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Automated assembly of non-rigid objects

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ABSTRACT

Many assembled products contain parts that are not rigid, and there is a large variety of such parts, which might be as different as cables, sheet metals, plastic covers, or foams. The assembly processes of such products may also involve non-rigidity in the tools used. Non-rigidity in the parts and tools adds additional degrees of freedom to the assembly processes and systems, which, on the one hand, adds engineering complexity, and on the other hand, may be the key for superior solutions. This paper reviews recent developments in models, methods, handling techniques, and control of such parts at the assembly station and systems levels with a main focus on applications related to the manufacturing industry. The core areas of knowledge addressed by this paper cover advanced models for non-rigid objects, process and system planning, new tooling, and new control concepts based on perception and human-robot interaction. More research work is expected in the field of modelling and perception due to the development of computer vision, robotics, and artificial intelligence. New advances on the processing and assembly hardware can also be expected due to the highly active research field of soft material robotics and high-payload-gripping with soft material versatility.

1. Introduction

Advances in factory automation have resulted in significant improvement in manufacturing quality and productivity. However, many manufacturing processes and systems involving non-rigid parts are still not yet as fully automated as for systems involving rigid parts. As presented in Fig. 1, this discrepancy is due to the uncertainty and engineering effort implied with the additional degrees of freedom introduced by the non-rigid parts. For example, non-rigid components such as thin sheet metals, flexible plastic coverings, cables, wiring harnesses, and fabrics introduce additional degrees of freedom into the production systems. While it is attractive or even inevitable to use non-rigid parts, components, and tools for increased flexibility in product configuration, it comes at the price of increased manufacturing complexity [178]. This dilemma is a core driver for new concepts and technologies for the assembly of non-rigid objects to be reviewed in this paper.

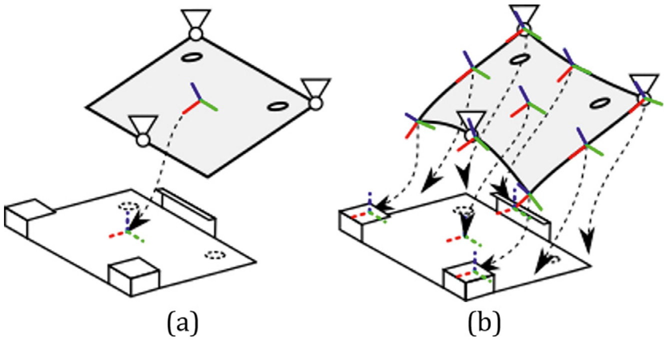
(a) (b)

Fig. 1. Analysis of assembly problem for: a) Rigid object, and b) non-rigid object [87].

In our literature review, we have observed that the interest in automating the assembly of non-rigid parts has increased significantly. We postulate that this is due to the increased cost of human labour, while the cost for industrial robots and equipment has dropped drastically and their abilities have increased substantially. It is hence reasonable that more and more attempts are made to automate advanced processes in non-rigid assembly. This hypothesis is supported by our observation that, while previous decades were dominated by the scientist's perspective of fundamental science, the advances in the recent decade are also pushed by the practitioner's perspective of empirical innovations driven by industrial applications. This plethora of recent activities unfolds a large variety of processes, which have triggered industry and academia to create new models, methods, and components for non-rigid part assembly. As the market grows and new technologies are developed, it is important to take a closer look at the types of non-rigid parts, devices, and

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methods used in automated production and assembly processes for such parts.

This paper reviews the state of the art in non-rigid part assembly, methods to model part behaviours and assembly systems performance, and advances in sensors and automation. It also discusses challenges in such assembly systems and opportunities for future research and technological advances. A holistic and systematic confrontation of non-rigid assemblies is performed by covering all aspects from material mechanics to complete robotized handling solutions. This is reflected to the organization of the keynote's sections where key aspects, that technologies should advance, are distinguished and discussed. Section 2 classifies the non-rigid part assembly processes and provides more detailed examples. Processes and challenges investigated in the literature are summarized, considering also aspects of non-rigidity of both tooling and actual parts. Section 3 discusses aspects of processes modelling and design, tooling, grasping, fixturing as well as modelling of material behaviors. Section 4 discusses aspects of assembly system design and implementation with consideration of system performances. Section 5 presents solutions for process sensing by evaluating different sensing solutions considered in the literature while discussing also different modelling approaches for machine control. Section 6 summarizes the main findings and provides outlooks for future research and developments. Finally, Section 7 concludes this keynote paper.

2. Classification of non-rigid objects and process types

Defining the concept of non-rigid materials and objects is a challenging task. In general, a part can be considered as non-rigid if its deformations are larger than at least one of its own dimensions due to weight, inertia or grasping or assembly forces. As a result of this possible change in shape, non-rigid parts require specific attention and solutions during part manipulation and assembly.

This section begins with a classification on non-rigid parts, followed by a non-exhaustive overview of its applications, and finally discusses the challenges for handling tools and multi-agent manipulation of non-rigid materials.

2.1. Classification of non-rigid materials

Within this paper we do not target a formal or systematic classification of non-rigid objects for which various criteria, such as for example, material, size, shape, geometry, production and assembly technology, can be used. In line with other reviews and surveys (e.g., Nadon et al. [148]), the proposed classification is selected as it facilitates the grouping of similar research approaches and related trends in modelling, tooling, sensing and control in a rather natural way. While Jiménez [101] proposed a classification method of deformable objects by considering only their geometric shape, Sanchez et al. [168] proposed a classification of deformable objects into four categories taking into account also their physical properties, as illustrated in Fig. 2.

In more detail, the objects are classified as:

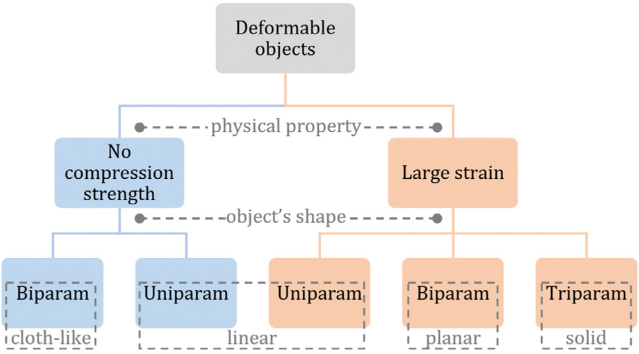

Fig. 2. Classification of deformable objects based on their physical properties, adapted from [168].

- **One-dimensional** objects, often referred to as linear objects. Those have one dimension significantly larger than the other two and they present neither compression strength (e.g., cables, ropes, coils, strings…) nor a large strain (e.g., elastic tubes and beams).
- **Two-dimensional** objects, that have one dimension considerably smaller than the other two. Those could be divided into two main categories:
  - Planar objects with elastic behaviour that present a large strain of displacement (e.g., O-rings, paper, cards and foam sheets).
  - Cloth-like objects which do not possess any compression strength. Examples within this object class are fabric sheets.
- **Three-dimensional** or volumetric objects. Those comprise objects such as sponges and food products.

2.2. Applications with non-rigid objects

Following the shape classification presented in Section 2.1, this Section provides a set of application examples regarding the automated handling of non-rigid parts amongst with their challenges.

As illustrated in Fig. 3, Sadaad and Nan further elaborated in this classification up to the level of respective industrial applications and individual manufacturing processes per material category [164]. A more exhaustive overview and description of this classification can be found in their report.

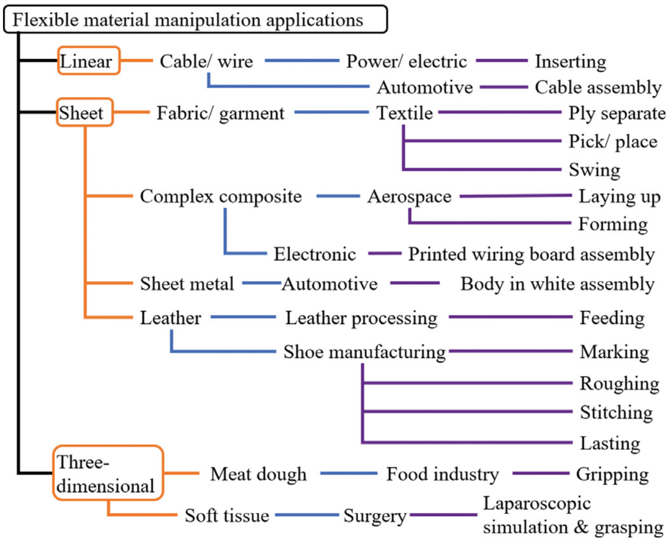

Fig. 3. Industrial classification of automatic manipulation of flexible materials (black: dimensional classification, orange: component type classification, blue: sector classification, purple: applications), adapted from [164].

2.2.1. One-dimensional objects: cable/wire harnessing

The manipulation of deformable one-dimensional or linear non-rigid objects such as ropes, cables and wires, often to be inserted into rigid holes or final products, remains a relevant challenge in many industries such as automotive and electronics [9,196]. Amongst others, manipulation tasks for this type of objects can be found in untangling ropes [129] and tying knots [89,95,166] for which dedicated perception, trajectory modelling and force control strategies are required.

Today's automotive and aerospace wire harness manufacturing and assembly processes are still dominated by manual tasks. A recent study at Mercedes-Benz describes the manufacturing and assembly process of high-voltage wire harnesses of electric vehicles, which is determined by a high level of manual work, reaching up to 85% of the added value [156]. The authors identified three main obstacles for further process automation: 1. complex supply chains, 2. lack of automation-friendly product, mainly the high-voltage connector, design, and 3. the adaptation of manufacturing processes for handling of deformable components that comply with industry requirements.

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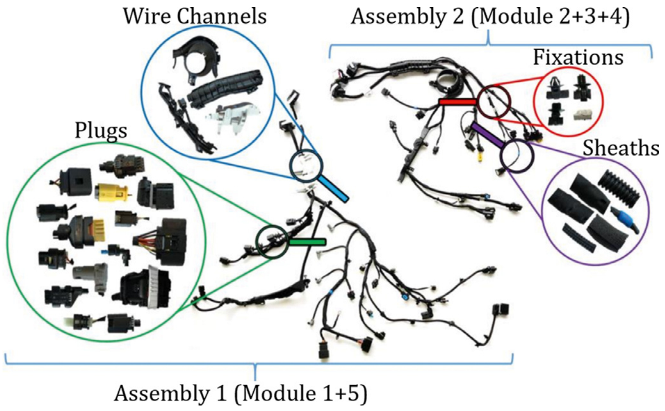

Fig. 4. Example of the variety and number of parts within a wire harness of a Mercedes-Benz OM654 engine [192].

Trommnau et al. [192] and Giang Nguyen et al. [153] present in-depth overviews of the state-of-the-art research and future trends in this field by discussing aspects related to the design of electronic and harness components (Fig. 4), process parameter monitoring, special purpose machinery and overall challenges in their automation.

While the demand and related research for automation solutions significantly increased during the last decade, the high diversity of variants, high number of parts within a wire harness, and the high investment costs represent important challenges for industrial implementation. In recent years, both academia and industry made first steps towards further automation in the wire harnessing industry [74]. Navas-Reascos et al. [151] present a literature review and call for developments regarding collaborative robots supporting the wire harness assembly process, whereas other authors focused on the robotic manipulation [157] of wire harnesses while taking into consideration collisions or interaction with the environment, as illustrated in Fig. 5. In addition to wire routing, special focus is also given in additional complex harness applications involving robotized wrapped connections using single solid round wires [78] in addition to electric motor assembly [110].

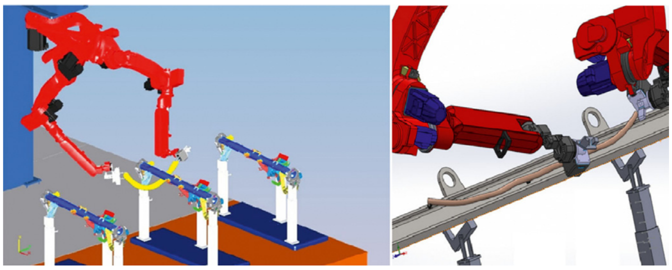

Fig. 5. Automated dual arm cabling assembly: collision detection during manipulation [157].

2.2.2. *Two-dimensional objects: sheet metal parts*

Manual and robotic handling of compliant sheet metal parts, as applied in automotive and aerospace manufacturing industries, leads often to sheet deformations which need to be controlled in order to obtain the targeted assembly dimensional quality.

Various research publications report about the influence of fixtures and grippers on the assembly quality of sheet metal parts [29,29,160,161,164,179]. Other authors either proposed methods for evaluating the ability of an assembly system to compensate dimensional part variabilities [33], or investigated the impact of fixture design on the dimensional quality of sheet metal parts after assembly [28]. In this study, the effect of both part and tool variation as well as assembly springback were considered. In [162], a methodology for significantly improving the geometrical quality of parts, by optimizing the location and type of holes and slots in each part, the slot orientation and the number and location of additional clamps, was presented. Having a similar objective, an automated approach for grouping multiple car body parts by clamping them into a single adjustable jig that was developed in [191], is discussed in [155].

Focusing more on hardware perspectives, a method for the design optimization of end-effectors for handling compliant sheet metal parts is presented in [68]. In parallel, an industrial example of a flexible gripper for sheet metal workpieces is recently developed and patented by the LVD Company. Their universal and auto-adapting gripper so-called ‘Ulti-Form’ gripper [220], as presented in Fig. 6, is able to accommodate the automated material handling of multiple part geometries during bending processes. This is achieved by changing the configuration of the suction cup arrays as well as the whole end-effector’s configuration through electric and pneumatic actuators. Another often robotized sheet metal manufacturing process can be found in (single point) incremental forming. While Duflou et al. provide a detailed state of the art overview and prospects in [49] for single point incremental forming (SPIF) processes, Lee et al. [34] broaden the scope to flexible forming technologies.

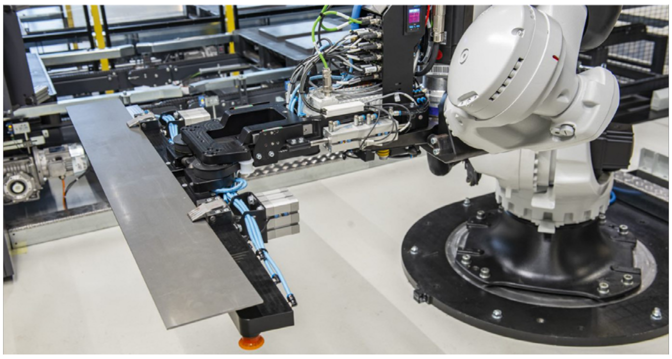

Fig. 6. ‘Ulti-Form’ gripper for flexible sheet metal part handling in robotic bending processes [220].

2.2.3. *Two-dimensional objects: composite materials*

In [60], Fleischer et al. presented an extensive overview of the different processes for the composite material part manufacturing in both current research fields and industrial applications. The discussed processes cover part generation, machining, post processing, joining up to quality control and composite recycling. Automated handling strategies form a key role within and between different steps of the composite manufacturing process chain, when further automation of composite manufacturing is intended.

Björnsson et al. [17] reviewed the use of pick-and place systems for automated material handling in composite manufacturing and concluded that it is hard to find a generic solution for automated handling of composite materials. Next to the highly varying properties of the material, amongst others, the various ply shapes, different fibre orientations, and complex mould shapes require different solutions. By following the methodology of [64], in a recent study, Jayasekara et al. [100] investigated the level of automation (LOA) for the different process steps of commonly used composite manufacturing processes in aerospace. The steps involved autoclave moulding (AM), filament winding (FW), automated tape layup (ATL), resin transfer moulding (RTM), and pultrusion (PL). While core process tasks typically show intermediate LOA’s, most non-value-added activities are still at lower LOA’s. In consequence, there is still a significant potential for further automation of composite manufacturing chains.

Focusing on the manipulation of composites itself, a wide range of strategies for the handling of single composite sheets can be found in literature. In [51], Elkington et al. defined the four categories illustrated in Fig. 7, namely:

- **Rigid:** the composite sheets are picked up using grippers mounted on a rigid frame resulting in a rather rigid sheet.

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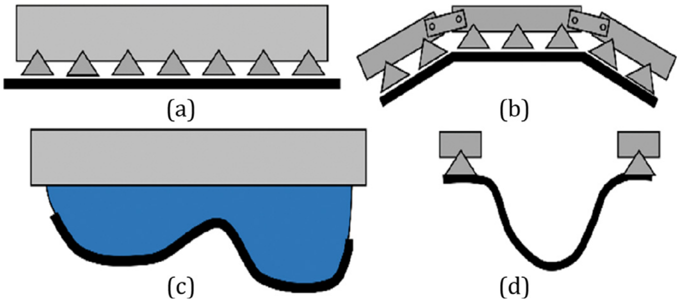

Fig. 7. Schematics of four commonly used composite sheet handling methods: (a) rigid, (b) kinematic, (c) compliant, and (d) free ply [51].

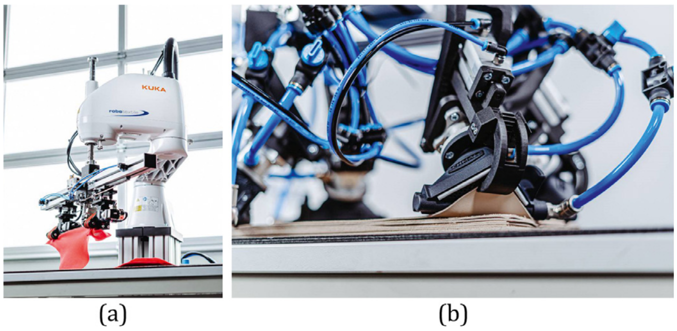

Fig. 9. Robot cell (a) and robotic gripper (b) of Robotextile [222] for automated destacking of textiles in the garment industry.

- **Kinematic:** deformable handling systems place the sheets in more complex molds. However, the complexity of the tool (e.g., number of linkages and actuators) increases rapidly when the sheets become larger or more complex, limiting the flexibility and applicability of this approach.
- **Compliant:** passive compliant elements which deform can be used for pressing the sheets to the mould.
- **Free ply:** in this method the sheets are grasped at a limited number of points, typically located at corners of edge, resulting in free hanging sheets.

In order to become more competitive, de Zeeuw et al. [214] evaluated the suitability of existing pick-and-place strategies to handle more and larger composite sheets in a faster way. While all four sheet handling strategies can be used, the free ply method becomes more relevant as the sheet size increases. In order to handle multiple sheets simultaneously, needle grippers are recommended. For all methods the sheets can be picked-up/placed down in a straight movement or through a rolling motion. Most used gripping methods include needles, vacuum, cryo-freezing, electrostatic and gecko inspired grippers. A comprehensive overview of gripper technologies is provided by Fantoni et al. [55]. A noteworthy tool, for composite sheets draping, is the membrane-shaped magnetorheological (MR) that is discussed in [175,176]. As presented in Fig. 8, this tool is able to cope with various product features, allowing companies to anticipate to the high mix low volume market demands in a cost-effective way.

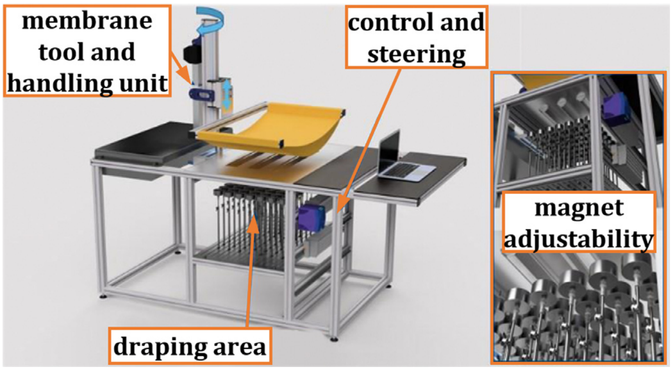

Fig. 8. Overview of the testing setup for the membrane-shaped MR-based draping tool, adapted from [176,175].

Further examples for composite manipulation, including preforming and stamp forming of reinforced thermoplastics, can be found in [14] and [23]. Whereas new manufacturing solutions for spacer prefroms for thermoplastic textile-reinforced lightweight structures are discussed in [75].

2.2.4. Two–dimensional objects: clothing, textiles and leather

The behaviour of fabrics used in the garment and textile industry is very similar to that of dry reinforcements from the previous section [168]. Next to pick and place, further challenges of this industry can be found in separation, untangling, flattening, folding and unfolding as extensively presented in [15,115,116,132] and [140]. Despite the large size of this industry, developments in automated part handling are rather limited and most approaches try to mimic manual operations [115,164], which often lead to intermediate regrasping step(s). Robotextile [222] is one of the first commercial equipment providers (e.g., Fig. 9) for the automated loading/unloading of industrial sewing and garment manufacturing processes.

Apart industrial applications, textile manipulation can be found in service robots as well. Previous studies have focused on perception of textile towards advanced cognition throghout step-by-step (un)folding operations [66,176,215].

2.2.5. Two-dimensional objects: belts and rings

Amongst others, automotive industry involves many operations where O-rings need to be installed mostly for sealing applications. To this purpose, grippers with multiple fingers have been designed for internal or external O-ring placement [221]. The installation of such components or belt drives has also been the topic in robotic competitions [208] since it is a complex process that requires deformation control and in some cases in-hand manipulation.

2.2.6. Three–dimensional objects: food and agriculture

Besides their soft deformable character, food products often have additional handling challenges such as, for example, uneven surfaces, non-uniform shapes and last but not least hygienic and food safety requirements. A study by Wang et al. [197] analysed the challenges and opportunities in robotic food handling. By investigating both academic as well as commercial systems, the authors listed three main aspects which need further improvements, namely: 1. better understanding of the physical properties and classification of food products, 2. better perception and recognition of the products, and 3. the development of compliant, hygienic and low-cost robotic end-effectors. While Fantoni et al. [55] provide an exhaustive state of the art overview of the latter, Masey et al. [136] presented guidelines for the design of robotic systems for the food industry. More specifically those guidelines indicate that related robotic systems should: 1. be easy to clean through hygienic design, 2. be low cost, 3. have high operational speed, 4. be safe during operation besides human workers, and finally 5. be easy (re)programmed. As shown in Fig. 10, an example of a commercial assembly application in the food industry can be found in the fully automated skewering and kabob machine of Pintro [218].

2.2.7. Two/three–dimensional objects: lithium-ion battery cells

An example of the insertion/stacking of limp two-dimensional objects into three-dimensional assemblies can be found in battery modules. An in-depth literature review on the current status and challenges for battery production technologies is provided by Ayerbe et al. [10] and Kwade et al. [114].

A feasibility study on the automated assembly of Li-ion vehicle batteries and more specifically on the automated assembly of the

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Fig. 10. Fully automated meat skewering machine [218].

extremely thin and limp cathodes has been performed in previous studies [36]. Technically, the stacking of the anodes and separators of Lithium-ion cells forms a major challenge. In this perspective, research activities focused on the development and integration of a cut & place module for highly productive manufacturing of lithium-ion cells [13]. This concept, as illustrated in Fig. 11, automated the z-folding (Fig. 11a) and cell stacking (Fig. 11b) processes.

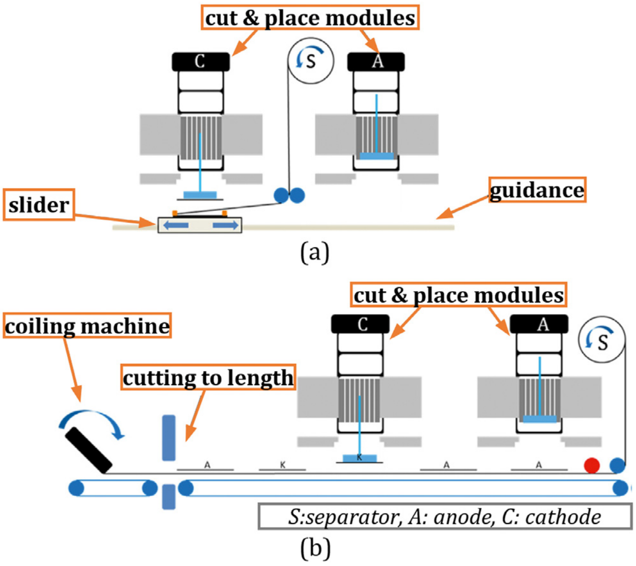

Fig. 11. Two conceptual integrations of the cut & place modules in (a) z-folding, and (b) cell stacking processes, adapted from [13].

Since particulate contaminations on the electrode surface is a disruptive factor, previous activities investigated this type of emissions during handling of electrodes for different vacuum-based technologies [63]. Since non-contact techniques as Bernoulli and cyclone grippers cause oscillations of the limp electrode material causing considerable detachment of the coating, area vacuum grippers are recommended for the handling of electrodes in the lithium-ion battery cell production. In order to reduce the handling force, dedicated force sensitive vacuum device for the handling of lithium-ion cell foils, as shown in Fig. 12, have been developed [56].

Besides assembly, also the automated disassembly and recycling of battery cells has gained a lot of research attention in the last decade. In [67], an analysis about the variety of lithium-ion battery modules and the related challenges for an agile automated disassembly system are discussed. Two main challenges are identified: the variety of battery modules, and non-detachable joints combined with hazards posed by lithium-ion batteries.

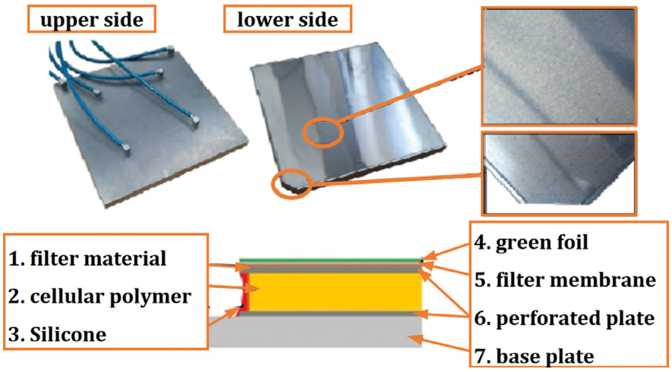

Fig. 12. Force sensitive vacuum device for the handling of lithium-ion cell foils. Inner structure of the device (bottom), adapted from [56].

2.2.8. *Three–dimensional objects: healthcare and robotic surgery*

A final application example in which three-dimensional non-rigid materials are assembled/disassembled with non-rigid tooling can be found in healthcare and robotic surgery [12,46,90,98,201,202]. As indicated by Taylor et al. [189], the related technologies can be grouped into two categories based on their mechanical design and application:

- Robots with high precision, high stiffness, low speed, (possibly) limited dexterity and often high gear ratios (thus low back-drivability) are very suitable for orthopaedic bone shaping or stereotactic needle placement.
- On the other hand, complex and minimally invasive surgery on soft tissues needs compact, dexterous robotic systems with high responsiveness, low stiffness and highly back-drivable mechanisms.

2.3. *Handling tools for non-rigid parts*

Building on Warnecke et al. [199] and Seliger et al. [178], who were amongst the first to discuss the automated handling of non-rigid parts, Fantoni et al. [55] listed the most important challenges in handling of non-rigid parts, in detail:

- **during grasping:** 1. deformation of the object, and 2. separation of the object from a stack
- **during transport:** 1. unexpected releasing of the object, and 2. collisions against obstacles, and
- **during releasing:** 1. spreading of the object on a surface, and 2. assembly of the object.

Furthermore, the authors presented an exhaustive overview of the grasping principles and related grippers for non-rigid objects based on their shape and material. Those are summarized on Table 1. Referring to the non-rigid properties of the object and/or the handling devices, three categories of tools can be distinguished, namely: 1. Rigid tools for non-rigid materials, 2. Deformable or compliant tools for rigid materials, and 3. Non-rigid tools for non-rigid materials.

For the second category, an example is shown in Fig. 13. The mechanics, fundamentals, components, systems and related sensing and control approaches for a wide set of handling (e.g., part grasping and part fixturing) and assembly tools and in addition to assembly systems will be thoroughly discussed in the next sections.

2.4. *Multi-agent manipulation of non-rigid materials*

Multi-robot handling of non-rigid parts, for example in multi-stage sheet metal press lines, is a challenging task. Glorieux et al. [68,69] indicated that by co-adaptively designing the end-effector with the motion planning of the robot, unwanted part deformations, drops or collisions could be avoided. Industrial validations, as

Table 1
Grasping principles of non-rigid parts [55] (XXX: very good, XX: good, X: fair).

Grasping principles	2D shapes				3D shapes			
	Fabrics	Leatherplies	Papersheets	Metalsheets	Plasticparts	Rubberparts	Food	Bags
Mechanical grasping	Xx	x	x		xxx	xx	xxx	xxx
Ingressive grasping	xxx						xx	xx
Electromag-netic grasping				xxx				
Electrostatic grasping		xx			xx			
Suction caps		xx	xx	xxx	xxx	xxx		
Air jet grippers		xx	x	x	xx	xx	x	
Cryogenic grippers	xx						xx	x

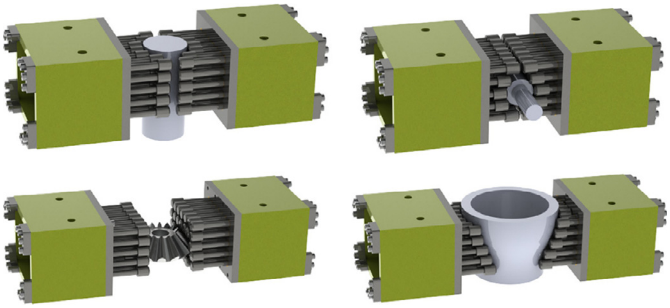

Fig. 13. Example of a compliance gripper [99].

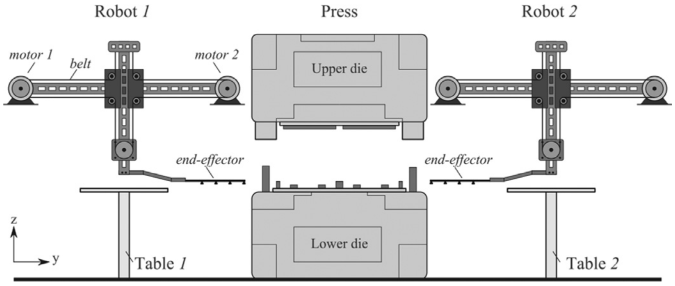

Fig. 14. Case study with two robots loading/unloading a single press [69].

illustrated in Fig. 14, showed the significant potential for improvements in productivity of such processes.

Even more challenging is the co-manipulation of flexible objects between human operators and robots. Depending on the inspiring industrial scenarios, previous work involves co-manipulation strategies using single arm or dual-arm configurations for the transferring of composite fabrics during composite layup [6,133], or even completed composite end-products [97]. While Andronas et al. [6] presented a model-based control framework for the handling of large, deformable materials during human-robot co-manipulation, Kruse et al. [108,109] showed that a hybrid control loop combining vision and force data outperformed a force-only controller. Other previous works in [171] and [172] developed a reactive control framework for human-robot mobile co-manipulation of flexible objects (e.g., transportation of large composite sheets) by fusing wrench and skeleton tracking data (refer also to Fig. 49, in Section 5). While the method provides in general satisfactory results, sideways movements of the platform could be further improved. An area of great interest is the co-manipulation of deformable objects using dual-arm robots.

3. Mechanics and fundamentals of non-rigid parts and tools

This section reviews the fundamental deformation mechanics and behaviours of non-rigid parts and tools at the individual part level. The impact of non-rigidity in assembly and assembly systems will be discussed in Section 4.

3.1. Mechanics of part deformation in assembly situations

The mechanics modelling of deformation depends on the type of object considered. This is aligned with the categories introduced in Fig. 3 (one-, two-, three-dimensional objects).

3.1.1. Mechanics of non-rigid workpieces: linear-shaped objects

A recent review of models for flexible cables is found in [131]. The article emphasizes reports about elastic effects and reports about different models, including mass-spring-models, multi-body models, elastic-rod-models, dynamic spline models, and finite element models. Furthermore, the properties, advantages and disadvantages reviewed for each model type are helpful to guide the choice of a model type in a given situation. The article compiles resources from a variety of applications, ranging from natural hair simulation (where the main purpose is to simulate the geometry), medical applications (where the purpose is to know about the kinematics, in order to establish manipulation control), hoses in complex geometries (automotive example, where inner forces need to be minimized) [72], with elastic rod model [21,121], with dynamic spline model [190]). The most complex applications with relevance for assembly are from branched cable harnesses [82,84,130]. In summary, there is a variety of model types available in order to achieve customized modelling accuracy given the available computing effort, and the memory consumption to the specific situation.

Accuracy of model prediction is always a strong motivation. For example, in [159] a refined cable model, which accounts for the counterforces in twisted cables, is presented. On the opposite hand, lowering the required computing effort triggers a serious amount of research activities. A noteworthy example is the simplification approach of Wnuk et al. [205], where the detailed elastic model is approximated by a coarser model of a very much reduced computing effort.

The calibration of the elastic models is a crucial task in practical situations. Those can involve direct agent control situations (i.e., model-based control), but also other engineering applications. In [204], an experimental approach uses a point cloud that is generated by a 3-dimensional sensor for estimating the skeleton of a hose. The hose model consists of a multi-body system, where a chain of stiff rods is coupled by hinges and spring boundary conditions to fit plausible solutions. A similar approach is proposed in [158], as a basis for robotic manipulation, using higher order analytical functions instead. Furthermore, the authors elaborated on gaining information about the kinematic behaviour during manipulation, in addition to finding out about what counterforces are expected. In [131], it is discussed that calibration (i.e., in static or dynamic situations) requires dedicated sensors and specifically prepared environment (e.g. lighting, background, free line of sight), which may be feasible in a lab environment but unpractical in industrial use cases.

All these modelling efforts have the objective in common to model a deformable, linear shaped object in one particular situation of nominal character. Beyond this, during the design and planning tasks, given the uncertainties in the object's properties, it may be interesting to know about the propagation of these uncertainties to the 'behaviour' of the assembly workstation itself. In other words, the deformation and springback of cablings is subject to stochastic and unpredictable variation. Thus, it may be desired to design an assembly where such outliers are avoided. Repetitions of cable simulations (i.e., with deviating cable properties) will result in a family of geometries. The importance of this problem in the advent of electromobility, where cables with strong counterforces and large variations can be involved, is presented in [86]. This article proposes to use rod-like

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models to simulate these to gain tolerance envelopes for further analysing and optimizing product and assembly design.

3.1.2. Mechanics of non-rigid workpieces: thin-walled panel, fabrics, foils

In panels assembly, the dominant effect of non-rigidity is elasticity. Commonly, this is modelled using finite elements, and there are further models based on variational inequalities which are claimed to have benefits only when compliant parts are partially in contact [139]. In industrial assembly, compliant panels mostly occur in sheet metal assembly, of which the handling engineering is closely related to fixture design and tolerancing design. Because of the importance, this topic will be addressed specifically in the subsequent section about assembly process modelling. Other applications include wafer handling, where the stress during handling is of relevance [22].

In fabrics handling and assembly, the dominant effect of non-rigidity is the limpness (i.e., bending elasticity with very low spring-back). A review of cloth modelling techniques is given by Hou et al., who present finite-element models, particle-based models, and mass-spring models [91]. Andronas et al. employed a mass-spring modelling approach [6] (Fig. 15), which is fast enough for online-execution in a human-robot co-manipulation situation (Fig. 16).

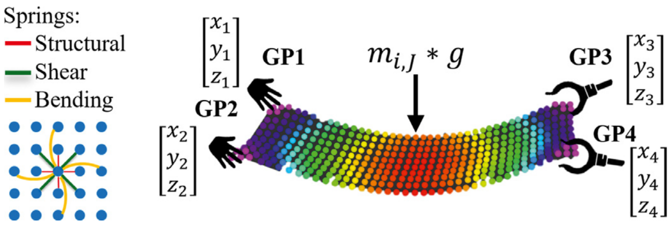

Fig. 15. Mass-spring modelling approach in fabric manipulation [6].

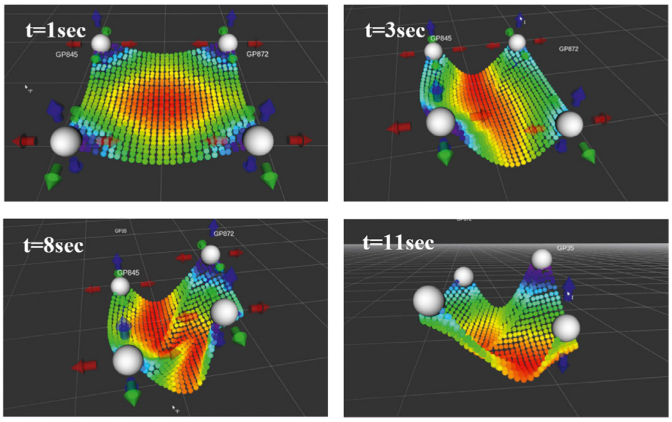

Fig. 16. Modelling and simulation of fabric manipulation [6].

Foils behave similarly to fabrics, except for the fact that their specific mass per surface area is lower. Subsequently, they are more prone to aerodynamic effects and they present smaller bending radius under suction cups [144]. In addition, in terms of handling their buckling, wrinkling and bends are much more important [173].

3.1.3. Tooling mechanics: grasp modelling

Grasp modelling predicts the forces that a grasped object can withstand before it separates unintentionally from the gripper. For form closure, Gopal et al. proposed to consider the grasped object as a finite element mesh with a given stiffness matrix [70,71]. This model is employed to define the so-called D-space (deformation space) to describe the grasping state and the so-called "deform closure"; in terms of the work needed to release the part from a set of frictionless finger contacts. The modelling of deformable gripper fingers in contact with deformable objects is still a computational challenge and attracts current research interest [143]. For example, in [145], a detailed finite element model to predict the maximum achievable payload of upscaled soft finger grippers is described.

For vacuum gripping of large panels, an elastic model of the gripper and the panels to predict the overall deformation of the gripped panel is considered [118]. On a similar basis, a team at TU Braunschweig proposes models to describe the deformation of a vacuum gripper with granular jamming inside [48].

3.2. Part grasping

Grasping and releasing of workpieces draw intense attention in automated assembly development because this is the interface between the workpiece and the production equipment. This means that requirements and peculiarities from both sides influence their realization: grasping needs to be adapted to the shape and properties of the workpiece, to the type of joining process, on one side, and to the requirements of the handling processes, on the other side. The grasping device transmits the forces applied to the workpiece during handling and assembly, and grasping is a vital part to achieve the desired accuracy. In other words, grasping is a field where poor design choices affect the process reliability in a very direct way.

Fantoni et al. [55] give an overview about research into the types of gripping devices and the design methods and provides a large list of references for further reading. The paper cited addresses mainly rigid situations (i.e., rigid objects and rigid grippers), but there is also a section about non-rigid grippers with comprehensive coverage up to the year 2014. The scope of what follows below is hence to give a complementary update to the source cited.

A prescriptive method to select gripper types is presented in [54] while a descriptive approach of grippers which exist is used in [16]. In the latter article, catalogues of industrial gripper suppliers are analysed to find out about common patterns in industrial gripper design.

3.2.1. Rigid grippers and discrete-kinematics grippers for non-rigid objects

In the reviewed body of literature, the proposal of new rigid grippers for non-rigid objects addresses fabric handling by discrete contact points, and non-contact handling of sensitive objects (such as foils and wafers). Each of the following paragraphs is dedicated to one type of these kind of grippers.

The recent intensity of research into production of fibre-reinforced workpieces [60] has also spawned concepts and components for process automation. Of particular interest, for the scope of this paper, is the draping and fixing of fibre layups, where fabric pieces with complex (and individual) outlines need to be transferred from a cutter table (which is flat) into tolerated positions within the mould (which may have complex 3-dimensional shape) and fixed there.

If the fabric is dry (so that the textile layup builds a preform which is infused with resin in a subsequent resin transfer moulding process, RTM), the layup fixturing is realized by heating up a thin layer of pre-applied hot melt. Fleischer et al. propose to use suction cups and to linearly suspend them for passive shape adaptation [58,59]. A key idea in this work is not to use exact duplicates of suspended suction cup modules but to have individually adjustable suction cups. Furthermore, their work emphasizes the individual placement of the suction cups wherever they are most needed by the geometry and the process (which is what motivates the modularisation proposed). In this way, gripping points can be concentrated where needed specifically and reduced to a sparse population where not critical, but this requires some application-specific effort. The opposite, the arrangement of suspended/retractable suction gripper pixels in an equidistant matrix is investigated by the same working group in [61]. There, suction cups cannot be placed where it is most appropriate from a process point of view, which calls for more kinematic versatility in the individual suction cup modules. It is particularly the linear motion of the suction cup suspension, which limits the accessible mould geometry.

Alternatively, if the fabric is pre-impregnated with resin (which makes the costly resin infusion in an autoclave or in an RTM process

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obsolete), this implies that the gripper must cope with the tackiness [113].

Alternatively, if the matrix is required to be thermoplastic, the fabric is pre-filled and calendered with thermoplastic material and then heated up for draping, which is why the gripper system needs to cope with the limpness, the tackiness and the temperature requirements here. Again, linear vertical suspension of suction cups is suitable if the shape is not overly complex [142]. It is noteworthy that this resource presents an additional horizontal retraction mechanism which allows for a high deep drawing ratio in the mould.

A peculiar usage of limpness variability controlled by temperature in thermoplastics is investigated in [174]. There, the thermoplastic fibre reinforced fibres are joined with metal inserts in a pre-assembly step. During the subsequent handling and layup-process, the metal inserts serve then as gripping points and load distributing elements (Fig. 17). Appropriate workpiece design can even be so advanced that the metal insert holds the fabric in shape while the thermoplastic is molten (which is needed in very fast feeding of fast cycled overmold-processes).

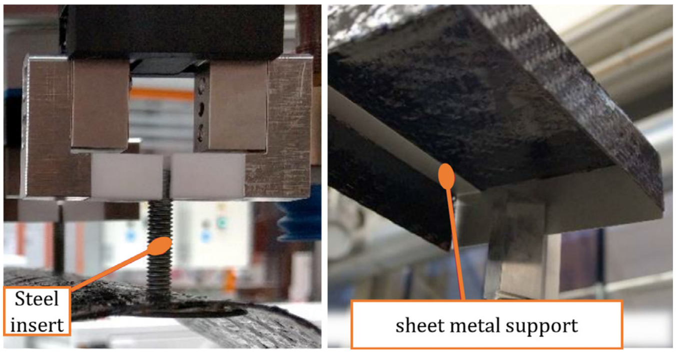

Fig. 17. A steel insert and frame are used to keep the fabric in shape during mould feeding, even if the thermoplastic is molten. A simple rigid gripper can be used, adapted from [174].

A key to these processes is the development of advanced suction cups. This refers to the contact geometry, the flow path, and the contact pressure sensors [52,59]. These are developed to optimize: 1. the resistance against shear forces or peel-off, 2. reliable grasping of only the top sheet from a stack, and finally 3. the reliable release of tacky material. A very unique gripping cup (note, it is a vortex levitation principle, not vacuum suction) is proposed by Bruns and Raatz, where hot air is blown through a vortex to grasp a piece of fabric and in parallel heat the thermoplastic matrix for the purpose of organo sheet preforming [23].

Research on battery production has spawned a concept of a Bernoulli-type gripper for limp electrode sheets [185]. Beyond its capabilities of contactless handling for limp electrodes, this design stands out in the fact that the fast and voluminous air flow is not exhausted into the environment (which causes unwanted particulate contaminations into the clean environment of battery production), but it is sucked away internally for further treatment.

Research on bin picking for small plastic bags has led to the proposal of discrete suction gripper kinematics with elasticity and built-in sensors [18]. The elasticity is embraced to compensate for disturbances or force peaks and increases the process success rate. At the same time, it lowers the effort for object recognition and task planning in such scenes.

Automotive assembly contains a number of 2-dimensional plastic covers with complex elastic deformation patterns. Researchers have proposed a method to 1. determine these deformation patterns by finite elements modelling and to train simplified discrete stiffness models therefrom, to 2. link these degrees of freedom to the degrees of freedom required for alignment at the joining points of interest, and 3. to deduct kinematic structures for gripping at discrete points and the degrees of freedom to be actuated therein [87], as presented in Fig. 18.

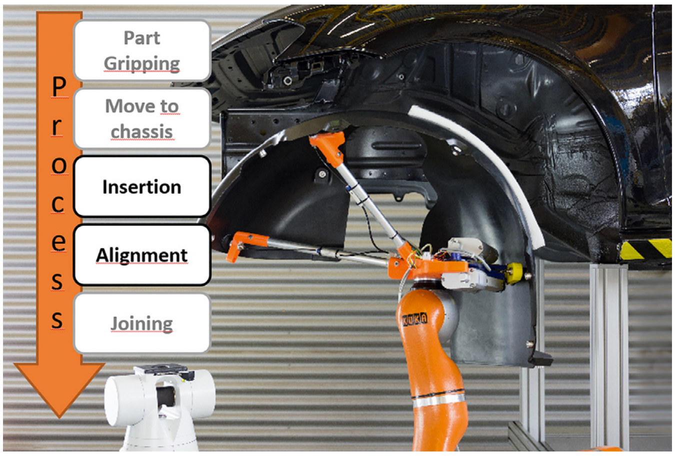

Fig. 18. Setup and process steps of experimental case study [87].

3.2.2. Non-rigid grippers with (passive) shape adaptability

Shape adaptation in grippers with continuum mechanics, i.e., grippers made of soft materials (which excludes discrete retractable gripping mechanisms covered above) has the purpose to maximize the friction, the geometric enclosure and/or to maximize the suction surface area. There is a number of proposals to achieve this, mainly from the robotics community, but only a small subset seems to be viable for applications of industrial assembly. The reasons for this rigorous rejection are, amongst others, the low achievable gripping force, the low stiffness of the gripped object, the difficulties to attain acceptable gripping reliability in industrial situations, the need for sophisticated perception, the limited durability of the materials and the predictability of the gripper's behaviour.

The choice of passive shape adaptation versus the actuated shape adaptation is mainly a compromise between simplicity and capability. Purely passive shape adaptation, for example as presented in [50], can be realized by foams. This simplicity gives the design space for the integration of further functionalities, such as heating devices for fibre preforming (Fig. 19); however, since the deformation is limited, the process presents limitations as well.

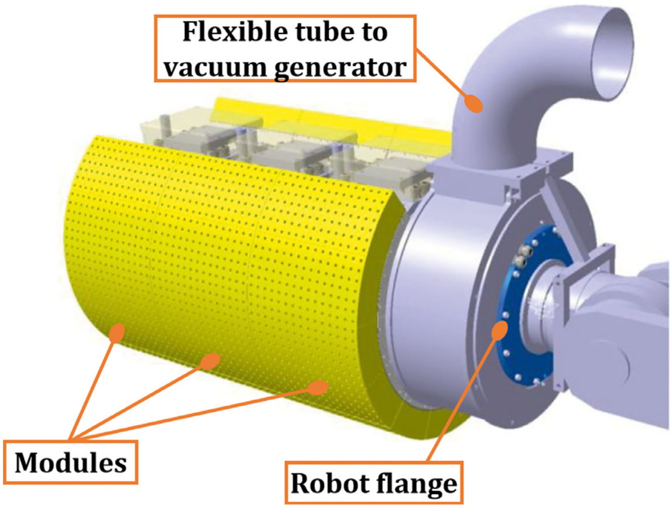

Fig. 19. Robot-based automation system for the flexible preforming of single-layer cut-outs in composite industry, adapted from [50].

Semi-active shape adaption is understood as a behaviour, where some shape variables can be influenced actively, but, clearly, the system remains underactuated so that the shape cannot be controlled

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Fig. 20. A vacuum-driven rubber band gripper [207].

fully without external contact. Yamada et al. [207] present such an approach, where an enclosing gripper is actuated to strangle the gripped object by evacuation of a ring-shaped hose chamber (Fig. 20). Such semi-actuation is favourable to maximize shape adaptability, as the figure shows impressively. This might be useful for a large set of handling applications, but, unfortunately, it is not straight forward to achieve geometrically accurate repeatability. This lies mainly in the lack of stiffness in such mechanisms.

The second group of semi-active shape adaption concentrates on the stiffness of the gripper. The research group around Löchte, Dietrich, Raatz, and Dröder have combined the granular jamming principle (which was featured previously by the Versaball in a form/friction enclosure setup) with large surface-area vacuum gripping [128] (Fig. 21). This combination creates a new class of highly shape-adaptable grippers, where the vacuum air flow does not only hold the object but does also stiffen the soft gripper cushion by granular jamming [112]. This advancement introduces an adaptation of stiffness and shape not seen before in semi-actuated continuous shape grippers.

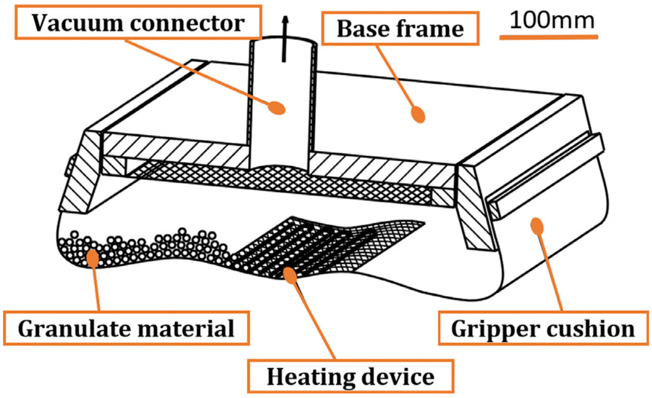

Fig. 21. Form-flexible handling and joining technology (formhand) for the forming and assembly of limp materials, adapted from [128].

Passive shape adaptation is also beneficial in mechanical gripping. The well-established Fin Ray gripper reacts to contact forces in such a way that the fins bend around the object to be enclosed. This makes such kinds of grippers attractive to compensate for variations of object geometry and grasping locations. In [145], a method for automating the design process and for maximizing the payload of such grippers is proposed; in [45], this is extended to multi-shape gripping. The objective is to establish such devices in industrial applications having far beyond 1 kg payload requirements.

3.2.3. *Non-rigid grippers with active shape control*

Active shape control with continuous degrees of freedom is of interest when the initial and/or the final shape of the object to be handled is known. For example, in [20], a gripper for fuel cell stacking (where the curvature of the layup surface changes as the stack size increases) is presented. The curvature challenge is addressed by proposing an actuation for a bending mechanism in the gripper to adapt to this behaviour, as illustrated in Fig. 22.

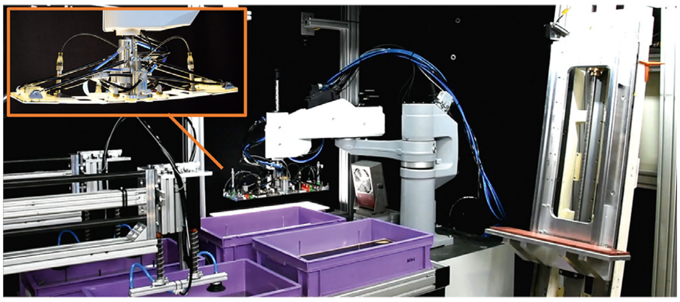

Fig. 22. Fast pick and place stacking system for thin, limp and inhomogeneous fuel cell component [20].

Active shape control is also a topic of interest, when the shape-shifting elements have very high aspect ratio and a very high depth of form enclosure is aspired. A noteworthy example is presented in [170], where a gripper, with an electrostatic holding principle, brings large limp flaps in large surface contact with the manipulated object using wire-driven actuation. It is stated that applications of interest are in the manipulation of large, thin foil-based structures during space flight missions.

3.3. *Part fixturing*

In the context of this paper, fixturing is understood as a device holding a workpiece in shape and in place. In difference to grippers, fixturing devices do not need to move the workpiece from one location to another [25]. This allows for other kinematic and actuation concepts, which are not convenient to be moved around by robots.

In the organo sheet forming process, the thermoplastic is heated up for deep drawing in a hot stamp. This idea of horizontal retraction, applied to organo sheet handling in [142], is pushed towards adaptive fixture retraction for organo sheet deep drawing by Bruns et al. [14]. This resource addresses multiple levels of detail, including the local shape shifting effects at the fixture clamps, the local details at the corners, and the global result of the whole workpiece. This shows how assembly and manufacturing blend into each other particularly in fibre reinforced parts production.

Other previous studies, like [176], address semi-active shape shifting in fixturing by proposing a forming tool with an elastic membrane at the face, filled with a fluid. As illustrated in Fig. 23, the membrane serves as an upper mould, which adapts to a lower mould with a rigid geometry. Gravity lets the fluid hold the mould well closed, and to drape a sheet of fabric laid into the cavity. An empirical

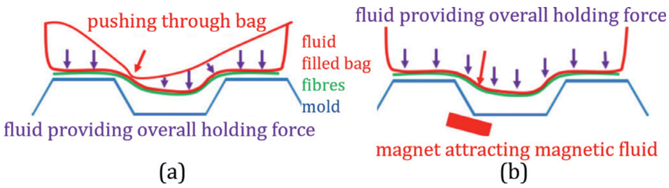

Fig. 23. Concept illustrations of the developed draping tools: a) water-based tool, and b) MR-based tool [176].

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(a) (b) (c)

Fig. 24. Three characteristic test moulds: a) medium-density polyethylene lid with reinforcement ribs, b) aluminium conical bowl, and c) composite air grabber [176].

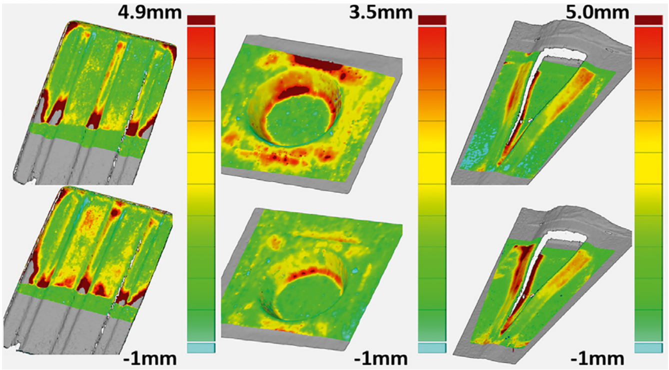

Fig. 25. 3D measurement data obtained by an ENSENSO stereovision 3D camera and inspected with the GOM Inspect software of a single layer twill-woven glass fibre sheet draped in three characteristic test moulds. Upper row: water-based results, lower row: magneto-rheologic fluid based results [176].

approach to obtain information about the local form closure pressure (which is important to evaluate the draping quality around filigrane geometry details) is used. The semi-active shape shifting is realized by adding magnetizeable particles to the fluid and by using a magnetic field to let the particles push the membrane deeper into the draw. Indicative test mould cavities and experimental results are presented in Fig. 24 and Fig. 25 respectively.

In specific cases, the resin transfer moudling process (RTM) may require that metal inserts are placed on or inside the fibre layup. Previous work elaborates on the process needed to insert and seal such inserts (particularly threaded bolts). It is proposed to use needle-style inserts, and counter-matrices to do this pinching assembly. This operation needs to be carried out while fixing the fibre layup with a preform draping tool in order to maintain the fibre placement accuracy [11]. This kind of usage of the draping tool as a fixture needs to be considered explicitly during the tool design, because this imposes a specific kind of load situation.

4. Implications of non-rigidity for assembly systems and product engineering

Assembly systems for deformable parts, considered at the abstraction level of multi-station / multi-step assembly configuration and its performance analysis, can be very similar to assembly systems with rigid parts. If the impact of non-rigidity is minimal or its impact for subsequent assembly operations can be ignored, then existing methods for assembly system design and analysis can be directly adopted without many modifications. This approach means that, at the assembly system level, the inputs and outputs of each station can be assumed of “rigid nature”, therefore the methods known from rigid body assembly can be applied. This opens the door for the plethora of methods known from ‘classical’ assembly systems that involve rigid objects. However, if part deformation is significant, then its impact for assembly systems in the aspect of quality must be considered.

The main objectives and targets of such assembly systems shall be reviewed briefly here in order to give awareness to the reader about the issues of such systems (section 4.1) [84]. This shall serve as a framework to which the aspects of non-rigidity added both at assembly systems level as well as at the interface with product engineering (section 4.2).

4.1. Assembly systems overview

4.1.1. System design

From the perspective of system layout or system configuration, the methods developed for assembly of rigid objects can be employed. For example, the assembly systems may take a large variety of configurations (e.g., parallel lines or hybrid configurations). Webbink and Hu [200] presented an algorithm for the automatic generation of assembly system configurations. Whereas Leiber et al. [117] presented an approach for automatically designing of fully automated multi-station assembly lines that includes the geometric positioning of the resources.

4.1.2. System performance modelling

The performance measures of an assembly system include quality, productivity, and responsiveness. Many papers have been published presenting methods for the prediction and evaluation of these or other performance measures. For examining system configurations, Koren, Hu and Weber [107] used six different systems configurations for analysing quality, productivity, and scalability (Fig. 26). Even though the examples were focused on machining applications, the authors stated that the analysis of these methods apply to other manufacturing systems as well. The goal of this system analysis was to predict the system level performance, given the system configuration, and the station level performances. When all performance metrics are considered, the authors advocate the use of parallel or hybrid configurations for better reliability, ease of scalability and convertibility.

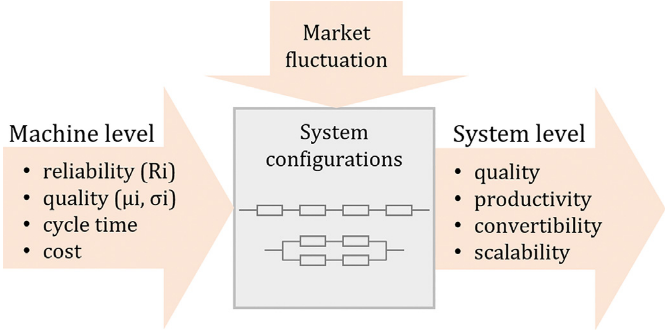

Fig. 26. Analysis of system configurations [107].

Hu et al. [94] discusses in detail the assembly systems configuration and their suitability for products with high variety. Throughput or productivity modelling has been an active area of research in production and industrial engineering. Analytical modelling and discrete event simulation are two popular approaches to productivity modelling. The goal of such modelling is to predict the system throughput (e.g., jobs per unit time) given the system configuration, machine level processing rate, reliability, buffer size and placement [77,122,203].

4.2. Additional models needed for multi-station, multi-step assembly with non-rigidity and development workflow

If an assembly system involves non-rigid parts, the respective development workflow needs to emphasize on the mechanical behaviour of the moving multi-body system with non-rigidity. A representative example of design for assembly involving non-rigid components is the engineering of products involving cables or tubes. Referring to previous work in this field, the identification of nominal routing paths, as represented in Fig. 27, in addition to the minimization of deformations during assembly or disassembly are important specifications [83,84,86]. On similar basis, other workstation design activities take in consideration the deformation of the flexible robot

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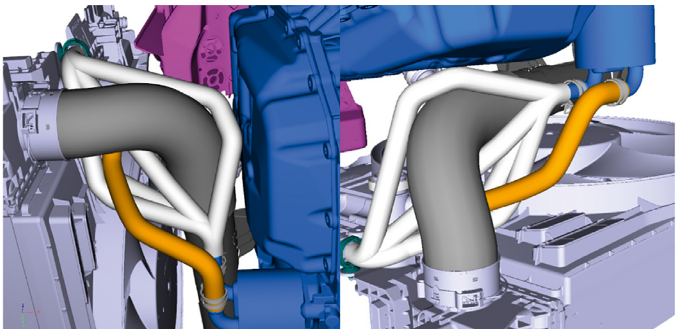

Fig. 27. Routing solutions for engine hose design and assembly [83].

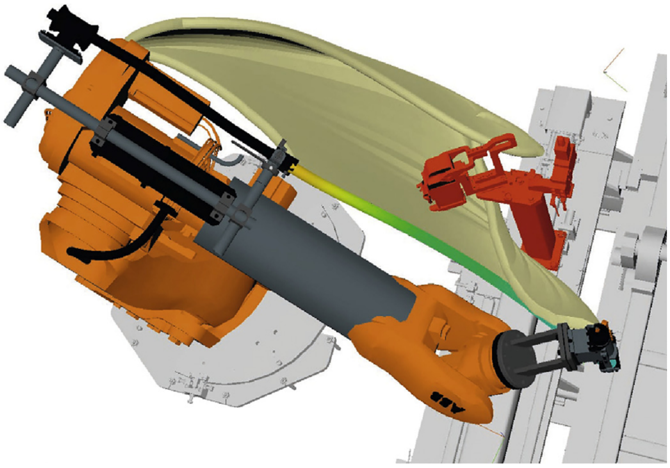

Fig. 28. Modelling of robot dresser and sweep of its volume along an optimized robot motion.

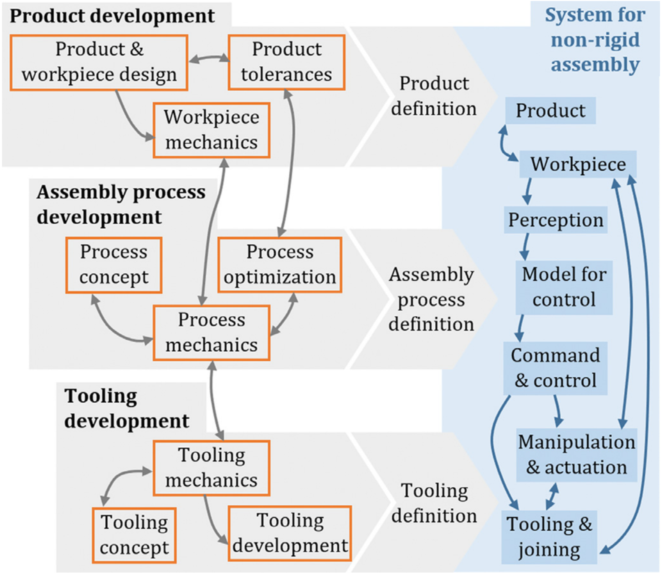

Fig. 29. Artefacts of the development workflow for non-rigid assembly and relations between these artefacts.

dressers [85] during robot operations (Fig. 28). In simple assembly situations, experimental try-out may be sufficient to develop a robust assembly process and tooling, but as it was pointed out in [48], the parameter space rapidly becomes too large to browse it by variation experiments. Also, if fast process changeover with minimum downtime is aspired in an existing production equipment (e.g., in situations when a new type of foil shall be handled in battery assembly [144]), there is no way that experimentation could be sufficiently efficient. In most applications, there is hence a strong need to adopt model-based techniques in the development workflow (and the hurdles implied with such models are, unfortunately, what makes it so hard to establish non-rigid assembly in practice). This motivates the further elaboration of research activities in this field.

In the reviewed literature, recurring development workflow patterns and artefact structures (e.g., mathematical concepts, models, couplings, programming architectures, hardware, control architectures) are observed, from which the reference framework for the development of non-rigid assembly, shown in Fig. 29, is deducted. This shall provide a better orientation for the reader and point towards future research directions.

The peculiarities introduced by non-rigidity are embodied in the blocks “Workpiece Mechanics”, “Process Mechanics”, “Tooling Mechanics”, “Process Optimization”, “Product Tolerances”, and their couplings. Section 2 introduced the different effects of non-rigidity, which may be relevant in the assembly involving geometric deformation effects and effects of force. These may be subject to elastic or plastic deformation, or a combination thereof. Naming a few, amongst the effects, there are springback, assembly accuracy, assembly deformation, etc. In overall, modelling in non-rigid assembly developments has four main purposes:

- **analysis and understanding of the geometry** (i.e., “Where is the object?”), and, often jointly, **of the kinematics** (i.e., “Which are the degrees of freedom of the object?”, “Which degrees of freedom are useful for assembly, which ones are useless?”): In difference to rigid objects, the geometry and kinematics are always subject to elastic forces, so that, always, these effects need to be implied in the model.
- **efficiency of process design**: This means that the model setup time and the engineering effort to realize the desired application to specification shall be as low as possible.
- **effectiveness of process control:** This suggests that the model, the control, and the process design must be suitable to solve the task in a reliable and economic manner. The third aspect is covered in the way that the assembly system design shall empower the control for maximum effectiveness.

The remainder of this section is dedicated to these models used in the development workflow. The consideration of models used for control of the assembly process (block “Model for Control”, right hand side in Fig. 29) is postponed to Section 5.

4.3. Assembly process modelling and assembly accuracy modelling, determination of fixturing points

On top of the number of variables to be defined in the assembly of rigid objects, the assembly of non-rigidity introduces a large number, if not even an infinite number, of additional degrees of freedom to consider. The tasks for simplifying this parameter space as well as for determining a set of reasonable design and process parameter values are hence much harder if non-rigidity is present in an assembly scenario. It is very cumbersome to search the design parameter space with an experimentation-centric approach, because the high number of degrees of freedom spawns many parameter variation experiments. Therefore, pure experimentation will lead to reasonable outcomes only in simple or very robust examples. It is hence straightforward to understand the high motivation for modelling such assembly processes in order to rationalize the development process (even if the effort to set up and calibrate the model is very high). This section is limited to models used in the process development (Table 2). For further reading about models used in control context, refer to section 5.

The first type of model-based rationalization of the assembly design procedure is to describe or design the geometry and/or the tasks to be performed. Such concepts underly the attempts to use visualization for the design process. There is research focusing into the architecture of such design support tools for automated layout [193]. This process can take place even in a virtual reality concept [152] or physical case studies that demonstrate the rationalization of the planning process [163]. In an effort to formalize and instruct operators on how to conduct the assembly sequence of wiring

Table 2
Modelling types and applications.

Station level model	System Level Model	Model Applications
Fixture design: [25,27,39,40] Joint design: [124] Station level variation simulation: [24,28,44,53,72,92,123, 125,126,130,139,143,154,184]	System layout and planning: [117,193] [194,200] Multi-station model: [30,102,107] [122,144] [203]	Performance prediction: [26,33] Sensor Placement: [29] Robust design: [84,209] Diagnosis: [127] Process optimization: [69,77]

harnesses, a language is proposed [134]. Apparently, the rationalization effect in these approaches is mainly due to the more efficient developer interface. On top of this, such formalization concepts can also be used to apply routing algorithms to find optimal wiring harness designs [193], but in the narrower sense, the non-rigidity of the wiring does not play a role in the underlying model. Acker and Henrich propose a kind of formalization to describe contact states of linear deformable objects, in order to automate the assembly process planning [2]. In the cited research activities, the modelling of the non-rigidity is kept as simple as possible. Apparently, this is because the information gained from such models is sufficient for the applications addressed. In the future, more detailed models might be seen in situations where design space is very cluttered or very tight, thus they require models with lower prediction uncertainty.

The next higher level of complexity is to use models that optimize the assembly with respect to the final assembly situation. This is of particular interest in panel assemblies, such as a car's body-in-white and aerospace structures. The objective in such applications is to determine the accuracy impact of parameter variations and to determine the assembly tolerances optimally. This determination comes in the sense that the assembly process robustness is maximized and that the design procedure is kept as efficient as possible [53,106]. Note, this design-centric consideration of the problem implies that the trajectory towards the final assembly position is not important here. It is hence a viable simplification to look solely at the assembled system (while neglecting the process and the equipment), and to model only the effects on the final tolerances. In rigid assemblies, the parameter space consists of positioning and orientation of the parts, whereas in non-rigid assemblies, this is extended by the deformations and the way they are introduced through fixtures, contact situations [27,39,40,106], and the joining sequence [165,180,194]. Even if finite-element models are viable representations of the deformation effects [26,125], a peculiar challenge with such models is to resolve the deadlock that the geometry of the contact, (which is a boundary condition for the finite element simulation) establishes not before the contact and deformation itself take place. To resolve this dilemma, previous research activities defined a cascaded approach where a rigid and a compliant simulation step are conducted in an alternating sequence [154]. If one wishes to have a simplified modelling approach, for example in early design stages, simplified compliant beam approaches have also been investigated [182]. These models are employed in variation simulations towards their optimization in respect to the objectives mentioned above. Indicatively, literature reports about the use of Monte Carlo approaches to gain stochastic distributions and Taylor-based expansion to gain deterministic optimization for such purposes [26].

The highest level of complexity in non-rigid assembly modelling is present, when also the path and/or trajectory towards the final assembly situation is of interest. Such applications can be found where material needs to be wrapped or bent around other geometries. Prominently, this applies to wiring harnesses [86,157]. A further example is the manufacturing of electric motors where wires are bent and wrapped around rigid geometries. In those examples, finite element analysis is a viable approach [79]. However, the necessity of a model-based development should be revised individually as experimental process development might be more efficient [111]. Another example is the z-fold assembly of electrode-separator-compounds in lithium-ion batteries, where the quality of the folding edge may be relevant for the overall assembly accuracy. The modelling of the elastic effects in the separator as well as the modelling approach for the process kinematics and accuracy prediction [44] are described [173]. The next stage is to integrate these two into an elastic battery assembly process model. In brief, the dynamic modelling of non-rigid effects in an assembly situation, is not common yet. This might be due to the significant effort required to implement this modelling successfully. Those limitations suggest that more research activities are needed here, for example to rationalize the modelling, the variation analysis, and the design decisions.

A category of its own for non-rigid modelling of assembly processes is represented by filament winding processes. This process can be used for the production of fibre-reinforced workpieces, but it can also be used to join workpieces [57]. Dackweiler et al. [38] presented a geometric modelling approach and experimental model calibration [37], to determine an optimal winding pattern, to compute the final joint geometry (with all the filament added), to predict the load bearing capacity of the joint, and to predict the probability of manufacturing defects.

4.4. *Quality in assembly systems*

For assembly systems with non-rigid parts, the prediction of assembly quality is challenging because of the possible deformation of the parts during the assembly process as a result of the clamping, joining/welding, and possible spring-back effects [183,198]. Variation simulation analysis is usually implemented in the evaluation of the geometry or dimensional quality of the assembled products. Typical methods for variation analysis include an assembly model and the assumption of statistical distribution of component and assembly dimensions. Analytical methods or Monte Carlo simulation are used to calculate the distribution of an assembly, given the dimensional variation of its components [184].

Traditional methods for assembly variation simulation were developed for rigid body assemblies as well. Liu and Hu [123], developed a set of progressively more general methods to simulate the variation in the assembly of non-rigid parts by incorporating in the process induced deformation and spring-back. Using one-dimensional beams as an example, an offset finite element model was introduced to predict sheet metal assembly variation. The simple mechanistic model provided insights on the variation propagation in non-rigid part assembly and how the part and assembly stiffness play an important role in the propagation of the variation; besides tooling variations, part geometry and kinematic relationship between parts. In addition, the authors (Liu and Hu) introduced a Finite Element based approach for predicting sheet metal assembly variation for 2-dimensional or 3-dimensional parts [126]. Using the Method of Influence Coefficient, the authors used the Finite Element Method to create a linear model linking the assembly dimensions to the component dimensions and then the Monte Carlo simulation is used to calculate the assembly variation. The linearized sensitivity approach, as presented in Fig. 30 was shown to be computationally efficient. Here v_a represents the assembly deviation, v_{pi} represents individual part deviation, v_{tj} represents individual tooling deviation, s_{pi} represents sensitivity to part variation, and s_{tj} represents sensitivity to tooling variation. Similar methods were developed by other authors as well [92].

When considering assembly variation in multi-stage assembly systems, a number of factors needs to be considered. At first, in each stage of the assembly, clamping, welding and releasing the clamping introduce dimensional distortion and spring-back. This can be analysed with a station level model for variation simulation. Secondly,

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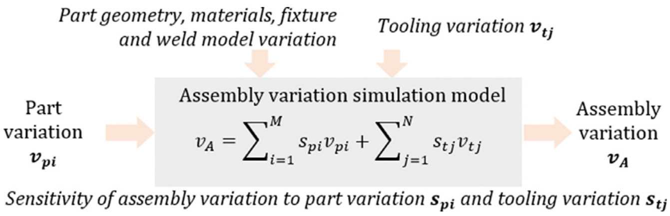

Fig. 30. A graphical representation of the linearized sensitivity approach for variation simulation in non-rigid part assembly [126].

the parts may be located using different fixturing schemes from station to station and the relocation introduces additional variation to the assembly. Relocation from one fixturing scheme to another requires the homogenous transformation in the part dimensions. Jin and Shi [102] introduced a state space model for modelling dimensional variation in multi-state assembly where the parts were assumed as rigid, but the analytical framework of using the station number as 'state' proves to be fundamental to many subsequent publications. Camelio et al. [30] applied this state-space modelling approach and introduced a multi-station model for variation propagation for non-rigid part assembly (Fig. 31). Here, part deformations due to fixturing, spring-back and relocation are all considered.

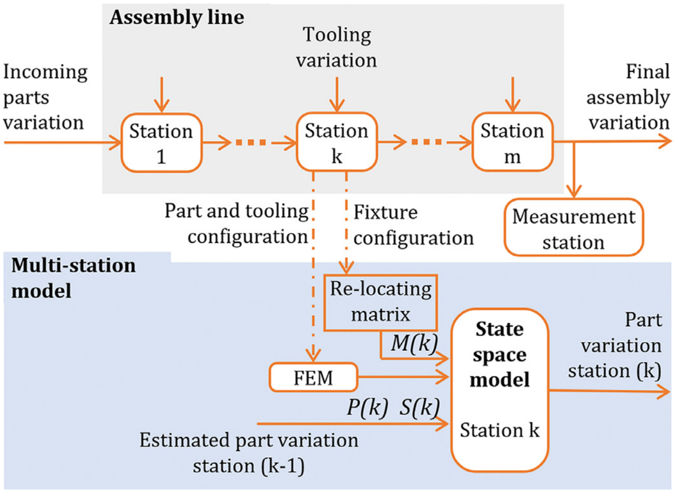

Fig. 31. Modelling variation in multi-stage assembly system with non-rigid parts [30].

The variation analysis model can be applied for designing more robust systems, including sensitivity analysis, joint design, fixture failure diagnosis, and sensor placement. Sensitivity analysis is applied to achieve robust design and tolerance allocation [93] [209]. In sheet metal assembly, the joints are designed to facilitate the welding of the parts. The three basic joints used in sheet metal assemblies are lap (slip) joints, butt joints, and butt-lap (corner) joints. Each joint configuration has its own variation characteristics [124] and benefits.

Principal component analysis (PCA) has been applied to assembly variation diagnosis. Using data from multiple measurement points on an automotive body, the patterns of variation were extracted based on the eigenvectors of the co-variance matrix. Rather than deriving the variation patterns completely from the measurement data, Liu and Hu [2005] proposed designated component analysis (DCA) for automotive body assembly systems variation pattern diagnosis [127]. DCA defines a set of variation patterns defined from the known product/process knowledge, estimate their significance from the data. Both approaches have found their applications.

5. Sensing, control and process supervision

Automating the assembly process of non-rigid parts has involved an effort in developing sensing methods. Those are intended for controlling the behaviour of machinery and robots during the actual process, but also for collecting measurement data that can help to further improve the processes and subsequently product quality. The actual manipulation process consists of a number of steps. Sensing allows for proper process perception which in turn can support to the appropriate control methods for guiding the machines and robots in cognitive flexible part manipulation. The sensing methods and the parameters that are identified in the literature are summarised in Fig. 32.

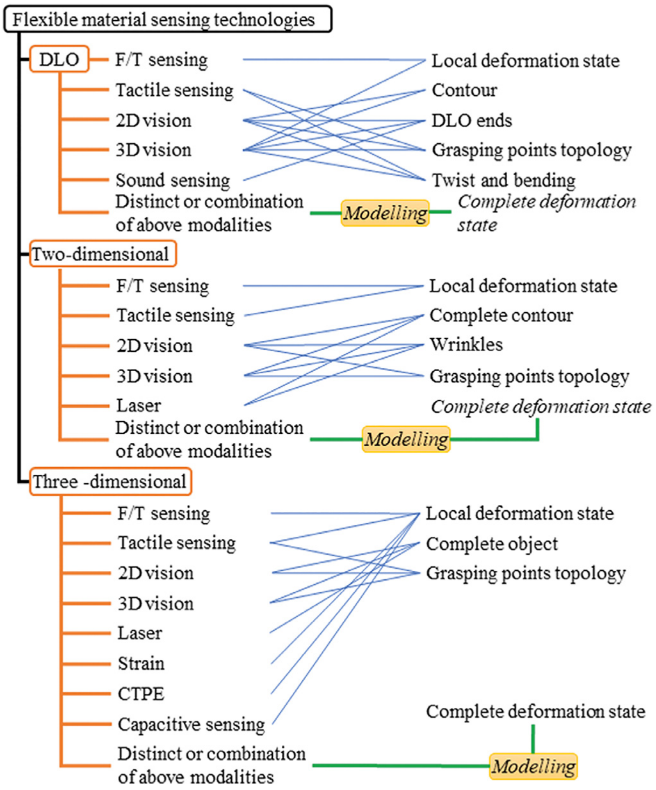

Fig. 32. Categorization of sensing methods reported in the literature.

5.1. *Sensing of objects during the handling process*

Automating the process of assembling non-rigid parts requires extensive use of sensing devices in order to allow machines and robots to perceive the behaviour of the physical parts and adapt their operating parameters accordingly. The outcome of the sensing process can involve the definition of parameters that are useful for planning systems. Such parameters are the position of the actual part, the geometry of the part being handled and its deformation amongst other parameters. The monitoring of such parameters suggests that algorithms can also be applied for controlling the quality of an assembly process and therefore update manufacturing processes accordingly. A mapping between object categories and mainstream sensing systems can also be found in Table 3.

Table 3
Non-rigid objects and conventional sensing methods per category.

Object Type	Vision	Tactile	Capacitive	Pressure	ForceTorque	Laser	Shearforce	Vibration	Electrostatic	Pneumatic	Ultrasonic	Inductive
Sheet-like	x				x		x				x	
Metal Sheet	x		x	x	x	x		x	x			x
Fibre Sheet	x	x			x	x						
Soft 3D objects	x	x	x	x	x				x	x		
Food	x				x							
DLOs	x	x			x			x				x

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5.1.1. Linear objects sensing

Handling of deformable linear objects (DLOs) is a rather complex process and vision-based control has been a key technology employed in a number of industrial cases. Vision data can either be used for real time robotic handling or quality assurance [1,3].

In control cabinet wiring applications, as visualized in Fig. 33, on-robot high resolution 3D snapshot sensors are used for detecting the location and the pose of the grasped wire tips and the ports to be inserted. By using machine vision, it is possible to detect wire ends with arbitrary cross-section geometries and the related component port shapes [80]. Experiments proved that detection accuracies up to 0.17 mm can be reached and vision servoing can decrease wire to port insertion forces by more than 15%. For this application, the positioning of the digital model is calibrated on the physical world using a stationary 2D vision sensor. CAD based template matching is used for correlating the detected modules and ports to the existing parts database [81]. For contact-based cable rooting applications, the 2D red-green-blue (RGB) image from an on-robot vision system using a stereo camera (RealSense D435) has been implemented. Based on hue, saturation, value (HSV) thresholding, the board contacts and cable ends are perceived towards robot motion planning [216].

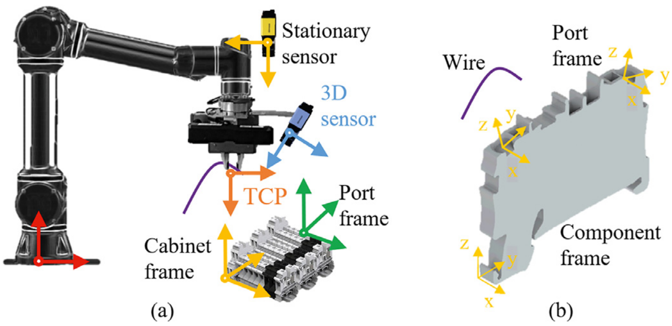

Fig. 33. Schematic illustration of: a) wire insertion framework, and b) clamp terminal frames [80].

Different approaches focus on perceiving rather the full DLO body than just its tip. In [204], a stationary 3D stereo camera Microsoft Kinect V1 is mounted 80 cm above a deformable hose of 40 mm diameter in order to generate a point cloud of the object (Fig. 34). After filtering, the object is modelled by 5000 points with a maximum geometric error of 10 mm. More specifically, after sorting and linear regression, the DLOs skeleton line is extracted. For balancing accuracy and computational complexity, the DLO is discretized into rigid segments interconnected by joints (Fig. 34b). The segmentation depends on the bending radius of the object and its properties.

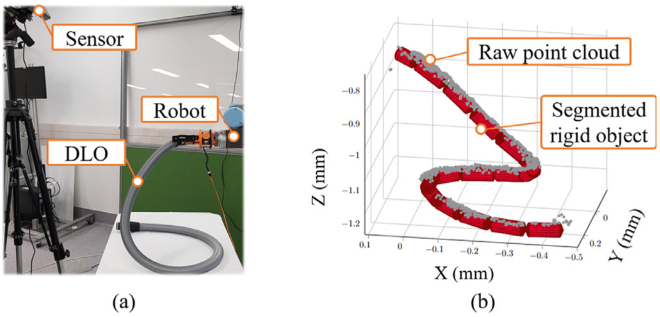

Fig. 34. 3D DLO recognition: a) experimental setup, and b) digital reconstruction of 3D point cloud data [204].

Assuming that in-hand DLO deformation can be managed by dexterous handling devices, the initial grasping still remains a challenge. In [169], the authors addressed this perception problem by implementing two distinct stationary 2D vision systems based on industrial 2D camera sensors (Fig. 35). The first vision system consists of a 2D image processing algorithm that calculates the coordinates and the orientation of a grasping point near an edge of the DLO based on its contour. After picking, the torsion of the DLO is still undefined, thus prior the assembly operation, the robot places the DLO at an intermediate grasping station inside the field of view of the second sensor. This vision system defines the orientation of the DLO, by detecting its features, allowing for the robot to regrasp the object by having the appropriate pose. A hybrid control framework (position and force/torque) is used for applying the required forces for deforming the gasket's sealing geometries towards its insertion along a dishwasher groove [5].

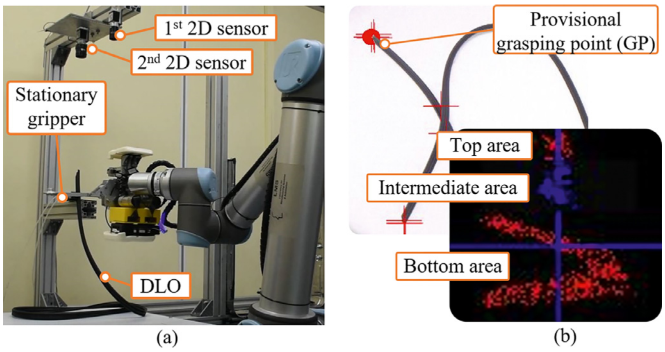

Fig. 35. Gasket assembly operation: a) robotic system setup, and b) vision detection for initial grasping point detection and DLO cross section orientation [5].

Bin picking is an industrial application, that presents challenges even for rigid objects. A concept for a simulation-based approach towards bin picking of soft objects is presented in [205]. The DLO is represented as a multi-body model and presuming reliable matching algorithms based on CAD data or geometric primitives, appropriate grasping positions and poses can be generated.

Except vision data, the perception or reconstruction of DLOs can also be achieved via contact-based sensing. Force sensors have been integrated on robot manipulators for measuring grasping or reaction forces. For long DLOs (e.g., long stainless-steel ruler with thin cross-section), the object's oscillation can be perceived through damp vibration forces and torques as they are monitored from the force-torque (F/T) sensor near the grasped tip (Fig. 36.b). Active vibration damping controllers can then be used for precise long DLO handling [210,211,212].

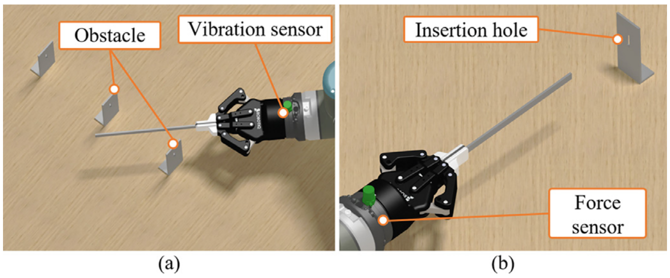

Fig. 36. Graphical illustration of metal ruler manipulation: a) acoustic handling, b) vibration handling [210-212].

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Contact based methods involve the usage of tactile sensors as well. Those are implemented on grasping fingers and depending on their resolution they can provide accurate pressure mappings of the grasping contact areas. In [62] and [65], tactile sensors are used for reconstructing the shape and orientation of the cable in order to perceive the local deformation status and optimize cable routing applications (Fig. 37). By adding a 2D vision sensor for initial localization of the cable, grasping performance can significantly increase [31].

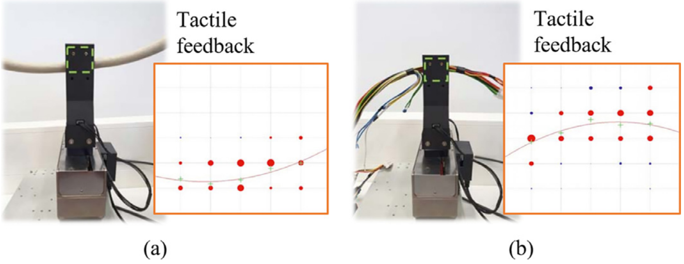

Fig. 37. Grasping and tactile feedback: a) single cable, and b) multiple cables [62].

An alternative approach suggests the usage of impact sound sensors to capture impact vibration signals upon DLO contact with the environment (Fig. 36.a). In comparison with microphones that are sensitive to environment noise, impact sensors are more reliable. However, they generate strong signal peaks and different contact scenarios are difficult to be distinguished [41].

5.1.2. Two-dimensional object sensing

The digital reconstruction of soft parts, such as fabrics or fabric-like materials, presents significant challenges since the number of degrees of freedom required to describe those parts is increased. In addition, these objects are able to translate mostly tensile forces thus compression forces or torques cannot be considered for digital reconstruction or planning. In [4], this issue is overwhelmed by equipping multiple agents (i.e. mobile robot manipulators) with force sensors. In detail, tensile-based force data are used for low-level control of the spawned manipulators, which retain manipulation and collision avoidance by passing forces to one another through the object, as illustrated on Fig. 38.

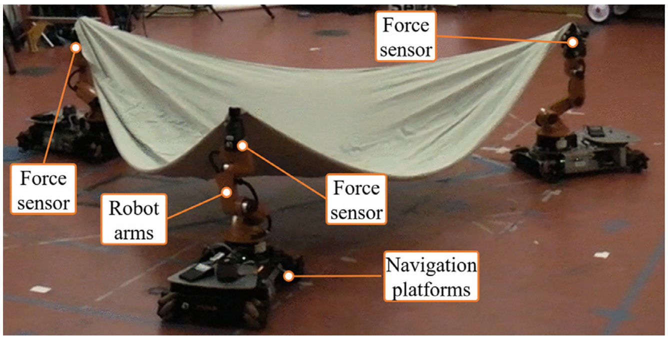

Fig. 38. Three mobile manipulators, equipped with force-torque sensors carrying a deformable bed sheet, adapted from [4].

An alternative force-based sensing method can rely on electro-adhesion [76,181]. Except the enhanced manipulation skills, those skins (Fig. 39.a) can be used for measuring grasping forces and dielectric properties of the object as well as enabling recognition of its shape.

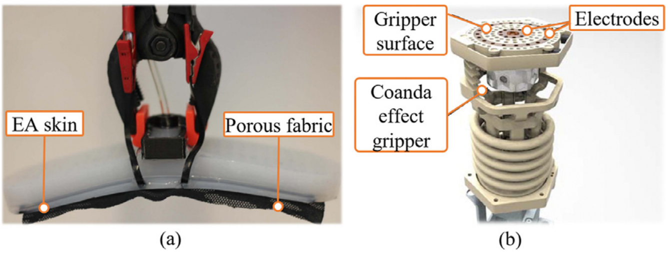

Fig. 39. Contact sensing: a) electroadhesive (EA) skin [76], b) copper electrodes [61].

Solely for grasping feedback, electrodes (Fig. 39.b) can be used for measuring grasping forces by monitoring the contact resistance between two conductive bodies [59,61]. The electrical resistance can be measured through the applied voltage by using a constant current source. The measured values depend on the force that presses the electrodes together.

Alternatively, the state of the deformable object can be perceived using vision sensors by identifying their appearance, shape, and configuration. In [195], a 2D vision camera (Nikon D90) is used within laboratory environment for the generation of objects datasets (i.e., shocks) as well as their identification during runtime via different classifiers. The datasets involved labelled top-view objects images against a green background towards the identification of their contour via simple colour segmentation. A holistic model of the shape and appearance is used for robotic manipulation by inferring the configuration of the item and provisional pairings. In contrary, when wrinkle detection is attained, high quality 3D visual data is usually preferred. An application for generic garment surface analysis and heuristic table-flattering proves that sensing systems using a combination of Digital single-lens reflex (DSLR) cameras (Fig. 40) can significantly outperform conventional stereo sensors due to their higher image quality [186]. In [32], a CamBoard Pico Flexx 3D camera is also used for cloth-like deformable objects based on an algorithm that first segments the source point cloud, while implements a wrinkledness measure able to robustly detect graspable regions of a cloth. After the identification of each individual wrinkle and its fitting in a piecewise curve, a target grasping pose for each detected wrinkle is estimated. For better detection of the object within a greater segment of the robot's working envelop, in [132], two pairs of stereo cameras were used, mounted on a dual arm robotic platform. Those are used for: 1. detecting the corners of cloths using geometric cues, 2. picking them from random poses, and finally 3. folding and stacking them after a series of regrasp and manipulation steps. On a similar basis, a 2D Logitec C270 was used for perceiving the state of the fabric. Through an optimized Shape-from-Template (SfT) algorithm, visual servoing was enabled towards the achievement of a desired fabric shape [8]. Focusing on high speed handling, an on-robot XIMEA MQ013MG-ON sensor with infrared LED was used for identifying the ends, the contour and provisional grasping centre of towels using traditional image processing [146].

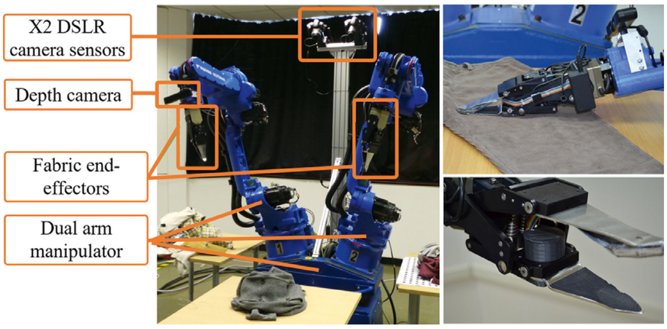

Fig. 40. Dual arm manipulator equipped with specialized gripping tools and sensors for cloth handling operations.

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Previous work also includes multi-modal sensing methods combining data from diverse sensors. For instance, a dual-arm robot is controlled by a hybrid controller that combines force and vision sensing data in order to coordinate its actions in accordance with the human operator's actions (Fig. 41.b.). Through joint torque sensors, and a head-mounted RGBD sensor (Microsoft Kinect), the robot can sense contact forces, and according to the human motion, visually analyse wrinkles, in order to maintain the tension of the sheet [108]. Similarly, force-torque sensor (RobotIQ) data and 2D vision data from a RealSense 3D stereo camera are used by a closed-loop hybrid controller [171]. The overall approach is proved with a co-manipulation experiment in which a mobile robot handles a flexible textile sheet together with a human operator as presented in Fig. 41.a.

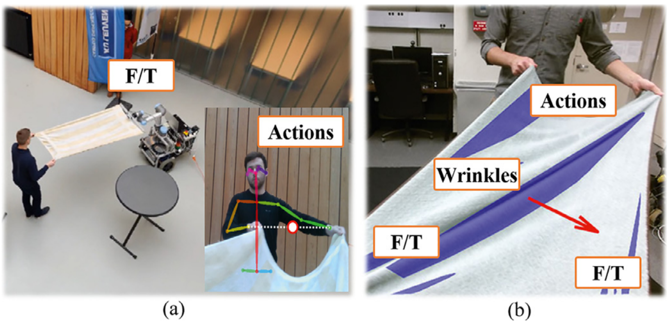

Fig. 41. Experimental setups for co-manipulation tasks when transporting a flexible, non-rigid composite fibre sheet to a workplace, adapted from [171].

A comparable monitoring framework is developed in [66] and [215], however it focuses on human dressing. In detail, an assistive robot plans its actions by recognising human poses and by monitoring force sensor data.

Previous studies also involve methods that instead of perceiving the state of the fabric itself, they rather monitor the actions of the handling agents and reconstruct the shape of the fabric using modelling techniques [6,109]. More specifically, hand or skeleton tracking is used for tracing the coordinates of the human grasping points.

5.1.3. Three-dimensional object sensing

Vision-based three-dimensional deformable object reconstruction is a research topic of interest. By integrating a stereo camera (i.e. RealSense) on the robot end-effector, a method was developed for dense and dynamic 3D reconstructions based on hierarchical database structures [138]. Other approaches are based on static cameras that monitor the behaviour of the object. For example, in [149], two charged-coupled device (CCD) cameras are used for capturing the object and iteratively estimating the unknown deformation parameters towards visual servoing. On the same basis, a Kinect sensor is used for identifying the object's 2D contour, as presented in Fig. 42. The identified contour is then compared with the targeted one for planning handling actions; based on heuristics related to grasp quality and stability [147]. Optical recognition can also involve laser-based methods. In [105], a SICK LMS1500 scanner is used for recognizing stacked sacks in the form of a 3D point cloud. Using segmentation algorithms, the objects are localized and can be robotically manipulated.

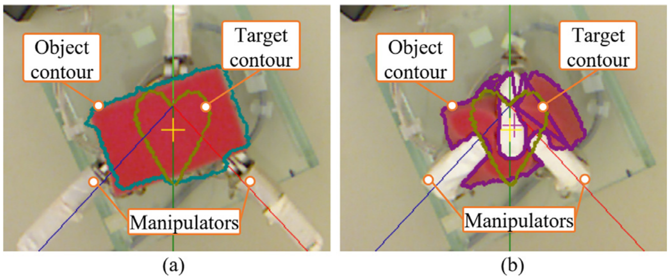

Fig. 42. 3D object shape-based servoing and example with heart-like shape: a) initial state and b) final state, adapted from [147].

Contact-based sensing methods involve force, strain, tactile etc. sensors. For deformable object surface sensing, conductive thermoplastic elastomer (CTPE) can be used for sensors that are incorporated into the object's body and allow differential sensing for determining the magnitude, orientation and localized deformation of those objects [96].

For in-hand recognition, as illustrated in Fig. 43.a and Fig. 43.b, tactile sensors and servo control can be used for measuring the softness of a part, which in turn helps to calculate the proper grasping force that ensures secure handling [43]. Those sensors can also be used for identifying and classifying objects via the k nearest neighbours (Knn) method as well as for the definition of the mechanical properties of the object by squeezing it, as demonstrated in Fig. 43.c [42,47].

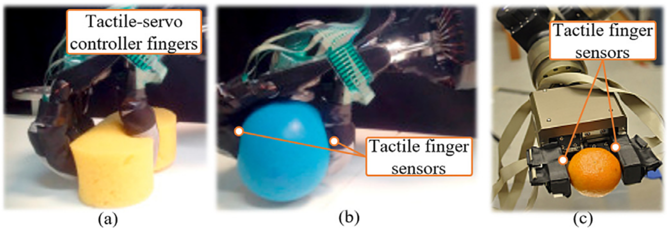

Fig. 43. Three-dimensional object sensing: a) and b) tactile sensors on fingertips for in-hand manipulation, adapted from [43], and c) tactile sensors on conventional gripper fingers, adapted from [47].

For greater accuracy on complex activities, multi-modal sensing is also investigated. As an example, in Fig. 44, soft capacitive and pneumatic sensing are used to monitor soft object's deformation and applied force intensity, in respect. A FEM-based numerical approach is used for integrating both sensing streams [150]. For active perception and modelling of flexible surfaces, force and vision data, (PrimeSense 3D-camera and 6-axis OptoForce force sensor) can be used for mapping the object via Gaussian process regression and position-based dynamics. A sampling method, using only a small number of vision-based measurements, allows for estimating the deformability distribution map of heterogeneous elastic surfaces; based on only a few physical interactions [24]. Last but not least, multimodal sensing can be used for grasping status monitoring and control, as presented in Fig. 45. In [187], bending sensors are used for retrieving grasping feedback, whereas ultrasonic sensors and air pressure sensors are used for highlighting object approaching and covering in respect. Extracted information is used for grasping and variable stiffness control as well.

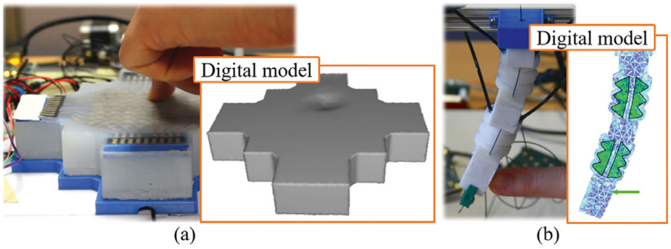

Fig. 44. Soft object deformation finite element modelling via capacity and pneumatic sensing for a) soft pad, and b) soft finger, adapted from [150].

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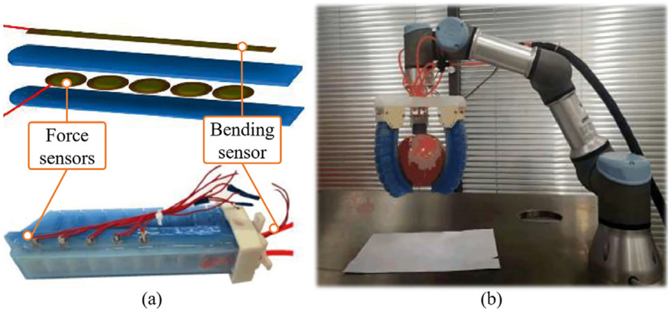

Fig. 45. Multimodal sensing: a) soft finger overview and sensors, b) soft fingers in action, adapted from [187].

5.2. Synthesis of sensor data and control

The perception of deformable objects, in terms of spatial coordinates, position and deformation, is the basis of more synthetical methods for their manipulation or assembly. By referring to experimental evidence, different approaches have been established for analysing or modelling data that are based on physics, artificial intelligence, finite elements, etc. The following subsections elaborate on distinctive applications and present the methodologies for control and planning during robotic handling or co-manipulation of deformable objects.

5.2.1. Physics based controllers

These controllers utilize the sensor data for reconstructing the deformable object, by using physics norms, and aim the deployment of controllers and planners that act upon the object's deformation state or goal.

Except vision data, in [108], the digital model that is implemented via Bullet Physics Engine [219] incorporates also force data as external disturbances. This method is tailored for the Baxter-on-Wheels mobile dual robot arm.

For two-dimensional objects, high modelling refresh rates of particle based, or mass-spring-based methods are optimal for online robot motion planning. In [133], a model-based co-manipulation planner is designed to orchestrate the handling actions of multiple agents for translational, rotational or 4DOF co-manipulation (Fig. 46).

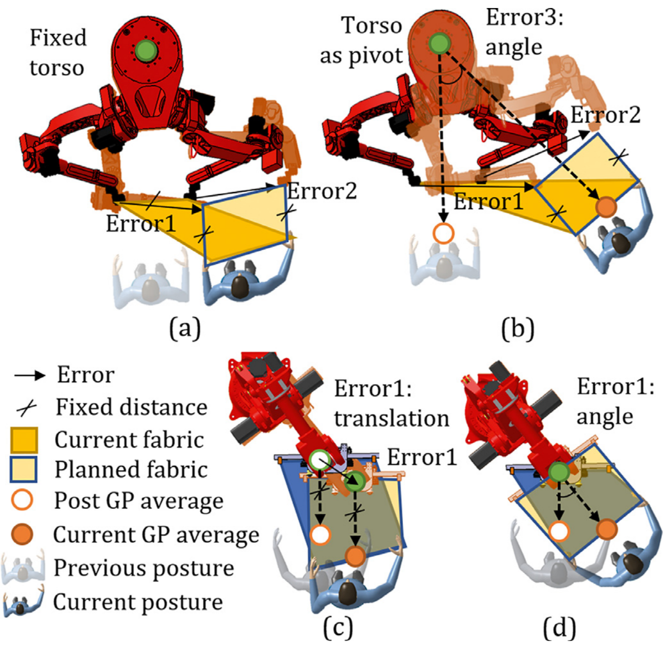

Fig. 46. Indicative Co-manipulation strategies: a) dual arm translation, b) dual arm rotation, c) single arm translation, and d) single arm rotation [133].

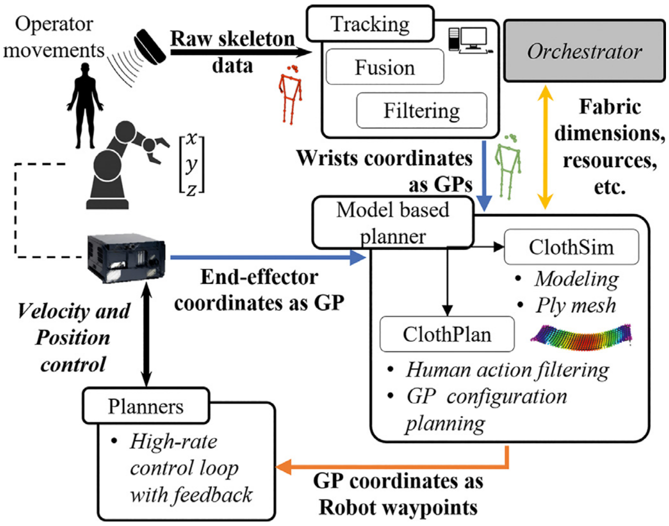

Fig. 47. Approach for controlling human-robot collaborative handling of fabric (GP: Grasping point) [6].

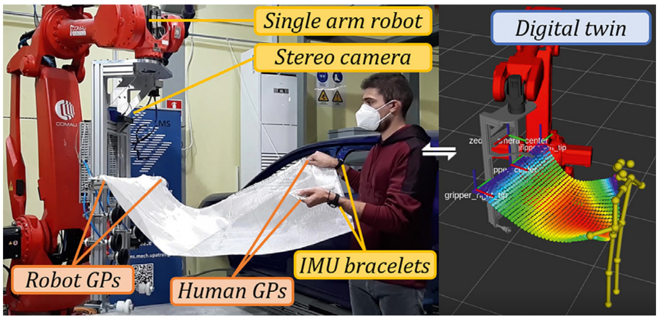

Fig. 48. Model-based co-manipulation of fibreglass sheet between an operator and a robot [133].

The heart of the system, whose architecture is illustrated on Fig. 47, is a mass-spring model that reconstructs the fabric by monitoring grasping point arrangements by the robot controllers and the dedicated human perception modules. Through closed-loop control, the planner generates velocity goals for the supportive robot (s) given the handling inputs of the main agent (i.e., human). A list of thresholds omits inputs that could lead to fabric overstress or robot arm collisions [6]. High parameterization and reconfigurability offer the capability for interpolating supportive agents' grasping point coordinates for human – single arm (Fig. 48) or human – dual arm configurations.

In the case of DLOs, the accurate handling of an underactuated end (i.e., by grasping the other end) is challenging. For this purpose, a nonlinear, partially IO-linearizing controller is used for robot motion planning towards the execution of a desired trajectory of the free end [88]. The controller considers a DLO digital model that reconstructs the object as a chain of distinct links, connected via ball joints with internal spring dampers. A method for updating such model's status, using 3D vision data, is validated in [204].

For DLOs with thin cross-sections, physics are important for handling oscillational behaviour. In detail, force data can be used for managing the handling of vibrating objects. More specifically, robot manipulators can have active damping skills [212] by monitoring the vibration forces and using the FT data in closed-loop controllers. Methods for template matching are employed to recognize the vibrational phase of the deformable objects for precisely inserting them into holes [210]. Previous experiments have assessed the performance of a proportional-integral-derivative

(PID) as well as a fuzzy and a P controller [211]. Results indicate that fuzzy based damping skills can be effective and stable even without parameterization of the controller based on the material properties.

5.2.2. *Model free closed-loop controllers*

In favour of computational performance and simplicity, there are control methods that bypass the implementation of object models assuming that co-manipulation routines will not stress the objects. In [171], a wrench controller (Fig. 49.a) is implemented for 4DOF collaborative co-manipulation of fabrics. More specially, as presented in Fig. 49.b the hybrid force-vision reactive controller is able to navigate the platform and plan robot arm's movements using impedance control according to the visual monitoring of operator's actions and the end-effector's force feedback.

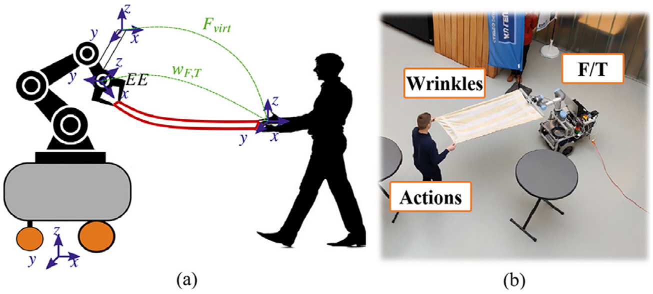

Fig. 49. Model-free co-manipulation: a) wrench-based strategy, b) experiment and inputs, adapted from [171].

An alike controller that fused force and vision data (i.e., human actions and wrinkles) is described in [109]. Based on those inputs, it determined optimal setpoints for position and velocity control of a mobile dual-arm robot. Methods of this kind could present mediocre performance during specific scenarios (e.g., robot end effectors at close proximity) mostly because they are unaware about improper handling actions until their execution, thus they might require prediction algorithms or models for further improvement.

5.3. *Geometrical model-based controllers*

Inspired by humans, a biomimetic approach on deformable object handling suggests the usage of the environment for modifying the shape of the deformable object. In [216], robotic manipulation of cables using contacts on routing boards is investigated (Fig. 50). By perceiving the contact point and the manipulated cable, the planner generates a target pose near the contact, and then rotates the pose using the current contact as an origin. The pose rotation is determined by the next contact location as well. During cable routing, the robot trajectories are updated in real time with different planning behaviours during the pre-contact, contact and post-contact phases.

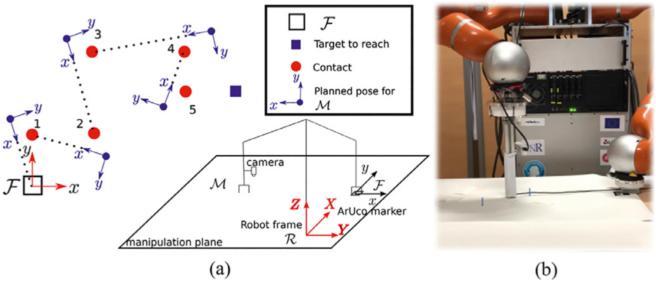

Fig. 50. Cable rooting: a) planning strategy and frames, and b) dual arm robot rooting cable on board [216].

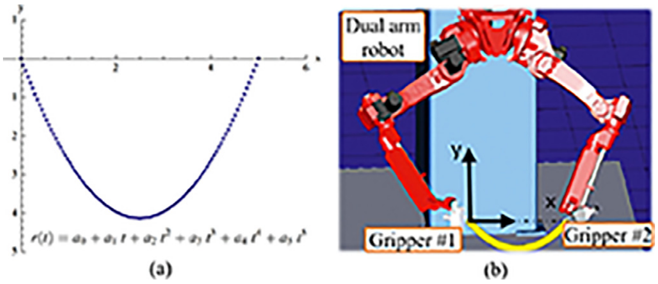

Fig. 51. Analytical model-based planning: a) equation and definition of deformation, and b) proof in simulation environment [157,158].

5.3.1. *Analytic model-based controllers*

Deformable linear objects can also be modelled through higher order differential equations. The type of derivative model has a significant effect on the representation of the cable and the type of boundary conditions. By using the robot grasping points as boundary conditions, quite accurate solutions could be achieved after parameter calibration [159]. For this purpose, second order derivative models require only the grasping point positioning, whereas the fourth order derivatives also consider their orientation. Depending on the magnitude of the equation's parameters, the properties of the cable (e.g., bending radius, stiffness, etc.) are represented. As illustrated in Fig. 51, a simulation environment was used for validating harness manipulation by dual arm robots in automotive scenarios [157,158]. An alternative approach for robot harness manipulation planning suggests the computation of stable wire configurations, upon manipulation constraints, that correspond to minimal energy curves [141]. The planner computes paths from one minimal energy curve to the other such as all the intermediate states have also minimal energy. This allows the generation of stable and collision free actions, however there are still dependencies, and the contact modelling needs enhancement.

5.3.2. *Machine learning-based control systems*

Alike numerous robotic applications, the advantages of machine learning (ML) can be used for addressing challenges in deformable material handling. For example, in Fig. 52.a, deep convolutional neural networks can be implemented for vision data processing towards the generation of grasping poses for DLOs [31]. In [116], a method for force-based manipulation using machine learning is investigated. Variations between demonstrations are used for extracting a single trajectory (augmented with forces and poses) resulting in a learned variable-impedance control strategy. Machine learning can also be used for improving robots' dexterity even after the initial object grasping. In detail, it was applied for the insertion of wire ends into terminals blocks by inferring tactile and force sensor data [73] (Fig. 52.b). ML can also be used for deformation control of objects using perception information. As an example, radial basis function (RBF) neural networks have been implemented for the soldering of flexible circuit boards while approximating the models of the unknown deformation and the uncalibrated camera [119].

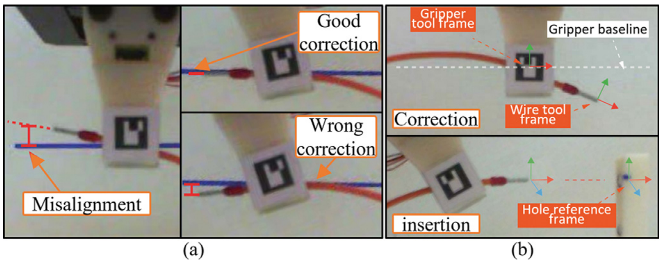

Fig. 52. Learning based optimization for wiring application: a) initial grasping, and b) wire tip insertion in terminal port, adapted from [73].

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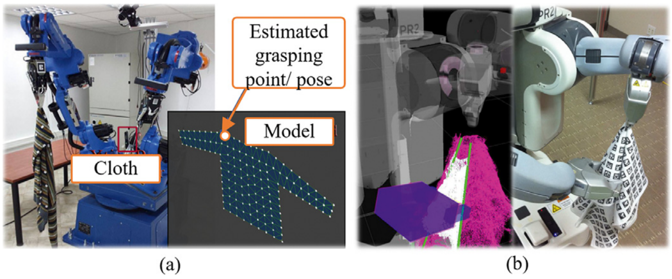

Fig. 53. Machine learning based: a) classification and recognition of garments for handling, adapted from [135], and b) overview of hierarchical approach.

For two dimensional objects, machine learning techniques based on Support Vector Machines (SVMs) have also been used for the extraction of grasping poses during cloth folding procedures. In overall, the algorithm involves mechanisms for folding, detection and grasping activities [15]. On the other hand, convolutional Neural networks (CNNs) have been implemented for pose estimation and recognition of grasped garments (Fig. 53) using two phases. The first phase focused on classifying the garment to one of the predefined categories, whereas the second one is used for pose estimation [135]. For a different kind of application, Artificial Neural Networks (ANN) have been used for the learning of automated assembly of deformable wheel arch liners. In this work [87], an ANN was important for associating the force and torque parameters with the trajectories for the insertion, alignment and joining of such parts. When accuracy is needed, ANN proved to be able to address the handling tolerance issues during the automated assembly of limp, high voltage fuel cell stacks using hundreds of thin, limp and brittle parts [19].

Prior handling, neural networks can be used for capturing the deformation of soft objects with unknown mechanical properties. In [188], 3D point cloud data are clustered with exerted forces for describing the particularities of the deformation. Reinforcement Learning (RL) implies a promising medium for robots towards their learning on how to manipulate deformable objects. Previous work includes many applications involving learning from expert demonstrations (i.e. imitation learning) [167,177], reinforcement learning [137,206], and a combination of reinforcement learning and expert guidance [217]. In [120], through a set of tasks related to manipulation of objects like ropes, cloths and fluids, methods like dynamics oracle, reduced state oracle, full state oracle and image-based reinforcement learning are compared. It is noted that image-based reinforcement learning demonstrated low performance highlighting the necessity for new algorithms that can also bridge the gap between high dimensional observation and learning from state representation.

5.4. Remarks on sensing, modelling and control

As discussed, unlike rigid objects, reliable manipulation and assembly of flexible parts requires technologies for deformable object perception. Such perception is integral for establishing controlling schemes for autonomous or collaborative manipulation scenarios. Depending on the type and properties of the object, different sensing strategies (single or multi-modal) are implemented, as Table 4 presents. Sensing data are utilized either for direct robot control or for the reconstruction of digital models representing the objects. Consequently, a number of challenges emerge due to the increased complexity in terms of data collection, synthesis, modelling and control that is also reflected in the increased computational requirements and network bandwidth. Subsequently, on each application there is a strive for balancing accuracy with computational costs and this is reflected on the type of sensors that are used and/or the selected modelling techniques.

As summarized in Table 5, contact-based sensing methods (i.e., force, vibration, tactile) proved to be ideal for perceiving the deformable objects' state near the 'grasped' or 'monitored' areas. This is also revealed on the controlling frameworks that are either based on closed-loop controllers or model-based planners. Former ones use this data as boundary conditions for their physics-based or analytical representation models. On the contrary, vision-based sensing approaches are ideal for holistic, yet macroscopic, deformation monitoring. Those methods can provide a complete overview of the deformation; however, the processing of such data requires dedicated fusion modules. For 'real-time' tracking, in terms of higher detection frequencies, 2D monitoring is preferred, whereas in the case of 3D capturing, segmentation of the data and representation of the object as a set of rigid bodies is a usual practice.

When there are not sufficient computational resources for perceiving the complete object, or it is not practical (e.g., occlusions), it is preferable to monitor either distinctive features (e.g., wrinkles for fabrics, tips for wires) or monitor the actions of their handling agents. By using those actions as boundary conditions on reconstructions models, it is feasible to acquire an overview of the deformation state. Selecting the type of model is a rigorous process and must consider accuracy, resolution, and refresh rates given finite computational resources. As an example, finite elements-based modelling methods [103] can demonstrate accurate results though they are not fast and most commonly available packages present compatibility limitations with standard middleware [7]. Mass-spring models appear to resolve those issues with high frequencies and performance at the cost of appealing unified representations. For methods, that use parameters known by material science or bibliography, parameter calibration is a straighter forward process. Instead, when the mechanical properties of the object are undefined or the model's mechanics are symbolic, the necessity of investigating automated calibration frameworks is highlighted.

As discussed, machine learning proved to overcome such limitations with robotic systems being able to define parameters or even augment their dexterity. These derive from heuristic methods or teaching by demonstration schemes that fundamentally take place prior deployment. As modern industry is characterized by recurrent changes, their long-term training for optimization and their sensitivity to changes (e.g., environment, resources, object features, etc.)

Table 4
Classification of robotic applications based on their sensing and control principles for the three non-rigid object categories.

Sensing	DLO				Two-dimensional				Three-dimensional			
	Model-free Machine learning (ML)	Non-ML	Model-based Machine learning (ML)	Non-ML	Model-free Machine learning (ML)	Non-ML	Model-based Machine learning (ML)	Non-ML	Model-free Machine learning (ML)	Non-ML	Model-based Machine learning (ML)	Non-ML
Tactile	[73]	[62,65]	[31]						[47]	[42,43]		[150]
Force–Torque		[5,80,81, 210-212]	[116,205]		[66,215]	[4,59,61,76, 108,171,181]	[116]	[109]	[87]	[76,181]	[116,188]	[24]
2D vision	[73,206,213]	[5,80,81, 169,216]	[31]	[159]	[119,195, 206]	[146,171]	[135]	[8]		[147]		
3D vision	[73]	[80,81,88]	[116,167,205]	[204]	[66,177,215]	[108,132]	[15,116 135 167]	[6,32,109, 133]		[43]	[116,188]	[24,138,149]
Laser										[105]		
Sound		[41]										
Vibration		[210-212]										

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Table 5
Qualitative comparison of sensing and controlling methods.

		Controlling capabilities	Product– depended	Global deformability	Local deformation	Microscopic deformation	Resolution	Fusion Resources
Sensing Methods	Tactile	x	x		xxx	xx	xxx	
	Vibration	x	x	xx	xx	xx	xx	x
	Force– Torque	x	x		xx	x	x	x
	2D vision	xx	xxx	xx	x		x	xx
	3D vision	xx	xxx	xxx	x		xx	xxx
	Laser	x	xxx	xxx			xx	xx
	Sound	x			x			x
Control Methods	Analytic	xx	xx	x	x	xxx	xx	xx
	Closed-loop (model free)	xx	x	x	x	x	x	xx
	Model-based	xxx	xx	xxx	xx	x	x	xxx
	Machine learning	xxx	xxx	xx	xxx	x	x	xxx

render these methods immature for industrial implementation. This is still a concern despite the investigation of methods for auto-generated datasets [74,213]. As for imitation learning methods, those tend to have performance issues when they encounter a new scenario or state. In addition, they are dependent from the quality and accuracy of the involved expert demonstrations.

6. Discussion, outlook and open issues

Assembly of non-rigid objects has enjoyed a long history of research and now a large body of knowledge has evolved and addresses the large diversity of applications, mechanical effects, implication of design approaches, and the adjoint production engineering and process control issues. Such advances are particularly noted over the last 10 years, where a large number of knowledge domains have received significant advances in form of new architecture concepts and systematic deep-drilling. It is hence somehow worth noting that, to the contrary, the implementation examples in industrial production remain scarce as those do not grow and mature at the same pace. This contradiction cannot all be due to a lack of interest, as there are areas, such as wire-harnesses in battery-propelled cars, where the appropriate solutions are intensely sought after [10]. The only explanation for this contradiction we can hence propose is that 1. either the research results are still not powerful enough, or 2. that the research transfer into industrial practice is still not feasible or sufficiently attractive. A variety of reasons might be considered as inhibitors, i.e., a lack of technology readiness and robustness, or engineering simplicity, and/or of engineering efficiency. In what follows, we address the most urgent of the remaining research and transfer issues we encountered during our analysis, or we can extract therefrom.

It was a conscious choice to emphasize our review in production engineering applications and control systems for the handling and assembly of objects with non-rigid material properties. Other applications, including service robotics, can be the main scope of other future reviews. This choice narrows the scope to applications and technologies where at least some a-priori knowledge and specifications are available and where safety/organizational concerns can be approached a lot more effectively than in fully public/unstructured situations. This reduces the plethora of uncertainty sources, decision trees and failure modes significantly, and, consequently, this lowers the engineering effort and the overall risk. This accelerates the pace towards the desired technology readiness levels and market readiness, and it mobilizes standardization activities such as the draft of the DIN standard 72,036 “Automation of the wiring harness production”, as well. However, despite these simplifications, the gap between research and industrialization remains to be bridged, mainly by further innovations.

6.1. Classification

One of this article’s aims is to provide orientation to the reader by classifying the different applications and their appropriate solution concepts and methods. In this sense, non-rigid or deformable objects are often classified on the basis of their object shape and/or geometry into clusters of one-, two- and three-dimensional objects [168]. Literature suggests that the most populated is the category of two-dimensional objects, which can be further divided into planar (e.g., sheet metal parts) and cloth-like (e.g., composite sheets) types of materials. This attention is mostly related to the size of the corresponding industrial sectors and the high number of applications behind the manufacturing of relevant products.

6.2. Mechanics of non-rigid objects

Deformation, thus its force and geometry effects, is a key behaviour to be mastered in any non-rigid assembly situation. For all categories of objects, there are quite powerful and accurate models to describe this. However, to set up the most appropriate model structure for a specific application and to tune its parameters requires a lot of experience and experimentation. Still, variations and degradations over time as well as randomly spreading effects from material deformation memory or part production are still not well reflected in the models and cumbersome to identify experimentally.

The improvement of the models to cope with stochastic effects or non-holonomic effects such as backlash material memory, must hence be a priority in this innovation field. Furthermore, while accepting that the models will inevitably be of high complexity, simplifications in the engineering interface must be found to improve engineering efficiency (e.g., [205]).

6.3. Engineering of assembly systems involving deformable objects

If an assembly system, namely multi-station system, shall adopt non-rigidity, the respective development workflow needs to emphasize on this non-rigidity as well. This affects the way the tasks are described, the way they are modelled (i.e., modelling parameters, conditions, etc.) as well as the sequence in which kinematic degrees of freedom are discretized [30]. This article advocates further research, which elaborates structured methods, for this sequence of choices.

Currently, the ever-increasing availability of computing power and the advances of automated modelling (e.g., by means of artificial intelligence) make it easier to master the vast number of degrees of freedom. The fundamental mathematics of the model structures have matured greatly, but still, significant efforts are required to make them efficiently employable in a specific engineering situation. By saying this, it is meant that model calibration and optimizations of designs and process plans are still too cumbersome. Future activities

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should focus on what kind of parameters the non-rigidity introduces in the system's modelling. Starting from layout design and scheduling, it is fundamental to correlate the intended handling accuracy (e.g., positioning, deformation) with the number of cooperating agents [7]. A precondition for this correlation is the identification and definition of robotic skills in terms of capabilities. Research must focus on normalizing what primitive or synthesized robotic actions can be considered as 'standard' and what are those to be mastered in the upcoming decade. Augmenting robot skill libraries with deformable object actions will contribute on the adoption of scheduling and layouting planners by the industrial sectors involving non-rigid assemblies as well.

Either through automated planning or expert-based engineering, given a defined manufacturing system, the next step involves the modelling of the system's runtime behaviour. Future research should elaborate on how tooling and robot interactions affect the final product shape and deformation state. Computer Aided Manufacturing (CAM) and software tools must introduce libraries for soft objects and give engineers the capacity to monitor tooling interactions with these objects. Existing commercial packages are competent in the simulation of rigid object manufacturing systems, but they do not offer unified modelling and robot programming toolkits. There is still a gap on how boundary conditions can dynamically be updated for deformation problem solving within a constantly changing scenario. In addition, new algorithms that balance accuracy, computational requirements and problem definition complexity need to be found to speed up the related engineering activities, thus reduce engineering costs (and risks).

6.4. Handling dexterity and tooling

Despite advances in material science and mechatronics, there is still significant margin for improvements in robot dexterity. Dexterity results from a combination of innovative end-effectors and controlling strategies [55]. Previous activities involve examples introducing soft grippers, biomimetic grippers, grasping strategies, multi-tool end-effectors, etc. in an ultimate effort to replicate or surpass human dexterity. It is noteworthy that literally no work was found about the interaction of a non-rigid workpiece and a compliant gripper. This identifies a gap where future activities should focus since this compliance matching, which can be found in the interaction of soft material robots and humans, would help to design even better adapted grippers and gripping processes. The rise of additive manufacturing of compliant materials can be an enabler for advanced design and manufacturing of complex compliant structures. So far, examples of such structures are mainly in lower technology readiness levels and have still a long road to take until industrial application. The advancement of graded materials with function-oriented (instead of manufacturing-oriented) placement of material nuclei will surely lead to a variety of tooling concepts not yet seen. There is still a gap to bridge on the selection and making of appropriate materials that can withstand industrial requirements and at the same time present properties that appear sufficient for sophisticated grasping concepts.

Inspired by the market's requirement for one-piece-flow without or with limited hardware modifications, research needs to continue its activities on gripping technologies. Grippers, as the physical interfaces between the production equipment and the emerging product, must adapt to the fed variety of workpiece geometries and compliance properties. This means that universality in the sense of shape adaptability will be the key for such success; and this needs a lot more effort for creating even more concepts of this kind. Adaptability through articulated, hand-like or multi-DOF devices still presents limited robustness [43]. As the number of moving links and actuation mechanisms increases, the chances of failure or errors also rises. Existing solutions cannot grant the repeatability and robustness that industry needs. In addition, despite some of the proved concepts demonstrate high dexterity, their efficiency is not great. Subsequently, effort needs to be allocated on making the existing and new concepts more reliable, fast and cheap.

The problem of complexity could be resolved through compliant robotics that does not seem to play a huge role in industrial assembly of non-rigid parts yet [187]. However, there is potential under consideration of "compliance matching". The main handicap of soft grippers is either their speed or their payload. If new materials, and compliant structure design do not overcome those limitations, future activities might need to start working on hybrid (i.e., soft and mechanized) grippers. The soft material robotics community has made considerable advancements, and the usage of soft materials as well as actuated stiffness and jamming effects is a very much appreciated overspill from there. The spawning of the industrialized VersaBall and the FormHand Technology [128], which both began from research roots, have shown that successful industrial implementation of such disruptive components does also need a significantly different process engineering approach (just replacing established components with soft grippers is doomed to fail). Henceforth, there is a need for further release of such soft material tooling concepts, and more overspill effects (coming from the soft material robotics domain or from the bionics domain) are anticipated for this purpose.

6.5. Software and hardware perspectives for deformable object sensing

Deformable object perception is important for dexterous handling, as well as proficient supervision of the manipulating agents. Regardless the usage of the sensor data, the balancing of accuracy and computational cost is an elemental requirement when designing a sensing system. This affects the selected sensor(s) types, the communication middleware, the network, the processing modules, and hardware, as well as the robot controlling framework [7]. Specified the outputs of a sensing module, different strategies can be directed; with the vast majority of them to either use information for the reconstruction of digital models or use them in direct closed-loop robot control (or a combination of both).

For applications where the complete object deformation perception is negligible (e.g., closed-loop controllers, or physics-based models), various contact-based sensing methods can prove their fitness by monitoring force, vibration or tactile data near the object's areas of interest. In comparison, vision-based sensing demonstrates good results in circumstances when holistic, yet macroscopic, non-rigid object deformation monitoring is needed. However, the extraction of valuable information out of visual data in a real-time fashion requiring high frequency data capturing, comes with an important computational penalty and susceptibility to lighting conditions and sensor occlusions. This kind of limitations can be circumvented with alternative approaches that monitor the status of the object indirectly. Typical examples involve tracking the actions of the handling agents for instance via tool centre point (TCP) echoing, or human tracking modules [6] as well as the tracing of noticeable features like wrinkles [171] for 2D fabrics or tips for DLOs.

Towards industrial adaptation of the aforementioned solutions, it is a precondition that in the following years, the sensor devices applied so far will become industrial grade as they need to withstand rather harsh environment conditions instead of only laboratory ones. Moreover, sensor companies need to start adopting existing research results and normalize the perception methods for deformable objects into reusable 'packages' similar to those of the rigid ones. It is desirable that researchers manage to support the explainability of the perception modules through fully parametrized algorithms that engineers will be able to rapidly deploy and reconfigure using interfaces. For vision-based solutions, the advances in image processing and reconstruction must be exploited for improving performance in challenging lighting conditions. Whereas for contact-based methods (e.g., tactile sensors, etc.) it is fundamental that sensing devices will not compromise the capacity or the robustness of the system, instead they should improve its performance through accurate force/torque or shear monitoring. Maturation of the hardware and software tools combined with edge processing modules will manage to abstract the

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perception procedures and provisionally reduce the overall system's complexity.

6.6. Supervision, controlling, and reasoning perspectives

Focusing on the aspects of control, in literature, the implemented strategies can widely be classified as model-based and model-free. The former ones are characterized by real-time robot control via closed-loop controllers; however, the state of the deformable object is neglected, or it is preserved through empirical thresholds and conditions. In contrary, model-based controllers, that control manipulators based on complete scene understanding, are ideal for simulation. However, for real-time scenarios, they need to resolve performance issues related to fast, yet accurate, representation of the objects. Based on the experimental results and the findings in deformable object modelling, the mass-spring models demonstrate the finest balance in terms of computational performance and accuracy [91].

As discussed in Section 5, the selection of a model is a rigorous process that needs to evaluate accuracy, resolution, and refresh rate attributes at specified computational resources. Off the shelf modelling solutions can provide accurate reconstruction mechanisms (e.g., based on finite element modelling), however there are limitations in data communication and performance. A typical example implies the limited available options for optimization through graphics and central processing unit parallelization (i.e., GPU and CPU) that makes them inapt for integrated robotic applications. Another important aspect is the capability of the model or the planner to be parameterized and reconfigured. Such capabilities prove to be valuable during commissioning and optimization phases; and they can ensure that any update on the product's characteristics will not sort out the whole framework as unusable. On the other hand, the high parameterization increases the calibration complexity especially when the digital models rely on symbolic values (e.g., modelling of fabrics as a grid of masses interconnected with springs). Reliable, fast and automated calibration methods is an area where future research activities should focus. Their outcomes could provisionally shorten the gap between industrial requirements and the state of the art in modelling. This effort can be supported by dataset sharing and online databases where material properties and modelling parameters are stored. Since manufacturing companies tend to preserve their data in privacy, such an effort should be mobilized and coordinated by research institutions, clusters and associations.

Under proper circumstances, machine learning could overcome these challenges through self-trained robotic systems that are able to either retrieve model parameters or even improve their handling skills [35]. Regardless the training methods such as heuristics, reinforcement learning, teaching by demonstration, etc. these systems are not yet sufficiently validated for large assembly systems as they prerequire the bridging of technological and ethical gaps behind the use of artificial intelligence in industrial environments. As an example, the performance of imitation learning algorithms is very dependent on the competence of the experts and their motivation on fully training the systems for every possible aspect. For this reason, they tend to be ideal for very simple operations given that the slightest difference between the training and the application scenes can lead to error or critical failure. Similar problems are also observed in reinforcement learning applications, where robots can optimize their behaviour. Research must focus on how such systems can improve their efficiency and avoid errors without requiring long periods before they reach their performance plateau. Simulation of industrial scenarios in physics-based simulations can partially address this challenge (with in-advance training), however researchers still need to improve their models and reconstruction methods. Currently, such applications are prone to errors during runtime, not only due to environment alterations, but also due to variances between the physical workstation and its digital twin.

In parallel, socio-ethical issues play an important role in the implementation of AI-based systems. At first, academia needs to improve the explainability of AI. The inability of comprehending the decision-making of AI will maintain the industry's lack of trust on such systems as those remain "black-boxes". Trust from industrial stakeholders and practitioners is integral not only for the decision-making algorithms but also for the required infrastructure. Making the systems progressively more data-depended suggests that they are also more sensitive to cyber-attacks or threats. These aspects in combination with architectures based on cloud-computing comes in contradiction with the intention of industries to preserve their data private and secret. Thus, cyber security emerges as an area of great interest for the following decade. Finally, the current regulatory framework is either outdated or inexistent. This delay nourishes a hesitation of industries to implement solutions that do not affirm conformity with legislations by restraining integrators or technology owners on deploying uncertified products into factory shopfloors.

6.7. An outlook on industrialization of technologies

The integrated industrial applications, that are either deployed in larger assembly systems or were validated in industrial relevant environments, are usually in vitro or demonstrate quite conservative solutions (i.e., automation of specific operations). In larger assembly systems, the deformation of non-rigid parts is tackled through hardware-oriented solutions that limit deformations and rather automate distinct assembly steps (e.g., wire insertion, object transferring, etc.) than the complete process. In overall, these solutions are characterized by low flexibility. For increasing robustness and maintaining low operational costs, their lack of advanced perception and cognition modules suggests that they are prone to become non-operational in case of unexpected object deformations or any kind of product characteristics changes.

Summarizing the challenges and gaps from the already discussed technological areas, the academic community needs to start tailoring existing advancements into industrial needs. When technical and financial support by industrial stakeholders is absent, non-rigid assembly problems can be appointed as competition challenges in order to motivate young engineers on presenting innovative solutions [208]. Despite sharing the same material handling challenges, special focus should also be given to disassembly scenarios as well. In some cases, perception can be characterized as more complex given that sensor data fusion has to address also defects due to wear. Starting from hardware, all materials for tooling and sensing need to be enhanced into industrial grade but in a cost-wise manner. This will contribute also to their robustness and resilience against errors. In terms of software, it is necessary to work on the abstraction of systems' functionalities in order for state-of-the-art prototypes to become modular plug and produce systems. This abstraction, supported by edge processing in some cases, will be appealing for industry due to: 1. availability of off-the-shelf solutions for specific deformable object related functionalities, 2. less tendency to errors as well as easier resolving and troubleshooting in case they appear, and most importantly 3. less complexity that means in-house implementation and maintenance is feasible. The last one is aligned with the objective of businesses to keep their data and practices private in an effort to maintain any competitive advantage. However, this preconditions a simplification of the involved technologies (and explainability), so companies can adopt non-rigid object assembly technologies even with less qualified personnel. Finally, as it comes with every new technology, it is important that standardization committees keep up with the state of the art through legislation norms that either certify existing solutions or set a clear pathway for future activities. It is worth to note, that except some research activities, there are not widely applicable standards or benchmarking for non-rigid assemblies [104].

7. Concluding remarks

This paper provides an overview of the state of the art in the handling and automation for the assembly of non-rigid parts. In literature those are classified into one-dimensional, two-dimensional, and three-dimensional types according to the part's geometrical

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characteristics. For each material type, the fundamental deformation mechanics are explained giving a better understanding about the challenges that their manipulation exhibits.

Despite advancements in the sensing technologies, computational performance, information technologies, maturation of physical and mathematical models etc., industrial sectors still encounter limitations in the automation of flexible material handling operations. The main challenge is that automated handling agents still have limited dexterity and cognition capabilities for managing such objects in a repeatable and proficient fashion.

Following the analysis of those objects' mechanics, this article summarizes existing gripping and fixture technologies and concepts. Given that for handing agents, their grippers are the mean for interacting with the environment, the importance of gripper design is thoroughly explained whereas existing gaps are identified for rallying future research.

After this analysis, the related grasping operations are then reviewed and summarised per key industrial sector. This review presents existing handling systems or research activities that aim to tackle the challenges that those sectors portray, due to the deformable nature of their assembly components.

In addition, assembly system design principles and issues for non-rigid parts are also interpreted. At first, the article communicates what theories and methods from rigid assembly systems can seamlessly be embraced and applied to the assembly systems of interest. This is followed by a description of modelling techniques as well as a thorough explanation about the effect of deformations to the overall product quality and tolerances. Examples from literature that focus on their estimation or definition, even during the design phase, are noted.

Furthermore, sensing and automation methods are also reviewed. Given the particularities of each deformable object category, a systematic presentation of the sensing hardware is given. The benefits and limitations of each sensing and perception method are explained with noteworthy application examples. Given the variety of sensing technologies, for holistic or local representation of those objects, multiple handling strategies for the synthesis of this data are described. The article provides a classification of those strategies (e.g., model-free, model-based, ML-based, etc.) with a thorough discussion about their features and performance, aiming to direct future research attempts. Given the increased interest and the latest advancements in machine learning, the capability of learning-based systems to understand the behaviour or the physical parameters of deformable objects is also highlighted. As explained, machine learning can be a powerful tool for the calibration of digital models, however in terms of handling agent behaviour, despite a number of promising results, there are still challenges that need to be addressed before industrial implementation.

Finally, based on the reviews per technological or assembly design aspect, the research opportunities and challenges are highlighted. The intention is to aspire future activities to finally bridge the gap between the rigid and non-rigid assembly automation maturities, through increased dexterity and cognition capabilities of handling agents.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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