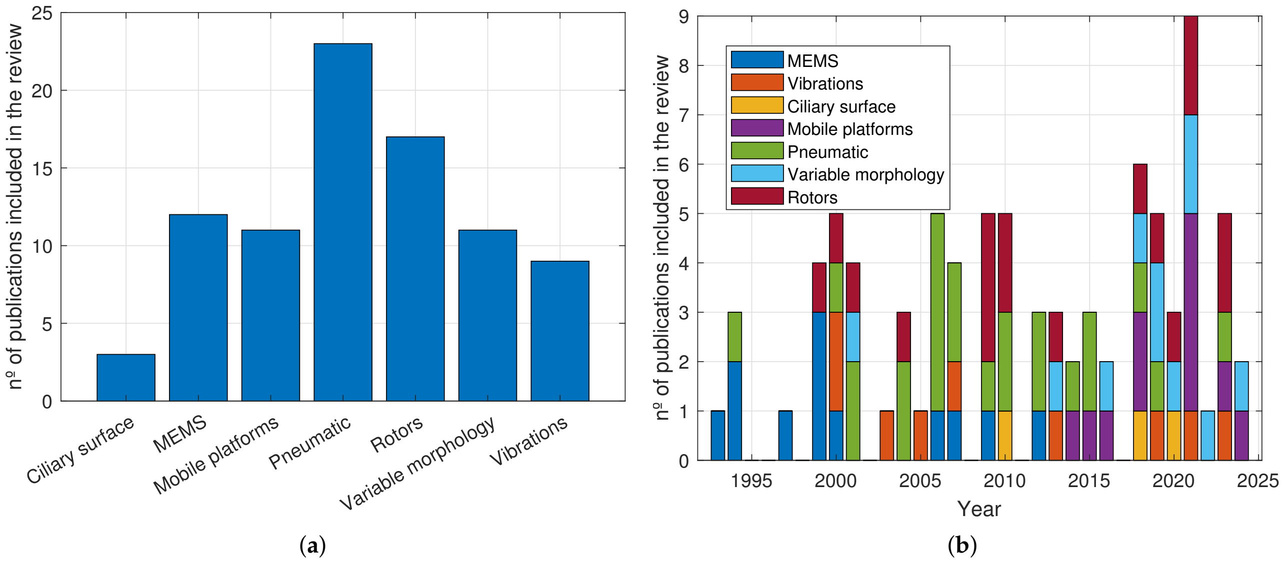


**Figure 7.** Number of articles according to the employed technology (**a**) and distribution over the years (**b**).

In summary, this subsection provides a comprehensive categorization of manipulative systems based on different technologies, addressing the second research question (RQ2). Through the classification of these devices according to their employed technology, transportable material characteristics, and field of application, insights into the diverse landscape of manipulative systems are presented. Additionally, leveraging this technology clustering, a complement to the bibliometric analysis is introduced, specifically concerning the distribution of publications across the different technology classes and over time.

### *3.4. Answer to RQ3*

This last subsection of Section 3 addresses the third research question (RQ3), concerning the latest in-plane solutions for package handling along transport lines.

Packages and parcels used in warehouses and factories for intralogistic purposes typically fall into the category of macroscopic objects, with weights ranging from light to heavy [95]. According to Figure 6, the main technologies for handling packages within the identified classes are pneumatic, variable-morphology, and rotor systems. However, among these, according to the reviewed literature, only rotor systems are truly effective for feeding, sorting, orienting, and generally manipulating parcels. This is due to the working principles employed by these technologies. Pneumatic surfaces, which use air jets or pressure fields, are complex to control and are preferable only when a contactless solution is required. Variable-morphology surfaces, which use vertical motion to manipulate objects in plane, operate at a slower pace and have reduced handling capabilities compared to rotors. Furthermore, they are limited to handling light and compact (yet still macroscopic) objects, similar to pneumatic surfaces.

Therefore, the answer to the third research question is rotor systems, with a focus on the latest solutions presented in [3,4,7,73]. These devices were introduced in the previous subsection (Section 3.3), where they were also categorized based on their rotor-axis mobility. While their detailed presentation is not repeated here, this section analyzes their strengths and weaknesses.

In reviewing the literature, it is noted that, with one exception [73], all proposals involve fully or even over-actuated rotors. This means that the rotors used in these systems are motorized, at least for spinning, and in the case of the second type of rotor class, the swiveling is also motor-driven. As noted in [73], this often results in at least two motors per module, for example, one motor for each perpendicular omniwheel, as seen in [5,9,31,88], or one motor for swiveling and one for spinning, as observed in [52]. In some of the latest commercially available solutions, such as the *Celluveyor* [3], there are three driving rotors, and in the devices proposed in [4,7], there are five and nine motorized wheels or rollers, respectively.

As a result, these systems excel in manipulation due to their distributed actuation [9]. However, they are complex to control, consume significant amounts of energy, and are expensive to build and maintain [73].

To address these issues, we proposed a solution in [73]. However, this does not preclude future research into designs that reduce complexity without compromising performance. This article aims to describe the latest advancements in in-plane manipulation as well as their applications and characteristics.

## 4. Discussion and Conclusions

This paper, following a systematic methodology, presents the latest devices employed for the in-plane manipulation of materials. At the beginning of the study, three research questions were highlighted. The first two concern the characteristics and classification of systems used for handling tasks in the literature. The last question focuses on the manipulation of packages and parcels, which is a significant topic in material transport within the industry.

Starting with a brief introduction of the methodology used to collect articles on the subject, this paper then presented an overview of the retrieved articles, first in terms of bibliometric data and subsequently through content analysis.

The main outcome of this work is a comprehensive review of the in-plane manipulation systems present in the literature. A systematic analysis revealed that this subject is relatively new to surveys and review articles. The closest related reports include a book on distributed manipulation published in 2000 [96] and two papers published in 2015 focused solely on pneumatic systems [56,97]. Among the retrieved articles, classes based on common features, fields of application, and working principles were identified. Consequently, a useful description of the functioning concepts and technology was provided to facilitate further research on the topic. Additionally, a comparison of these systems with a view to practical applications was included.

Ultimately, a hint about an open research topic concerning simplified rotor handling surfaces was discussed. Specifically, in the final part of the answer to RQ3, the extensive use of motors in these devices was highlighted.

Considering the trajectory of this field, there are several promising directions for future developments. Based on the analyses and research conducted on this topic, there appears to be a growing scientific interest due to the primary qualities of adaptability and flexibility. The authors believe future developments will be driven by technological advancements, particularly in materials science; robotics; and, most importantly, artificial intelligence (AI).

New materials and manufacturing processes, among other things, will enable the further miniaturization of parts, improve system performance through reduced friction, enhance the durability of components, and offer improved magnetic properties. Advancements in robotics are equally crucial, as more sophisticated and miniaturized robotic systems can enhance the precision and versatility of in-plane manipulation devices, allowing them to handle a wider array of tasks with greater dexterity and control.

Furthermore, AI is expected to play a pivotal role in the evolution of in-plane manipulation systems. AI can optimize the operation of these systems through the use of advanced algorithms, enabling better path planning, object recognition, and adaptive control. This convergence of technologies will significantly enhance the efficiency and capabilities of in-plane manipulation systems, meeting the growing demand for flexible and adaptable solutions in various industries.

In conclusion, in light of the presented analyses and the described potential future developments, this paper serves as a valuable resource and guide for future advancements in in-plane handling systems.

**Author Contributions:** Conceptualization, E.B., F.J.B.D. and J.A.Y.-F.; methodology, E.B.; software, E.B.; validation, E.B.; formal analysis, E.B.; investigation, E.B.; writing—original draft preparation, E.B.; writing—review and editing, E.B., F.J.B.D. and J.A.Y.-F.; visualization, E.B.; supervision, F.J.B.D. and J.A.Y.-F.; project administration, F.J.B.D. and J.A.Y.-F. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data are contained within the article.

**Acknowledgments:** This research work was undertaken in the context of the DIGIMAN4.0 project ("Digital Manufacturing Technologies for Zero-defect", https://www.digiman4-0.mek.dtu.dk/, (accessed on 18 August 2024). DIGIMAN4.0 is a European Training Network supported by Horizon 2020, the EU Framework Programme for Research and Innovation (Project ID: 814225).

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Fantoni, G.; Santochi, M.; Dini, G.; Tracht, K.; Scholz-Reiter, B.; Fleischer, J.; Kristoffer Lien, T.; Seliger, G.; Reinhart, G.; Franke, J.; et al. Grasping devices and methods in automated production processes. *CIRP Ann.* **2014**, *63*, 679–701. [CrossRef]
2. Rizescu, C.I.; Pleşea, A.I.; Rizescu, D. Modular Transport and Sorting System with Omnidirectional Wheels. *MATEC Web Conf.* **2021**, *343*, 08011. [CrossRef]
3. Uriarte, C.; Asphandiar, A.; Thamer, H.; Thamer, H.; Benggolo, A.Y.; Freitag, M. Control strategies for small-scaled conveyor modules enabling highly flexible material flow systems. In Proceedings of the ScienceDirect, Procedia CIRP Conference on Intelligent Computation in Manufacturing Engineering, Gulf of Naples, Italy, 18–20 July 2018. [CrossRef]
4. Keek, J.S.; Loh, S.L.; Chong, S.H. Design and Control System Setup of an E-Pattern OmniwheeledCellular Conveyor. *Machines* **2021**, *9*, 43. [CrossRef]
5. Bedillion, M.; Messner, W. Trajectory Tracking Control for Actuator Arrays. *IEEE Trans. Control Syst. Technol.* **2013**, *21*, 2341–2349. [CrossRef]
6. Will, P.; Liu, W. Parts Manipulation on a MEMS Intelligent Motion Surface. *USC Inf. Sci. Inst.* **1994**, *310*, 822–1511.
7. Zhou, Z.; Zhang, H.; Liu, K.; Ma, F.; Lu, S.; Zhou, J.; Ma, L. Design of a Two-Dimensional Conveyor Platform with Cargo Pose Recognition and Adjustment Capabilities. *Sensors* **2023**, *23*, 8754. [CrossRef]
8. Sanghai, R.A.; Saundalkar, P.P.; Mallick, J.A.; Shah, B. Sort X Consignment Sorter using an Omnidirectional Wheel Array for the Logistics Industry. In Proceedings of the 2020 International Conference on Convergence to Digital World—Quo Vadis (ICCDW), Mumbai, India, 18–20 February 2020. [CrossRef]
9. Luntz, J.E.; Messner, W.; Choset, H. Distributed Manipulation Using Discrete Actuator Arrays. *Int. J. Robot. Res.* **2001**, *20*, 553–583. [CrossRef]
10. Dang, T.A.T.; Bosch-Mauchand, M.; Arora, N.; Prelle, C.; Daaboul, J. Electromagnetic modular Smart Surface architecture and control in a microfactory context. *Comput. Ind.* **2016**, *81*, 152–170. [CrossRef]
11. Becker, K.P.; Chen, Y.; Wood, R.J. Mechanically Programmable Dip Molding of High Aspect Ratio Soft Actuator Arrays. *Adv. Funct. Mater.* **2020**, *30*, 1908919. [CrossRef]
12. Tranfield, D.; Denyer, D.; Smart, P. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. *Br. J. Manag.* **2003**, *14*, 207–222. [CrossRef]
13. Fiedler, F.; Ehrenstein, J.; Höltgen, C.; Blondrath, A.; Schäper, L.; Göppert, A.; Schmitt, R. Jigs and Fixtures in Production: A Systematic Literature Review. *J. Manuf. Syst.* **2024**, *72*, 373–405. [CrossRef]
14. The PRISMA Statement for Reporting Systematic Reviews and Meta-Analyses of Studies That Evaluate Health Care Interventions: Explanation and Elaboration. *Ann. Intern. Med.* **2009**, *151*, W-65–W-94. [CrossRef] [PubMed]
15. Ho, P.T.; Albajez, J.A.; Santolaria, J.; Yagüe-Fabra, J.A. Study of Augmented Reality Based Manufacturing for Further Integration of Quality Control 4.0: A Systematic Literature Review. *Appl. Sci.* **2022**, *12*, 1961. [CrossRef]
16. Boysen, N.; Briskorn, D.; Fedtke, S.; Schmickerath, M. Automated sortation conveyors: A survey from an operational research perspective. *Eur. J. Oper. Res.* **2019**, *276*, 796–815. [CrossRef]

17. Konishi, S.; Fujita, H. A conveyance system using air flow based on the concept of distributed micro motion systems. *J. Microelectromec. Syst.* **1994**, *3*, 54–58. [CrossRef]
18. Bohringer, K.F.; Donald, B.; Mihailovich, R.; MacDonald, N. A theory of manipulation and control for microfabricated actuator arrays. In Proceedings of the IEEE Micro Electro Mechanical Systems an Investigation of Micro Structures, Sensors, Actuators, Machines and Robotic Systems, Oiso, Japan, 25–28 January 1994; pp. 102–107. [CrossRef]
19. Bohringer, K.F.; Donald, B.R.; MacDonald, N.C. Programmable force fields for distributed manipulation, with applications to MEMS actuator arrays and vibratory parts feeders. *Int. J. Robot. Res.* **1999**, *18*, 168–200. [CrossRef]
20. Frei, P.U.; Wiesendanger, M.; Büchi, R.; Ruf, L. Simultaneous planar transport of multiple objects on individual trajectories using friction forces. In *Distributed Manipulation*; Springer: Berlin/Heidelberg, Germany, 2000; pp. 49–64.
21. Boutoustous, K.; Laurent, G.J.; Dedu, E.; Matignon, L.; Bourgeois, J.; Le-Fort-Piat, N. Distributed control architecture for smart surfaces. In Proceedings of the 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, Taipei, Taiwan, 18–22 October 2010. [CrossRef]
22. Kamagaew, A.; Stenzel, J.; Nettsträter, A.; ten Hompel, M. Concept of Cellular Transport Systems in facility logistics. In Proceedings of the 5th International Conference on Automation, Robotics and Applications, Wellington, New Zealand, 6–8 December 2011; pp. 40–45. [CrossRef]
23. Mayer, S.H. *Development of a Completely Decentralized Control System for Modular Continuous Conveyors*; KIT Scientific Publishing: Karlsruhe, Germany, 2009; Volume 73.
24. Chapuis, Y.A.; Zhou, L.; Fukuta, Y.; Mita, Y.; Fujita, H. FPGA-Based Decentralized Control of Arrayed MEMS for Microrobotic Application. *IEEE Trans. Ind. Electron.* **2007**, *54*, 1926–1936. [CrossRef]
25. Ataka, M.; Omodaka, A.; Takeshima, N.; Fujita, H. Fabrication and operation of polyimide bimorph actuators for a ciliary motion system. *J. Microelectromec. Syst.* **1993**, *2*, 146–150. [CrossRef]
26. Böhringer, K.F.; Donald, B.R.; Kavraki, L.; Lamiraux, F. Part Orientation with One or Two Stable Equilibria Using Programmable Force Fields. *IEEE Trans. Robot. Autom.* **2000**, *16*, 157–170. [CrossRef]
27. Bourbon, G.; Minotti, P.; Htlin, P.; Fujita, H. Toward Smart Surfaces Using High-Density Arrays of Silicon-Based Mechanical Oscillators. *J. Intell. Mater. Syst. Struct.* **1999**, *10*, 534–540. [CrossRef]
28. Böhringer, K.F.; Bhatt, V.; Donald, B.R.; Goldberg, K. Algorithms for Sensorless Manipulation Using a Vibrating Surface. *Algorithmica* **2000**, *26*, 389–429. [CrossRef]
29. Liutkauskienė, K.; Kilikevičius, S.; Česnavičius, R.; Bakšys, B.; Paukštaitis, L. Manipulation of small parts being assembled on a horizontally vibrating plate. *Mechanics* **2019**, *25*, 377–382. [CrossRef]
30. Zeggari, R.; Yahiaoui, R.; Malapert, J.; Manceau, J.F. Design and fabrication of a new two-dimensional pneumatic micro-conveyor. *Sens. Actuators A-Phys.* **2010**, *164*, 125–130. [CrossRef]
31. Luntz, J.; Messner, W.; Choset, H. Discrete actuator array vectorfield design for distributed manipulation. In Proceedings of the 1999 IEEE International Conference on Robotics and Automation (Cat. No.99CH36288C), Detroit, MI, USA, 10–15 May 1999; Volume 3, pp. 2235–2241. [CrossRef]
32. Kavraki, L. Part orientation with programmable vector fields: Two stable equilibria for most parts. In Proceedings of the International Conference on Robotics and Automation, Albuquerque, NM, USA, 20–25 April 1997; Volume 3, pp. 2446–2451. [CrossRef]
33. Varsos, K.; Luntz, J. Superposition Methods for Distributed Manipulation Using Quadratic Potential Force Fields. *IEEE Trans. Robot.* **2006**, *22*, 1202–1215. [CrossRef]
34. Moon, H.; Luntz, J. Prediction of Equilibria of Lifted Logarithmic Radial Potential Fields. *Int. J. Robot. Res.* **2004**, *23*, 747–762. [CrossRef]
35. Varsos, K.; Moon, H.; Luntz, J. Generation of quadratic potential force fields from flow fields for distributed manipulation. *IEEE Trans. Robot.* **2006**, *22*, 108–118. [CrossRef]
36. Whiting, J.; Mayne, R.; Melhuish, C.; Adamatzky, A. A Cilia-inspired Closed-loop Sensor-actuator Array. *J. Bionic Eng.* **2018**, *15*, 526–532. [CrossRef]
37. Chen, Z.; Deng, Z.; Dhupia, J.S.; Stommel, M.; Xu, W. Trajectory Planning and Tracking of Multiple Objects on a Soft Robotic Table Using a Hierarchical Search on Time-Varying Potential Fields. *IEEE Trans. Robot.* **2024**, *40*, 351–363. [CrossRef]
38. Ataka, M.; Legrand, B.; Buchaillot, L.; Collard, D.; Fujita, H. Design, Fabrication, and Operation of Two-Dimensional Conveyance System with Ciliary Actuator Arrays. *IEEE/ASME Trans. Mechatron.* **2009**, *14*, 119–125. [CrossRef]
39. Barr, D.R.; Walsh, D.; Dudek, P. A Smart Surface Simulation Environment. In Proceedings of the 2013 IEEE International Conference on Systems, Man, and Cybernetics, Manchester, UK, 13–16 October 2013; pp. 4456–4461. [CrossRef]
40. Turitto, M.; Ratchev, S.; Xue, X.; Hughes, M.; Bailey, C. Pneumatic contactless microfeeder design refinement through CFDsimulation. In Proceedings of the 4M 2007, the Third International Conference on Multi-Material Micro Manufacture, Borovets, Bulgaria, 3–5 October 2007.
41. El Baz, D.; Boyer, V.; Bourgeois, J.; Dedu, E.; Boutoustous, K. Distributed part differentiation in a smart surface. *Mechatronics* **2012**, *22*, 522–530. [CrossRef]
42. Yahiaoui, R.; Zeggari, R.; Malapert, J.; Manceau, J.F. A MEMS-based pneumatic micro-conveyor for planar micromanipulation. *Mechatronics* **2012**, *22*, 515–521. [CrossRef]

43. Laurent, G.J.; Delettre, A.; Zeggari, R.; Yahiaoui, R.; Manceau, J.F.; Fort-Piat, N.L. Micropositioning and Fast Transport Using a Contactless Micro-Conveyor. *Micromachines* **2014**, *5*, 66–80. [CrossRef]
44. Arora, N.; Khan, M.U.; Petit, L.; Prelle, C. A planar electromagnetic actuator based on two layer coil assembly for micro applications. In Proceedings of the 2014 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Besançon, France, 8–11 July 2014; pp. 174–179. [CrossRef]
45. Shi, Z.; Bélier, B.; Martincic, E.; Petit, L.; Moulin, J.; Lefeuvre, E.; Terrien, J.; Prelle, C.; Lamarque, F. Development of a 2D array of micromachined electromagnetic digital actuators for micro-conveyance applications. *Microsyst. Technol.* **2018**, *24*, 411–417. [CrossRef]
46. Kritikou, G.; Aspragathos, N. Activation Algorithms for the Micro-Manipulation & Assembly of Hexagonal Microparts on a Programmable Platform. In *Advances in Service and Industrial Robotics: Proceedings of the 27th International Conference on Robotics in Alpe-Adria Danube Region (RAAD 2018)*; Springer International Publishing: Berlin/Heidelberg, Germany, 2019; pp. 475–482. [CrossRef]
47. Huayu, W.; Shunsuke, Y.; Shuji, T. Fabrication of Multi-Axis Moving Coil Type Electromagnetic Micro-Actuator Using Parylene Beams for Pure In-Plane Motion. In Proceedings of the 2021 21st International Conference on Solid-State Sensors, Actuators and Microsystems (Transducers), Orlando, FL, USA, 20–24 June 2021; pp. 667–670. [CrossRef]
48. Zhang, X.; Trakarnchaiyo, C.; Zhang, H.; Khamesee, M.B. MagTable: A tabletop system for 6-DOF large range and completely contactless operation using magnetic levitation. *Mechatronics* **2021**, *77*, 102600. [CrossRef]
49. Mitani, A.; Sugano, N.; Hirai, S. Micro-Parts Feeding by a Saw-tooth Surface. In Proceedings of the 2005 IEEE International Conference on Robotics and Automation, Barcelona, Spain, 18–22 April 2005; pp. 825–831. [CrossRef]
50. Mitani, A.; Yoshimura, T.; Hirai, S. Feeding of submillimeter-sized microparts along a saw-tooth surface using only horizontal vibration: Effects of saw-tooth pitch, vibration frequency, and humidity. In Proceedings of the 2007 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Zurich, Switzerland, 4–7 September 2007; pp. 1–6. [CrossRef]
51. Kilikevičius, S.; Liutkauskienė, K.; Česnavičius, R.; Keršys, A.; Makaras, R. Investigation of the Motion Characteristics of Parts on a Platform Subjected to Planar Oscillations. *Appl. Sci.* **2023**, *13*, 9576. [CrossRef]
52. Krühn, T.; Falkenberg, S.; Overmeyer, L. Decentralized control for small-scaled conveyor modules with cellular automata. In Proceedings of the 2010 IEEE International Conference on Automation and Logistics, Shatin, Hong Kong, 16–20 August 2010; pp. 237–242. [CrossRef]
53. Overmeyer, L.; Ventz, K.; Falkenberg, S.; Krühn, T. Interfaced multidirectional small-scaled modules for intralogistics operations. *Logist. Res.* **2010**, *2*, 123–133. [CrossRef]
54. Safaric, R.; Uran, S.; Winther, K. Closed-loop control of rigid and flexible objects on a pneumatic active surface device. In Proceedings of the 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2000) (Cat. No.00CH37113), Takamatsu, Japan, 31 October–5 November 2000; Volume 1, pp. 486–491. [CrossRef]
55. Šafarič, R.; Uran, S.; Winther, T. Control of rigid and flexible objects on a pneumatic active surface device. *Trans. Inst. Meas. Control* **2004**, *26*, 139–165. [CrossRef]
56. Laurent, G.J.; Moon, H. A survey of non-prehensile pneumatic manipulation surfaces: principles, models and control. *Intell. Serv. Robot.* **2015**, *8*, 151–163. [CrossRef]
57. Oyobe, H.; Hori, Y. Object Conveyance System "Magic Carpet" Consisting of 64 Linear Actuators—Object Position Feedback Control with Object Position Estimation. In Proceedings of the 2001 IEEE/ASME international Conference on Advanced Intelligent Mechatronics, Como, Italy, 8–12 July 2001. [CrossRef]
58. Robertson, M.A.; Murakami, M.; Felt, W.; Paik, J. A Compact Modular Soft Surface With Reconfigurable Shape and Stiffness. *IEEE/ASME Trans. Mechatron.* **2019**, *24*, 16–24. [CrossRef]
59. Chen, Z.; Deng, Z.; Dhupia, J.S.; Stommel, M.; Xu, W. Motion Modeling and Trajectory Tracking Control for a Soft Robotic Table. *IEEE/ASME Trans. Mechatron.* **2021**, *27*, 2667–2677. [CrossRef]
60. Raptis, I.A.; Hansen, C.; Sinclair, M.A. Design, modeling, and constraint-compliant control of an autonomous morphing surface for omnidirectional object conveyance. *Robotica* **2022**, *40*, 213–233. [CrossRef]
61. Subburaman, R.; Selvaggio, M.; Ruggiero, F. A Non-Prehensile Object Transportation Framework With Adaptive Tilting Based on Quadratic Programming. *IEEE Robot. Autom. Lett.* **2023**, *8*, 3581–3588. [CrossRef]
62. Bhattacharjee, A.; Lu, Y.; Becker, A.T.; Kim, M. Magnetically Controlled Modular Cubes with Reconfigurable Self-Assembly and Disassembly. *IEEE Trans. Robot.* **2021**, *38*, 1793–1805. [CrossRef]
63. Rosenfelder, M.; Ebel, H.; Eberhard, P. Force-based organization and control scheme for the non-prehensile cooperative transportation of objects. *Robotica* **2024**, *42*, 611–624. [CrossRef]
64. Fantoni, G.; Santochi, M. Development and testing of a brush feeder. *CIRP Ann.* **2010**, *59*, 17–20. [CrossRef]
65. Deng, Z.; Stommel, M.; Xu, W. A Novel Soft Machine Table for Manipulation of Delicate Objects Inspired by Caterpillar Locomotion. *IEEE/ASME Trans. Mechatron.* **2016**, *21*, 1702–1710. [CrossRef]
66. Deng, Z.; Stommel, M.; Xu, W. Mechatronics Design, Modeling, and Characterization of a Soft Robotic Table for Object Manipulation on Surface. *IEEE/ASME Trans. Mechatron.* **2018**, *23*, 2715–2725. [CrossRef]
67. Deng, Z.; Stommel, M.; Xu, W. Operation Planning and Closed-Loop Control of a Soft Robotic Table for Simultaneous Multiple-Object Manipulation. *IEEE Trans. Autom. Sci. Eng.* **2020**, *17*, 981–990. [CrossRef]

68. Tone, T.; Suzuki, K. Surface Deformation Control of a Ferrofluid-Based Robotic Sheet for Object Handling. *IEEE Trans. Autom. Sci. Eng.* **2019**, *16*, 851–862. [CrossRef]
69. Chen, J.; Gauci, M.; Li, W.; Kolling, A.; Groß, R. Occlusion-Based Cooperative Transport with a Swarm of Miniature Mobile Robots. *IEEE Trans. Robot.* **2015**, *31*, 307–321. [CrossRef]
70. Naeem, M.A.; Rizwan, M.; Shiakolas, P.S. Micropart Motion on a Surface Due to Controlled Surface Excitation. *IEEE Access* **2021**, *9*, 98916–98927. [CrossRef]
71. Matignon, L.; Laurent, G.J.; Le Fort-Piat, N. Design of semi-decentralized control laws for distributed-air-jet micromanipulators by reinforcement learning. In Proceedings of the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, St Louis, MI, USA, 11–15 October 2009; pp. 3277–3283. [CrossRef]
72. Tisnés, S.D.; Petit, L.; Prelle, C.; Lamarque, F. Modeling and Experimental Validation of a Planar Microconveyor Based on a 2 × 2 Array of Digital Electromagnetic Actuators. *IEEE/ASME Trans. Mechatron.* **2021**, *26*, 1422–1432. [CrossRef]
73. Bianchi, E.; Jorg, O.J.; Fantoni, G.; Brosed Dueso, F.J.; Yagüe-Fabra, J.A. Study and Simulation of an Under-Actuated Smart Surface for Material Flow Handling. *Appl. Sci.* **2023**, *13*, 1937. [CrossRef]
74. Mobes, S.; Laurent, G.J.; Clevy, C.; Fort-Piat, N.L.; Piranda, B.; Bourgeois, J. Toward a 2D Modular and Self-Reconfigurable Robot for Conveying Microparts. In Proceedings of the 2012 Second Workshop on Design, Control and Software Implementation for Distributed MEMS, Besancon, France, 2–3 April 2012; pp. 7–13. [CrossRef]
75. Skima, H.; Varnier, C.; Dedu, E.; Medjaher, K.; Bourgeois, J. Post-prognostics decision making in distributed MEMS-based systems. *J. Intell. Manuf.* **2019**, *30*, 1125–1136. [CrossRef]
76. Suh, J.; Darling, R.; Bohringer, K.F.; Donald, B.; Baltes, H.; Kovacs, G. CMOS integrated ciliary actuator array as a general-purpose micromanipulation tool for small objects. *J. Microelectromec. Syst.* **1999**, *8*, 483–496. [CrossRef]
77. Skachek, S.; Adamatzky, A.; Melhuish, C. Manipulating planar shapes with a light-sensitive excitable medium: Computational studies of closed-loop systems. *Int. J. Bifurc. Chaos* **2006**, *16*, 2333–2349. [CrossRef]
78. Kilikevičius, S.; Liutkauskienė, K.; Fedaravičius, A. Nonprehensile Manipulation of Parts on a Horizontal Circularly Oscillating Platform with Dynamic Dry Friction Control. *Sensors* **2021**, *21*, 5581. [CrossRef]
79. Reznik, D.; Canny, J. A flat rigid plate is a universal planar manipulator. In Proceedings of the 1998 IEEE International Conference on Robotics and Automation (Cat. No.98CH36146), Leuven, Belgium, 20 May 1998; Volume 2, pp. 1471–1477. [CrossRef]
80. Ferreira, A.; Fontaine, J.G. Dynamic modeling and control of a conveyance microrobotic system using active friction drive. *IEEE/ASME Trans. Mechatron.* **2003**, *8*, 188–202. [CrossRef]
81. Vose, T.H.; Turpin, M.H.; Dames, P.M.; Umbanhowar, P.; Lynch, K.M. Modeling, design, and control of 6-DoF flexure-based parallel mechanisms for vibratory manipulation. *Mech. Mach. Theory* **2013**, *64*, 111–130. [CrossRef]
82. Chen, X.; Zhong, W.; Li, C.; Fang, J.; Liu, F. Development of a Contactless Air Conveyor System for Transporting and Positioning Planar Objects. *Micromachines* **2018**, *9*, 487. [CrossRef] [PubMed]
83. Mita, Y.; Arai, M.; Tixier, A.; Fujita, H. Bulk Micromachined Durable Air-Flow Microactuator Array for Robust Conveyance Systems. In Proceedings of the Transducers '01 Eurosensors XV, Munich, Germany, 10–14 June 2001; Obermeier, E., Ed.; Springer: Berlin/Heidelberg, Germany, 2001; pp. 718–721. [CrossRef]
84. Fukuta, Y.; Chapuis, Y.A.; Mita, Y.; Fujita, H. Design, fabrication, and control of MEMS-based actuator arrays for air-flow distributed micromanipulation. *J. Microelectromec. Syst.* **2006**, *15*, 912–926. [CrossRef]
85. Moon, H.; Luntz, J. Distributed Manipulation of Flat Objects with Two Airflow Sinks. *IEEE Trans. Robot.* **2006**, *22*, 1189–1201. [CrossRef]
86. Ku, P.J.; Winther, K.; Stephanou, H.; Safaric, R. Distributed control system for an active surface device. In Proceedings of the 2001 ICRA, IEEE International Conference on Robotics and Automation (Cat. No.01CH37164), Seoul, Republic of Korea, 21–26 May 2001; Volume 4, pp. 3417–3422. [CrossRef]
87. Gurtner, M.; Zemánek, J.; Hurák, Z. Alternating direction method of multipliers-based distributed control for distributed manipulation by shaping physical force fields. *Int. J. Robot. Res.* **2023**, *42*, 3–20. [CrossRef]
88. Bedillion, M.; Messner, W. Control for actuator arrays. *Int. J. Robot. Res.* **2009**, *28*, 868–882. [CrossRef]
89. Fukuda, T.; Takagawa, I.; Sekiyama, K.; Hasegawa, Y. Hybrid approach of centralized control and distributed control for flexible transfer system. In *Distributed Manipulation*; Springer: Berlin/Heidelberg, Germany, 2000; pp. 65–85.
90. Elahidoost, A.; Keshmiri, M. Final position and trajectory control of an object on a distributed manipulation system. In Proceedings of the 2009 6th International Symposium on Mechatronics and Its Applications, Sharjah, United Arab Emirates, 23–26 March 2009; pp. 1–6. [CrossRef]
91. Tao, S.; Youpan, Z.; Hui, Z.; Pei, W.; Yongguo, Z.; Guangliang, L. Three-wheel Driven Omnidirectional Reconfigurable Conveyor Belt Design. In Proceedings of the 2019 Chinese Automation Congress (CAC), Hangzhou, China, 22–24 November 2019; pp. 101–105. [CrossRef]
92. Murphey, T.D.; Burdick, J.W. Feedback control methods for distributed manipulation systems that involve mechanical contacts. *Int. J. Robot. Res.* **2004**, *23*, 763–781. [CrossRef]
93. Bianchi, E.; Jorg, O.J.; Fantoni, G.; Dueso, F.J.B.; Yaüge-Fabra, J.A. Design of a test bench to measure in-plane friction forces produced by a new under-actuated modular device. *Adv. Sci. Technol.* **2023**, *132*, 155–164. [CrossRef]
94. Guelpa, V.; Laurent, G.J.; Dahroug, B.; Le Fort-Piat, N. Modular Contact-Free Conveyors for Handling Planar Fragile Objects. *IEEE Trans. Robot.* **2017**, *33*, 92–101. [CrossRef]

95. Piatkowski, T.; Szempruch, J. Ranges of application of sorting manipulators. *J. Pol. CIMAC* **2011**, *6*, 235–244.
96. Böhringer, K.F.; Choset, H. *Distributed Manipulation*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2000.
97. Zhu, L.; El-Baz, D.; Ning, H. Survey on Air Levitation Conveyors with Possible Scalability Properties. In Proceedings of the 2015 IEEE 12th International Conference on Ubiquitous Intelligence and Computing and 2015 IEEE 12th International Conference on Autonomic and Trusted Computing and 2015 IEEE 15th International Conference on Scalable Computing and Communications and Its Associated Workshops (UIC-ATC-ScalCom), Beijing, China, 10–14 August 2015; pp. 802–807. [CrossRef]